Investigation on the implications of passive fire barriers on the fire fighting tactics of the Royal Canadian Navy

by

Peter John O'Hagan

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Mechanical Engineering

Waterloo, Ontario, Canada, 2021

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The Royal Canadian Navy (RCN) is currently in the process of recapitalizing the fleet under the National Shipbuilding Strategy (NSS). This will result in a modern fleet that includes new marine safety requirements that did not exist at the time when the current warships were built and will be the first major vessels operated by the RCN that include passive fire barriers fitted at watertight divisions. In case of a fire, these barriers are intended to control the spread of fire between the steel compartments by preventing the conduction of heat through the steel structure into adjacent compartments, and use a non-combustible mineral insulation that is tested and certified under the International Maritime Organization (IMO) rules.

Because this is a new design requirement, fire fighting tactics and decision-making processes are based on the existing context where the watertight division is an uninsulated steel structure. In this context, the temperature on the side unexposed to fire is a good indicator of conditions on the side that is exposed to fire. Surface temperatures and any visual cues on the painted steel surfaces (such as off gassing, blistering or burning paint) are useful in determining if safe entry through a door or hatch is possible, and what tactics should be used. If the unexposed side is cool, then it can reasonably be assumed that there is no fire in the immediate vicinity of the opening.

With the inclusion of fire insulation in the new vessels, these assumptions are no longer valid, as the mineral wool insulation is specifically intended to prevent the transfer of heat to the unexposed side. Since the unexposed surface is cool, personnel responding to the fire using existing tactics and training tend to be more aggressive and may not follow the normal entry procedures. The demonstration of full-scale results from live fire testing including video, temperature data, and infrared images will be invaluable in explaining the impact to RCN personnel. In turn, this will allow personnel to modify their approach to include suitable caution in the new circumstance.

The RCN currently uses a two-tiered response, which consists of an initial response by the Rapid Response Team (RRT), and a second response by a fully equipped Attack Team (AT). The RRT uses visual cues and the sense of touch, and the AT uses both visual cues and the infrared readout on a thermal imaging camera (TIC). Although the certification testing demonstrates that the fire insulation will prevent the unexposed side from exceeding a threshold temperature within a specified time rating, it does not provide the full temperature data during the certification testing, which will have an impact on current tactics.

The thesis includes a description of the experimental design, instrumentation, a continuous data capture setup, and construction details for the custom steel test wall that

includes features such as pipe penetration and a simulated door to replicate a typical watertight division that you would find on a ship. Key results for each of the 10 large-scale tests from the simulated marine compartment fires demonstrate the unexposed surface temperatures for both uninsulated and insulated cases, giving insight into how the insulation changes the context, and how feasible different structural features may be to use as 'tell-tales' when assessing how to safely conduct the compartment entry.

How paint responds to fire is a key piece of information for the fire fighting tactics. Small scale testing methods were developed to evaluate how the fire insulation interacts with a painted structure and predict how the surface temperatures relates to various visual cues (such as when the paint on the unexposed side begins to smoke, blister and eventually burn). Understanding paint responses in this environment will help improve current training, help naval architects understand how to safely scale up insulated and painted structures, and provide input for improving marine compartment fire modeling.

The inclusion of fire insulation to create passive thermal barriers on ships represents a significant safety improvement, and its efficacy has been demonstrated in both certification testing and in shipboard fires. The results from this thesis provides data that shows real temperatures on the unexposed side during both the RRT and the AT time frames will be used to improve the current training, and adjust existing fire fighting tactics and decision making process in the RCN. Additionally, fire insulation is installed on merchant vessels, and thus these results will therefore be of interest to land-based fire fighters responding to marine fires.

Acknowledgements

The completion of this Masters program would not have been possible without the support and advice from Dr. Elizabeth Weckman. Her expertise, advice and mentoring was critical in developing a thesis topic that was relevant to the Royal Canadian Navy, while considering the practical realities involved. Dr. Weckman went above and beyond to ensure the experiments and thesis remained focused on the core issue to ensure the results were relevant, and could be applied by the Royal Canadian Navy to improve the current fire fighting tactics used by serving sailors using simple, and practical changes. Her dedication to her students and the quality of the research from the Waterloo Fire Science lab is incredible, and with the normal events in life plus the additional challenges presented by COVID 19, I don't know if I would have finished this program without her support. I look forward to continue to collaborate with Dr. Weckman (and other fire scientists) to continue to improve fire safety in the Royal Canadian Navy.

I would also like to thank Mr. Andy Barber for his help and support in the design and setup of the experiments. He was critical in getting the wall unit installed and instrumented, and I learned an immense amount from him about troubleshooting circuits and other practical issues that you run into in a customized experiment setup. He's an essential asset to the Fire Research Lab, and without his help, I would not have been successful in translating designs on paper to reality.

Completing this research would also have not been possible without the assistance of my fellow student, Vusal Ibrahimli. Doing the academics remotely and traveling onsite to conduct the research experiments was only possible with his help in instrumenting the wall test unit and conducting the 10 full scale experiments in a limited window. Additionally, with the COVID-19 restrictions, the small scale bench test results were only possible with his assistance, so will be forever grateful for his help. The contributions of paint to compartment fires onboard ships may be a significant and overlooked risk factor (particularly for older vessels painted by overzealous sailors), and this is an area that, based on the preliminary results, should get some more attention. I think Vusal was much more help to me in my research than I was for his, but I look forward to continuing to see his future contributions to the field.

I would also like to thank the other students at the Fire Research lab (in no particular order); Bronwyn Forrest, Jennifer Ellignham, and Alexander DiPaola. I learned a lot from everyone, and it was a really supportive, collaborative environment, especially coming in as a mature student 15 years after completing my bachelors. I looked forward to every day I spent at the research lab, and my only regret for this Masters was that I wasn't able to spend more time in Waterloo to work with this great team of people.

Only minor changes were required to the wall test unit to conduct this set of experiments, so I also owe a debt of gratitude for to Matt DiDomizio for all the work he did in the design and build of that unit, and his continued assistance and technical support. These results were only possible by building on his previous work, and hope to continue to leverage that wall test unit for future work to expand on these results.

Much thanks to Mr. Ricky Seto at Rockwool, who donated the Searox insulation used for the experiments, as well as technical support that helped develop and inform the experimental setup. Similarly, thanks are owed to the team at AzkoNobel, who donated the marine primer and painter used in the small scale experiments, and made the arrangements so that I could pick it up in the Waterloo area.

I also received a lot of technical support, advice and general support from a number of experts from within the Royal Canadian Navy, so much thanks to (in no particular order); Francois Lepage, John Chaulk, Gille Labrie, Dr. James Huang, Dr. Royale Underhill and Dan Salvage. Finishing this thesis as a part time student while juggling work has been interesting, so appreciate all the support from the the various people within the Navy that have really embodied the idea of 'max flex' in getting this done during a pandemic. Additionally, thanks to Tom Sheehan, who got me excited about this area of interest; I never thought I'd go back to school again but this became as much of a passion project as an education and job.

Finally, thanks to my family, who have continued to provide love, support, and occasional jokes to help me get through all this. My wife jokes that this all boils down to 'put water on it', and usually can't disagree (but it's more complicated than that!). This lifetime interest in figuring out how things work started early, so thanks to my Mom, Dad and sisters for having patience when I occasionally took things apart and helped find a productive use for that curiosity.

I'm sure I've missed a number of people, so a blanket thank you to everyone that contributed in some way. Any errors in this thesis are my own, but this was only possible with a lot of help along the way.

Dedication

I'd like to dedicate this to all the sailors serving their country, as well as all the merchant sailors around the globe that keep the complex global maritime supply chain running. I joined the Navy for the adventure and stayed for the people, and it's been quite the ride so far with some experiences I'll never forget. Never thought I'd go back to school, but the chance to maybe do something that would help keep sailors safe was a pretty great motivator, and let me 'Hold Fast' on more than one occasion. Hope for 'Fair Winds and Following Seas', but optimistic that this will contribute to safer responses for when things don't go as well.

Copyright Authorization

Table of Contents

4 Results and Discussion 95

List of Tables

List of Figures

List of Abbreviations

ABS American Bureau of Shipping 12

CCG Canadian Coast Guard 1

FTP Fire Testing Protocol Code (2008) 1

IFSTA International Fire Service Training Association 7

IMO International Maritime Organization 1

IR Infrared 5

LR Lloyd’s Register 12

NFPA National Fire Prevention Association 7

NSC Naval Ship Code 1

NSS National Shipbuilding Strategy 1

RCN Royal Canadian Navy 1

SOLAS Safety of Life at Sea 1, 11

TIC Thermal Imaging Camera (sometimes Thermal Imager Camera) 5

Chapter 1

Introduction

Canada is currently in the midst of a long term project to replace the combat and non-combat vessels for both the Royal Canadian Navy (RCN) and the Canadian Coast Guard (CCG). New ships are currently under construction and will be delivered under the National Shipbuilding Strategy (NSS); these will be compliant to the current international marine safety regulations and other regulatory requirements. In particular, these will be the first major vessels operated by the RCN that include passive fire barriers, which are intended to prevent spread of fires between watertight compartments using non-combustible mineral wool insulation. While this requirement has been in place for several decades, it became law after the last major warship was built for the RCN. Since the current class of warships operated by the RCN does not include any fire insulation, the non-insulated boundary conditions form the context for which the current fire fighting tactics have been developed. The work carried out for this thesis begins to quantify if and how this new requirement will impact existing fire fighting tactics in the RCN, and also to identify areas that may warrant more in depth study.

The updated requirements for fire safety were developed by the International Maritime Organization (IMO), a United Nations organization that is responsible for setting the global standards on safety, security and environmental issues for marine vessels. These are laid out under the Safety of Life at Sea (SOLAS) regulations, with the fire safety requirements further detailed in the Fire Testing Protocol Code (2008) (FTP), both of which will be further explained in the section below on the regulatory framework and requirements. Canada and other allied nations have committed to meeting or exceeding the same standard of safety for warships. These efforts have led to Canada's participation in the development of the Naval Ship Code (NSC) which includes design guidelines for fire insulation using methods suitable for the unique needs and risks faced by warships.

For consistency, when discussing ship structure, a wall will be referred to as a bulkhead, a floor will be referred to as a deck, and a ceiling as a deckhead. Horizontal openings in walls are still referred to as doors, and a vertical opening through the floor or ceiling is referred to as a hatch.

For understanding the unique context of marine fires, it is important to understand that, unlike a land based fire, evacuating the ship is not a safe option. For a vessel underway, evacuation is a last resort, as the ocean is a dangerous environment, and even with the advances in life rafts and search and rescue, there are are significant risks to the crew. To account for this, ships are subdivided into independent sections to allow for compartmentalization, with both horizontal and vertical internal divisions that are smoke and watertight. In either a fire or flood emergency, this will contain the emergency as much as possible to a single section and allow the ship to continue to operate (with warships typically having a much greater degree of compartmentalization compared to commercial ships due to the associated combat risks).

Redundant systems that are geographically separated are required to maintain basic propulsion and navigation capabilities during an emergency, as are sheltered areas for the crew on board the ship. In the SOLAS regulations, these design requirements are particularized based on the size and function of the vessel, so that factors such as passengers and different cargo risks are considered. Because of their unique operational requirements, warships need different design solutions, which is why the NSC and other naval standards were developed. In either case, the addition of fire insulation improves the compartmentalization by adding a thermal barrier to aid containment of both the heat and smoke in the main fire compartment without the necessity for additional intervention from the crew.

When a watertight division on board a ship is designated as a fire division, any opening in that bulkhead will meet the same insulation standard as the fire division. The level of insulation required is based on the fire risk, and is a performance based insulation requirement to meet either a 15, 30 or 60 minute fire rating. This creates a consistent thermal barrier to prevent heat from the fire conducting through the steel structure and spreading throughout the ship. For commercial ships that rely on containment and fitted systems to control the fire, the presence of the thermal barrier ensures that there will be a safe area for evacuation. This is needed since firefighting efforts by the crew on commercial ships is typically defensive in nature and intended only to prevent further spread. With limited equipment and training for the crew, fitted systems (such as sprinklers) are relied upon as the primary method used for putting out any fire.

In contrast, on navy vessels, such heat transfer previously was prevented by setting 'fire boundaries', with a damage control crew that manually prevented the heat from spreading beyond the initial watertight compartment by using cooling water. This was done because most naval crews are equipped and train extensively to engage in offensive firefighting which is a key survivability consideration when engaged in combat after battle damage has been sustained. Therefore, instead of relying on sprinklers to control the fire, a naval crew might enter the compartment where the fire is located in order to control or extinguish it. Unique considerations such as this means that the context of fire fighting tactics between commercial vessels and naval vessels can be vastly different. Therefore, it is important to review and update fire fighting tactics as design standards are updated on a naval vessel as the design changes may also impact the underlying assumptions and conditions that originally formed the basis for fire fighting operations. Further, there is increasing interest in taking advantage of technology to reduce crew sizes and save on in-service costs by the Navy. Thus, new understanding of where the fire insulation can be taken advantage of and what risks remain are key to safely incorporate this feature into both vessel design and fire fighting tactics in the RCN.

In current marine firefighting tactics, the temperature of uninsulated steel divisions can be used to judge the local fire severity prior to entering a fire compartment (via a door or hatch). In the new designs, the doors and hatches on the fire divisions will be insulated to the same standard as the divisions to create a continuous thermal barrier. As a result, surface temperatures on the bulkhead around the opening to a compartment with a fire may no longer be a reliable indicator of the temperature and conditions on the interior to that compartment. It then becomes difficult for the fire fighting team to judge the severity of the situation in the immediate area. In simple terms, previously a 'cold' entry door to the compartment was an indication that it was safe to enter the compartment, while things like high surface temperatures, blistering paint, warping metal and other indications of a 'hot door' would indicate that that 'door' may not be a safe entry path without proper fire fighting equipment, and that specific tactics would be required as part of the entry. This change would significantly affect the decision loop that needs to be made as part of the entry procedure, since in the current process the surface temperature is used to determine if it is safe to open. Further, because the fire ratings at different divisions will vary based on the design requirements, understanding specific changes to the installation of insulation as the fire rating increases is also important in understanding how heat transfer and thermal cues to severity may be impacted during a fire scenario.

As noted above, the spread of fire via conduction of the heat into adjacent watertight compartments is currently restricted by boundary cooling, which consists of the manual application of water to cool the deck or bulkhead as needed and create a thermal break to protect against heat conduction to other areas. While this tactic may not be necessary where insulation is installed on a fire division to prevent heat transfer, it is not understood what effect the containment of heat by the insulation will have on the painted steel bulkhead surfaces. It is, then, also of interest to determine whether there will be sufficient heat built up to pyrolyze the paint underneath the insulation and generate sufficient quantities of smoke in adjacent compartments to impact tenability.

Because the crew cannot simply evacuate the ship safely, part of the fire safety design requirement for a ship is to include systems to maintain a tenable atmosphere in as much of the vessel as possible by automatically preventing any smoke generated by a fire from spreading to adjacent areas. In addition to providing safe egress routes during the initial stage of the fire, maintaining tenable conditions throughout the majority of the ship is critical to the crew's ability to safely respond and recover from a fire, and typically includes additional precautions to protect the areas required to safely operate and navigate the vessel.

To supplement the automatic systems, part of the current fire response includes personnel in the adjacent compartments to the fire providing cooling to those areas and preventing further spread of smoke by additional compartmentalization in the vicinity of the fire. Thus it is critical to understand any changes in the way in which smoke will develop in adjacent compartments with fire insulation installed prior to any potential revision to the roles of personnel employed at the fire boundaries relative to how they are employed under existing tactics. For example, making assumptions that the boundary personnel are no longer required because the fire insulation provides a thermal barrier may lead to uncontrolled spread of smoke throughout the ship and thereby endangering the crew and disrupting fire fighting efforts which rely on staging areas having tenable atmospheres. So prior to changing current fire fighting tactics, it is critical to understand what is the difference between the certification testing and the real world fire scenario that you would find on a ship.

Finally, because the insulation strategy implemented at each fire division has a different time rating depending on the compartment fire risk, it is not known what happens during fire scenarios that extend past the rated fire duration. In particular, it would be of interest to determine, when fire insulation is installed, how effective boundary cooling tactics with water might be to create a thermal break late in a fire of extended duration.

This research was undertaken in an attempt to begin to develop answers to the above-listed unknowns, as well as to develop useful testing and analysis methods through which to later extend experimental results and outputs from computer modeling to situations even more representative of the actual configurations encountered on naval vessels.

1.1 Research Objectives

The objectives of this research is;

1. To examine the temperature differences on the unexposed side of a non-insulated bulkhead and the insulated bulkheads to determine if changes are required for the RCN firefighting tactics and training; and
2. To undertake a preliminary, small scale study to determine how the presence of paint, in combination with the new insulation, might affect the fire fighting response and procedures.

The addition of fire insulation is a significant improvement in fire protection on board vessels; however, the FTP Code test requirement is a PASS/FAIL result designed to ensure the unexposed side of a bulkhead does not pass a threshold temperature within a designated time period. This is effective in preventing a fire from spreading through a watertight division by preventing the transfer of heat and does constitute a significant safety improvement. At the same time, it changes the fire compartment boundary conditions as well as the overall context for the current set of marine firefighting tactics and procedures.

While common sense dictates that the unexposed side of an insulated division will have lower temperatures than a non-insulated one in a fire scenario , there is no data available to judge how much lower the temperatures may be, particularly in more realistic, less severe fires than those used in the certification testing. Therefore this research was tailored to verify the expectation and quantify the resulting thermal differences, particularly for a bulkhead that included some structural features representative of a bulkhead that would be found on a ship. By using a representative, well instrumented test wall with controlled fire exposures it was aimed to better evaluate how current marine firefighting tactics may be affected by the use of insulation required under the new SOLAS regulations.

To meet the above objective, a steel test bulkhead was designed to include structures that would be found on a typical marine bulkhead and door way, including a pipe penetration, structural reinforcement, door securing arrangements and a door handle. This created a composite structure representative of a realistic ship setup that could be tested under the complex heat transfer scenario found during a fire to better evaluate what personnel involved in an emergency fire response on a RCN ship would see at each of the different stages of fire development.

The data captured includes temperature distribution within the fire compartment and video characterizing the fire conditions, as well as continuous temperature monitoring of key points on the unexposed side of steel bulkhead to gather data relevant to personnel looking to enter the fire compartment as part of their response.

In addition to capturing research data, an important objective of this study was to gather data that was useful for training of RCN personnel about the response of the new insulated walls to fire exposure. High Definition video and Infrared (IR) images captured using the Thermal Imaging Camera (sometimes Thermal Imager Camera) (TIC) observing the unexposed side of the test wall were useful for documenting and analysing the experiment, but will also be combined and edited to enhance current personnel training. These clearly demonstrate what a responder might see with their own ruggedized TIC, as used by RCN fire fighting teams. In addition, the video results and IR images are generally more illustrative across a wider field of view than can be represented by raw temperature data plotted on graphs.

As a final step in the research, preliminary bench tests were done to quantify the temperature at which the paint coating system will begin to discolour, smoke and blister. This complements the above information and is useful to correlate the observed temperatures on untreated steel surfaces to what visual indications may be evident for personnel responding to a fire emergency. Further, it provides information about the threshold temperature at which the paint will begin to off-gas and produce smoke, which is important to understand for safety of personnel and for taking action to prevent the spread of smoke. Additional bench testing methods were developed and conducted to investigate how the paint coating interacts with the installed fire insulation, as well as how smoke generation and heat release rate from the coating will change over the life of the ship due to accumulation of paint layers over time. This is of critical importance to understand prior to making changes to the current roles of personnel employed in adjacent compartments, who are responsible for both boundary cooling to provide a thermal break, and smoke management to maintain tenable conditions in the remainder of the ship.

The combined results from this research thesis are of particular value for modeling purposes, as they could potentially have a significant impact on analysis and determination of the escape routes and tenability conditions in a main watertight fire compartment, while taking typical changes over the vessel's life into consideration as well.

Chapter 2

Background Information

2.1 Literature review

Marine firefighting is a niche subject in the fire safety arena where the focus primarily is on structural or outdoor fires. This corresponds directly with the relative number of fire incidents in each context; for example between 2005 and 2014 the National Fire Information Database in Canada recorded 439,256 structural, vehicle and outdoor fires [6]. For comparison, during a ten year period from 2008 to 2017, the Transportation Safety Board of Canada had an average of 41 fire incidents reported [28]. Accordingly, a literature review for the present research did not find any previous work done on how the introduction of insulated fire divisions may affect fire fighting tactics on marine vessels.

There are several commonly used standards and references related to marine firefighting but these similarly approach the subject from a different perspective than that in this research. Typically, the topic is approached from the perspective of land based fire fighters who are responding to a marine fire, so is intended more for civilian vessels in a harbour, with the local fire department personnel acting as the primary responders. In North America, National Fire Prevention Association (NFPA) has published Standard 1005 for the training of land based fire fighters for marine fires, which is widely used as a qualification standard in local fire departments located near waterways or harbours that may respond to a fire on a ship [23]. For more detailed manuals that discuss the basic of how ships are constructed, general procedures, tactics and risks the International Fire Service Training Association (IFSTA) manual for marine fire fighting for land based fire fighters details information relevant for the response of a local fire hall to a ship fire in harbour on typical civilian vessels. The information is not complete for the present purposes, however, as it only notes that insulation may be present on the bulkheads, without discussing any implications of the presence of the insulation on the fire progression, or on the tactical decision making process [11].

The other widely used IFSTA reference is the Marine Fire Fighting guide (see [10]). This is the most in depth public reference on marine fire fighting tactics that could be identified. This reference includes a description of procedures and tactics, as well as some basics about the existence of fire divisions. However, with the exception of a note that high surface temperatures on a fire division would likely indicate a severe fire on the opposite side, it does not specifically address how that may affect fire fighting tactics, such as space entry procedure or boundary cooling [10].

In addition to the publicly available references, the author reviewed the specific Royal Canadian Navy manual for fire fighting. While it includes specific considerations for naval vessels, such as fire fighting in areas of ammunition storage, it also does not specifically address any impacts of the design of fire divisions (i.e. with or without insulation, et cetera) on fire fighting tactics and decision making [7].

Based on the lack of specifically relevant literature, the design of experiments in the present research focused on gathering some basic data to begin to quantify the possible impacts on fire indicators of installing insulation on compartment divisions, using a generic fire scenario and representative ship features built into a composite wall. No RCN considerations from [7] were included in the investigation to ensure wide and open publication of the results, though the basic procedures are comparable to what is described in detail in [10] and summarized below for context.

2.1.1 Recent example of a major fire on a naval vessel

Even though it is a much lower frequency event, the recent fire on the US navy ship *Bonhomme Richard* while alongside in San Diego is a good example of the possible severity and impact of a shipboard fire that underlines the importance of understanding fire indicators as they relate to fire fighting tactics in the RCN. While the *Bonhomme Richard* may be an extreme example, as the ship was undergoing significant maintenance, firefighting systems were not available and normal compartmentalization procedures to limit fire spread were not feasible, it gives an idea of both how difficult it can be to put out a fire on a ship once it grows beyond the initial compartment, as well as the potential order of magnitude of the financial losses and loss of operational assets that can result. At the same time in this instance, the US Navy was able to deploy multiple large teams of trained fire fighters as well as significant external assets such as fire tugs and helicopters with water buckets to prevent an even larger event. While it was fortunate that there were no injuries, the ship was a total loss due to an estimated repair cost of between 2.5 and 3.2 Billion USD and a timeline of between five to seven years [32], which is comparable to the cost and timeline to build a new vessel as a replacement.

While most marine fires are not this extensive and ships can be repaired afterwards, it does illustrate why these are 'low frequency, high impact' risk events, and also demonstrates why there is a greater investment in fire safety equipment and training than for a civilian ship. Particularly for dedicated combat ships, robust fire safety design/equipment and high level of crew training are key considerations when looking at surviving combat damage.

2.2 Civilian vessels versus naval vessels

Typically naval vessels are more complex with additional and unique risks over the typical civilian ship. In particular, they have different operational requirements, including possibly sustaining and continuing to operate with combat damage. Therefore, their designs do not fall under the same regulation as civilian vessels, as those may not be appropriate for naval requirements. Instead a separate set of standards has evolved with the general intent of meeting or exceeding the safety performance standard set for civilian vessels as far as practicable, while simultaneously responding to the unique requirements for naval vessels. Since it is key to the context for this work, the naval regulatory environment will be discussed in greater detail below.

2.2.1 Vessel differences

Depending on the function of the vessel, some will be built to/near civilian standards, but may incorporate additional features such as ammunition storage, or at sea refueling capabilities not normally found on civilian vessels. The typical warship on the other hand is quite different as they have unique explosion/shock and similar combat requirements. From a fire safety perspective, the biggest general differences seen on a warship relate to features such as greater redundancy in critical systems such as the fire main, redundant control station locations for emergencies, and a higher degree of compartmentalization.

In common, any modern ship will have similar detection and suppression equipment, and have systems in place to control the spread of smoke and close watertight doors and hatches to limit the spread of fire outside of a compartment of fire origin. For the purposes of this research, many aspects of the basic marine fire fighting approach would be the same. The primary difference would be that a warship design is more subdivided and includes systems to better compartmentalize the fire to a smaller area. More equipment is also distributed around the ship to allow a fire fighting team to put out the fire directly, rather than rely solely on a set of fitted systems for fire control and suppression.

2.2.2 Crew differences

Generally a civilian crew will have extremely limited firefighting training. Therefore, the crew will primarily respond by evacuating an area, confining the watertight section, and activating any fitted system (if available). If that is unsuccessful, they will likely leave the area sealed off, attempt to keep the boundaries cooled down using fire hoses and allow the fire to self-extinguish once it consumes the available air in the now sealed compartment. Additionally the crew itself will normally be quite small, with large container ships having 20 crew members or less on board.

In contrast to a commercial ship, every member of a naval crew will generally have some basic fire offensive and defensive fighting training, with some having more specialized and in depth training. Because naval vessels may be expected to sustain damage during combat operations while engaged in several concurrent activities over an extended period, they will typically have significantly larger crews for the size of vessel. This allows the crew members to be more proactive and engage in direct fire fighting operations, with the appropriate equipment, training and regular practice to remain prepared.

2.2.3 Civilian versus naval tactical response

Even if the general ship systems are similar, there is a significant difference in tactical response between civilian and naval vessels because the Naval crews are equipped and trained for offensive fire fighting (i.e. entering the fire compartment and using a fire hose or similar to put out the fire), while the typical civilian crew will only engage in defensive firefighting (i.e. confining the fire and preventing it from spreading outside the compartment of origin).

For a civilian crew, the addition of insulated fire divisions into the vessel design are a key safety feature that is intended to prevent further spread. In a scenario where the fire is not put out quickly with a fitted system, the fire divisions prevent thermal transfer through the steel structure to adjacent compartments and thus form a passive measure to limit the spread of fire outside the watertight compartment with no intervention by the smaller and less well trained commercial crews. Prior to the introduction of fire divisions, heat was able to spread through uninsulated steel so that even though the fire may be sealed inside a water and smoke tight compartment, it was still possible for it to spread by heating up adjacent compartments enough for auto-ignition of available fuels. This risk was partly mitigated through the IMO standards that limited the compartment fuel loads and the flammability properties of all materials used on board. The recent addition of fire insulation further decreases the risk of fire spread by inhibiting the spread of heat to adjacent compartments.

For a naval crew, the new fire divisions perform the same function in terms of preventing the spread of fire by containing the heat. At the same time, they eliminate the previous direct feedback to responding crew members about the conditions of the fire compartment from the opposite side of the division. Before the new insulation regulations came into effect, an uninsulated steel bulkhead could reasonably be expected to be 'thermally thin', with no thermal gradient across the cross section of the plate steel. This meant that any hot surfaces forming the boundary of the fire compartment would be evident from adjacent unexposed compartments. Further, this exterior temperature indicator is built into current RCN tactics, which now need to be evaluated to see if they require adjustment on new vessels that incorporate fire insulation. Specific tactics will be discussed individually below, after providing some context about the regulatory environment for naval vessels and why the present research issue is now relevant for the Royal Canadian Navy.

2.3 Naval regulatory environment

Because the treaties and international laws governing marine safety standards specifically exclude military vessels, a brief description of the Naval regulatory environment is included for context. This includes a description of how the normal marine regulatory environment works, and how the RCN self-regulates under the Naval Material Assurance program, with the Naval Ship Code being used to meet or exceed the marine safety standards developed for commercial vessels. This self-regulation includes the selection of which standards will be applied and how they are interpreted during the design, and how the oversight and verification process to ensure compliance to the safety standard occurs while the vessels are in service.

In the global environment for marine transport, the management of safety standards falls under the auspices of the International Maritime Organization (IMO), which is a UN specialty organization responsible to manage and update the maritime conventions. The key convention that deals with marine safety is the Safety of Life at Sea convention SOLAS, which includes fire protection, detection and suppression and other related elements. As the IMO signatories include 174 member states and 3 associate members, these standards have been effectively accepted around the globe. [12]

While this is effective for merchant ships, the unique requirements of naval ships results in design solutions that are not compatible with all the provisions in SOLAS, and in fact, adherence to some of the SOLAS provisions could result in a reduction of capabilities, or significant increase in costs. In 2004, NATO countries established a team made up of specialists from both the Navies and classification societies to develop a goal based safety structure that uses common worldwide standards but at the same time recognizes military operational requirements. This led to the development of the Naval Ship Code and the publication of the first edition in 2009. This document is updated annually and includes a number of safety areas, including specific fire safety requirements. [22]

In Canada these conventions have been adopted under the Canada Shipping Act and related regulations, with Transport Canada being designated as the department responsible for merchant and commercial activities. In addition to Transport Canada, a number of classification societies have been recognized as responsible third parties that can inspect and issue safety certificates for vessels. Some examples of the classification societies includes Lloyd's Register (LR), American Bureau of Shipping (ABS) and DNV-GL (from the merger of the two classification societies *Der Norske Veritas* and *Germanischer Lloyd*). These classification societies have their own design standards that provide further guidance on how to achieve the performance requirements. In order to be certified as conforming to the classification society rules, the major components and equipment need to be reviewed and accepted by the class society, as well as the overall vessel design. For fire insulation and paint coatings, both of which are included in the subject of this thesis, this means that the results of IMO fire tests[12] are submitted to the classification society, which includes the specific configuration that was tested with a certificate from a recognized laboratory that it passed the IMO test.

In this thesis, only the requirements for surface ships are discussed, as the submarines have a distinct and very rigorous safety program to deal with their unique requirements. In general, unless particular military specifications exist, different civilian standards are used. Thus, fire insulation meeting the IMO requirements will also be used in modern RCN vessels, with some additional selection criteria used during implementation of the design to account for the different fire risks found on warships.

2.4 IMO fire testing requirements

The standards for the fire insulation, as well as the testing protocol is found in the IMO Resolution MSC.307(88), the International code for application of Fire Test Procedures, with the most recent version ratified in 2010 (also known as the 2010 FTP Code)[12]. This protocol details the testing procedure used to certify fire insulation material, as well as doors, windows, floor covering material and furnishings to meet the SOLAS requirements.

The test standard looks at these components individually and uses a PASS/FAIL procedure to rank the performance the fire insulation, and also includes smoke and toxicity testing requirements for the surface finishes (such as flooring or paint coatings).

Based on the above requirements, the underlying experimental design for experiments conducted in this thesis is based on the IMO testing protocol for fire insulation. Additional structural features were also built into a composite test bulkhead to more realistically represent a bulkhead that would be seen on a typical ship. The experimental test fires deviate from those in the IMO standard as they are selected to represent more realistic fire scenarios than are used in the IMO fire testing. The experiments conducted in this research are also instrumented with continuous data acquisition to document what a crew may see during different stages of responding to a fire. This will be discussed further in the applicable section, but a summary of the IMO test protocol is included here to provide context.

The IMO FTP uses common building and transport fire performance testing procedures (such as ISO 834-1, fire resistance tests, and ISO 1182, Non-combustibility test), so no specialized laboratory setup or certification is required for marine testing. This setup forms the basis on testing for materials to be certified as meeting either the “A” or “B” classification requirements for a specified length of time.

Prior to testing the insulation values, the material is tested for non-combustibility, as well as for smoke production and toxicity.

Fire performance testing is done in accordance with the ISO 834.1 procedure, with the sample mounted as part of a standard wall setup. Thermocouples measure the temperature rise of the unexposed surface of the steel core, with the insulation installed on the exposed side. The structure can be constructed of either steel or aluminum, with minimum dimensions of 2440 mm in width, and 3040 mm in length, with stiffeners spaced at 600mm. [12]

The furnace temperature used to represent a fire temperature follows the standard ISO 834.1 temperature-time curve, which is given by;

$$T_g = 20 + 345 \times log(8t + 1) \tag{2.1}$$

This results in the temperature curve found in Figure 2.1.The temperature undergoes a very rapid temperature growth to temperatures exceeding 800 °C in the first 2 minutes of the test with a peak temperature exceeding 1000 °C during a 2 hour test in the furnace. This is intended to represent an exposure scenario that is more severe than a typical fire scenario, which would generally have a slower, more parabolic growth period to a peak temperature in the range of 600 - 800 °C, and would then decay once the combustibles are consumed.

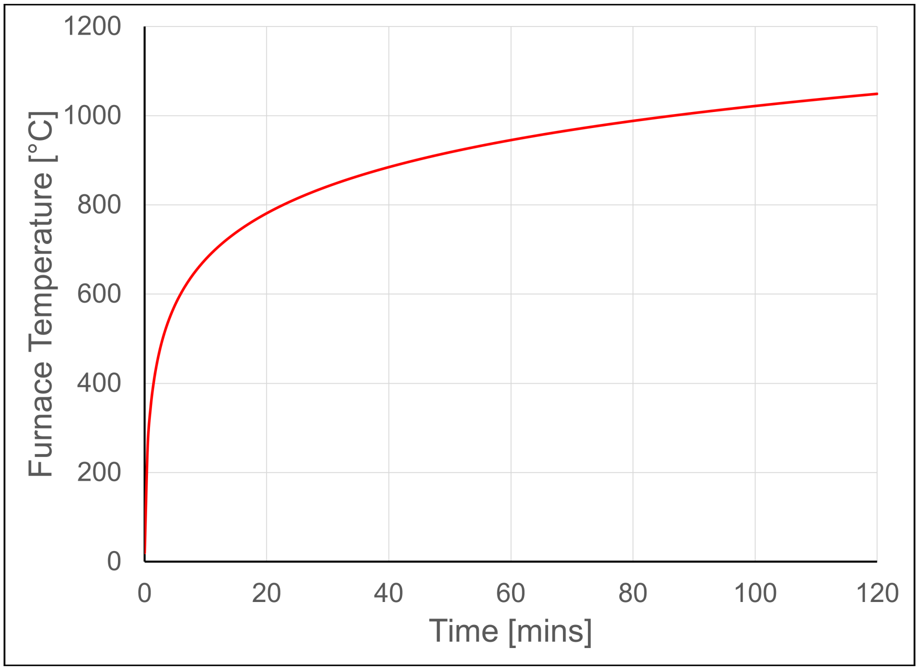


Figure 2.1: ISO 834-1 standard fire curve

2.4.1 Marine fire division - designations

There are two different fire insulation ratings; ”A” and ”B” class divisions. The classification criteria are performance based, using PASS/FAIL criteria that the fire insulation must not exceed a maximum measured temperature on the unexposed face during a defined time period. Of the two designations, ”A” class criteria require a lower maximum temperature, which requires better insulation performance than the ”B” class rating under the same test conditions.

The fire boundary also has a time rating component, measured in minutes, and uses the syntax of (Class) - (Time Period) to indicate what level the particular test configuration is qualified to. For example, an ”A-15” certification indicates that the particular configuration of fire insulation tested meets the criteria for the ”A” class division for a time period of 15 minutes, while a ”B-60” meets the ”B” class division criteria for a period of 60 minutes.

The class of fire insulation required is determined in the regulatory standards by the vessel classification system, which takes into consideration the size of the ship (based on gross tonnage) and crew size, the role of the vessel, if passengers are embarked and other relevant factors that affect the fire risk. These requirements are detailed in either the classification society standards (based on SOLAS) or the Naval Ship Code requirements, and provide design guidelines to determine what fire rating (if any) is required at each division. Generally, larger ships, passenger ships, or ships with high risk cargo will require ”A” class fire insulation, while smaller vessels with lower fire risk will only require ”B” class fire insulation. This is specified to allow a suitable level of fire protection that takes the context of the vessel into account, which balances the additional cost and weight of the fire insulation against the fire risk of the particular vessel.

2.4.2 Marine fire division - test criteria

Of interest to this research are the criteria that are required to be met to be certified for use as an “A” or “B” class steel division for the one hour fire test. These can be summarized as:

“A” Class divisions:

- The average temperature of the unexposed face shall not rise by more than 140 ºC
- no measured temperature rise can exceed 180 ºC

“B” Class divisions:

- The average temperature of the unexposed face shall not rise by more than 140 ºC
- No measured temperature rise can exceed 225 ºC

Time periods allowed for each classification [12]

- 0 minutes (A-0 or B-0)
- 15 minutes (A-15 or B-15)
- 30 minutes (A-30 or B-30)
- 60 minutes (A-60 or B-60)

Successful test results will allow the product to be certified for the specific classification, and will include details such as mounting arrangements and orientation (bulkhead, deck, et cetera) and insulation thickness, which can then be used in the design of the vessel to ensure it meets the code requirements. These details also need to be followed during installation onboard the vessel for the fire insulation to meet the required standard.

Additionally any door or hatch through the division needs to be certified to the same fire performance level, with any penetration (such as wiring, piping or HVAC) similarly protected, subject to the same test conditions and criteria. For the experiment, this means that a uniform level of fire insulation can be installed on the customized test wall, which is consistent with both the insulation certification process and a ship board installation.

2.5 Marine Fire Division - Insulation installation and mounting

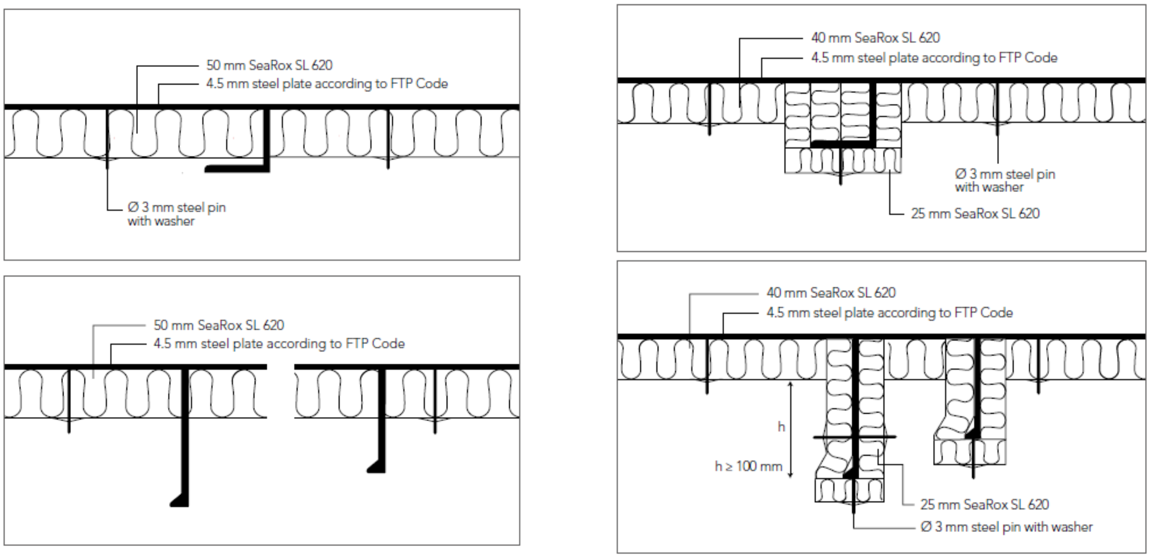
As part of the design process, the level of protection required at the fire division is determined based on either the SOLAS requirements (incorporated into class society standards) or something similar to the NSC requirements for naval vessels. Once this is determined a qualified supplier is selected and the insulation will be installed as per the setup that was tested.

For example in Table 2.1 shows the standard installation configurations for the marine grade SeaRox 620 SL insulation used in this experimental setup for A-15, A-30 and A-60 classifications. These configurations have all been tested using the IMO protocol and have been reviewed by the classification societies for approval.

Insulation Standard	Location	Thickness
A-15	Plate	50mm
	Stiffener	**no insulation**
A-30	Plate	40mm
	Stiffener	25mm
A-60	Plate	60mm
	Stiffener	25mm

Table 2.1: Rockwool Searox 620 SL approved installation configurations [16]

The change in the required level of insulation as the time period is increased is demonstrated in Figure 2.2. Initially only the large plate sections are insulated, with the stiffeners exposed. As the time rating increases to 30 minutes, the stiffeners are also insulated to eliminate the thermal conduction path from the face of the stiffeners to the unexposed side. As the time rating increases further, the insulation thickness increases as well.



(a) A-15 Standard installation

(b) A-30 Standard installation

Figure 2.2: Comparison of SeaRox 620 SL standard A-15 and A-30 configurations [16]

The insulation itself is mounted on standard 3 mm stainless steel pins with 38 mm spring washers to hold it in place. The pins extend nominally 10 mm past the washer and are typically bent over and capped/taped over to avoid a sharp protrusion. The maximum spacing allowed between pins is 300 mm, with a 150 mm offset from the structural stiffeners.

Where the fire division terminates at the edge of a deck, in order to prevent thermal conduction along the boundary, additional insulation is installed around the adjacent structure for least 380mm for steel structure (450 mm for aluminum alloy)[12].

On board a vessel, the installed fire insulation will include a surface finish on the visible side in the compartment. This could be a reinforced aluminum foil or glass cloth and is intended to prevent moisture and oil penetration. A variety of additional decorative facings are also available to cover the exposed surface of the fire insulation for aesthetic purposes, which may include a non-structural sheet metal facing that can be either painted, or have simulated surface finishes (wood, marble et cetera) applied. The decorative facings will also be tested to meet the IMO FTP standards, but do not contribute to the fire rating of the division. These finishing products are not typically included on RCN vessels, so were not examined as part of this research.

2.5.1 Marine fire division- treatment of penetrations

Similar fire rating requirements exist for penetrations, such as piping, electrical conduit and HVAC trunking. In addition to the air and water tight seal required to maintain compartmentalization, fire insulation is installed at specified distances along the penetration from the bulkhead or deck. The material specifications for the penetrations are determined by a variety of standards, and include requirements such as low smoke generation for wire insulation, with the IMO standard containing specific instructions for how to insulate the penetration, as well as prohibiting certain materials from penetrating A class bulkheads and decks (such as piping with a melting point below 1000 °C).

Under the IMO FTP, in order to meet the fire division rating requirement, piping with a melting point greater than 1000 °C must be welded directly to the bulkhead, or bolted onto a flange welded to the penetration point. Insulation meeting the same standard as the fire division is installed on the piping a minimum of 380 mm from the steel bulkhead (or 450 mm if it had been aluminium structure). [12] Figure 2.3 demonstrates this arrangement for a steel pipe that is penetrating an insulated bulkhead, and how the fire insulation is incorporated onto the piping to maintain the fire division thermal barrier.

Electrical conduit and HVAC trunking that penetrate fire divisions have similar exterior insulation arrangements, with the HVAC trunking also including internal fire dampers to

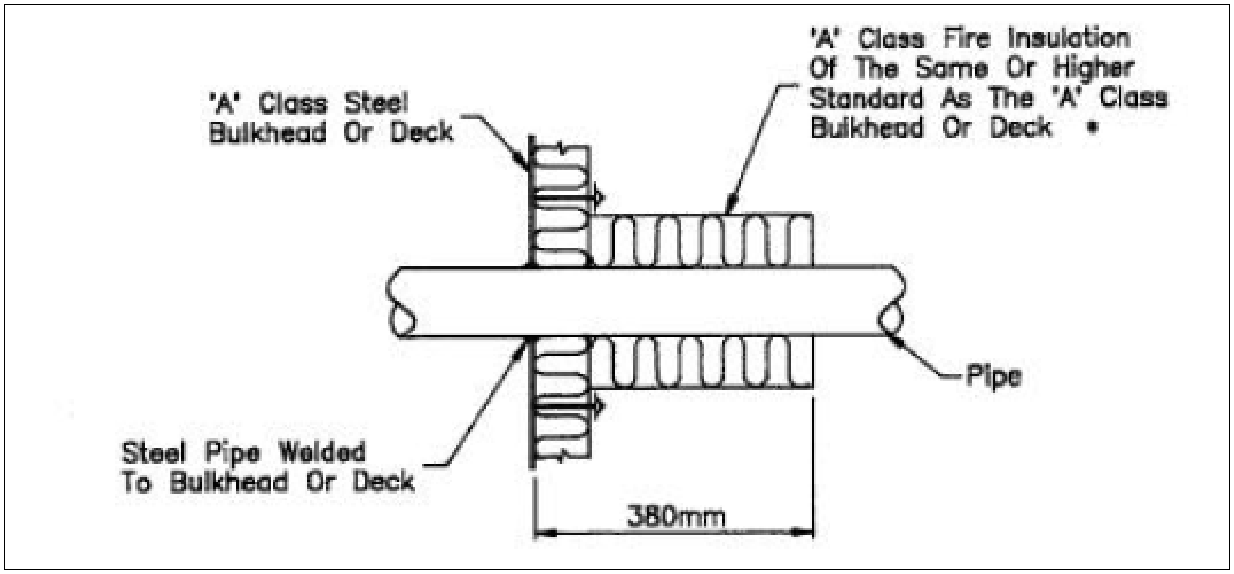


Figure 2.3: Diagram showing pipe penetration fire insulation installation requirements[30]

prevent the spread of smoke in case of a fire. Those elements were not examined in this research due to the limited wall surface available in the test unit.

2.5.2 Other considerations - Paint coating used for Corrosion protection

Because ships are normally made of carbon steel and operating in a corrosive salt water environment, the inspection and maintenance of the paint coatings that protect the structure is a critical regime to prevent rust from causing significant damage to the vessel. Because most of the boundaries in a compartment will consist of a painted surface, the IMO FTP includes a test procedure for paint, with specifications that must be met to be used onboard a ship. This testing includes performance specification for the flame spread characteristics as well as smoke generation rate and toxicity, and is designed to minimize the contribution of the paint to fire spread as well as the impact of any smoke from the paint on compartment visibility and tenability.

In a typical compartment, the bulkheads and deckheads will be painted with a two part primer and topcoat system, and any HVAC or fire insulation required will be installed over top. Mineral wool fire insulation can be applied on the ceiling of the compartment below a deck but instead, most decks have a tile or similar flooring system installed that also must comply with IMO FTP requirements. This research focused on the use of the mineral wool fire insulation as that is the solution used on RCN vessels, so fire rated flooring systems were not examined, but may be relevant to marine fire fighting on yachts or cruise ships where it is more commonly used.

The paint coatings are normally renewed every 5 years during a docking period, which can be done either via application of another topcoat (after suitable preparation to remove salt and ensure adhesion), or through the complete removal and application of a new coat of primer and topcoat. The complete removal is typically only done if the paint is in poor repair, or if the steel requires repairs, because of the labour required to properly prepare and remove the paint coating back to bare steel. Thus, it is not normally done if the paint is in generally good condition and is properly adhering to the steel. In the experience of the author it is common for paint to accumulate on compartment walls and ceilings during the life of the vessel, particularly in accommodation spaces and corridors in the vicinity for quality of life reasons, and may impact the safe available egress time for a fire in the vicinity if it impacts the flame spread, smoke or toxic byproduct generation characteristics of the coating beyond what is allowed under the IMO FTP. As RCN ships also can be used for diplomatic purposes by hosting guests while in foreign ports on behalf of Canada, the accumulation of paint can be particularly prevalent in the high traffic areas that VIP guests would have access to while on board, as these areas may be more frequently repainted while in service prior to high profile diplomatic events. As these corridors can form part of the boundaries for higher fire risk compartments (such as high powered electronic spaces) this may increase the risk of fire spread and the smoke generation in adjacent compartments during those fire scenarios.

The paint renewal usually includes a coating onto existing visible HVAC insulation installed along the ceiling as well as the outer hull for a uniform colour and appearance in the accommodation and working areas. It is not clear if this practice will continue with new vessels that include installed fire insulation causing an accumulation of paint on the exposed surface of the fire insulation, but the accumulation of paint on normal steel surfaces is expected to continue. Both situations are of interest here since no data is currently available on how the accumulation of paint over a vessel's life may affect the visible indicators of fires currently used in fire fighting decision making and response, or contribute to the compartment heat load, smoke generation rate and toxicity levels in the fire compartment and potentially surrounding areas.

2.6 Naval Ship Code regulations

In order to take a more systematic approach to designing and maintaining the safety standards on warships, the RCN is adopting the principals of the Naval Ship Code, and is an active member in the development and updating to the standard done in partnership with other NATO allies. The Naval Ship Code (NSC) has eight separate safety areas to aid in management and certification, and follows similar organization to the SOLAS standard. These areas include structure, engineering systems, navigation, communication and other key safety areas. For ease of use, it is split into three separate parts: goals, solutions and justifications and guidance respectively. The requirements are performance based, and the level of compliance is at the discretion of the country, but does offer a workable rule set that can be applied to design and maintenance of a warship throughout it's life. These goals cover the same scope and an equivalent level of safety as SOLAS, while taking the operational requirements and capabilities unique to warships into account. [22].

2.6.1 Fire protection requirements

Fire protection requirements have a dedicated chapter in the NSC. In this, the primary goal of fire insulation is to contain the fire to the compartment. It also relates to minimizing effects of local heating, as well as maintaining the structural integrity of the vessel by preventing any loss in strength that may occur when the steel is heated. Specifics are described in detail below, but essentially a non-flammable insulation material is mounted to compartment boundaries to keep the temperature rise under a specified limit over a given period of time. As one part of the fire safety goal, the insulation can also be combined with other measures that prevent the spread of smoke and facilitate quick detection and suppression of a fire.

Ships, unlike buildings, have walls ("bulkheads") and ceilings ("deckheads") made of steel plating with typical plate thicknesses of approximately 5-8 mm. During a fire, although the structure itself is non-combustible, the steel is highly thermally conductive unless some kind of insulation is applied. This allows fires to spread to adjacent compartments via heat conduction and secondary ignition of combustibles, even if there is no direct flame spread or smoke propagation from the original fire compartment.

For this reason, the level of insulation required for various compartment boundaries is specified during the vessel design phase. The Naval Ship Code allows for two separate solutions; one is based on SOLAS requirements, and the other is risk based. Both determine what level of insulation is required, and are based on identifying the fire risk within a space, as coupled to the function of the space and the function of adjacent spaces.

This approach ensures that in the event of a fire, sufficient insulation is available to prevent the fire from spreading to adjacent compartments, but rationalized to minimize the added weight and contain costs.

Prior to the requirement for fire insulation being incorporated into IMO standards, any insulation between compartments was strictly for HVAC purposes, and intended for a maximum temperature of up to 50 °C . In cases where insulation was installed on doors and hatches, it was typically mounted at locations on the ship leading to outside and it was assumed that the HVAC insulation would fail under typical fire conditions (in excess of 500 °C). In this context, a valid assumption made in defining fire fighting tactics was that the entrance was 'thermally thin' and thus that the surface temperature at the entry point could safely be used as an indicator of fire progression during the fire fighting tactical decision making process.

It is therefore important to understand how the Naval Ship Code impacts design in naval vessels. This is particularly critical to the RCN and other navies, given that the non-combatant and auxiliary vessels will typically be built to meet commercial marine standards, with the Naval Ship Code only applied to combatants. In the present context, insight into the impact of any approach to fire insulation of compartment boundaries is useful and provides the necessary context to understand how those approaches might impact fire tactics and decision making. Depending on the code requirements, or with new insulation requirements, tactics may have to differ on warships relative to other vessels or alternately may remain similar across vessels where there is common ground in the marine standards. In all cases, the design changes must be taken into account to ensure that the current approach to using common individual fire fighting training for the crew, with collective training to address any class-specific issues, is still valid as the RCN undergoes a full renewal of the fleet.

The Naval Ship Code, Part 2, provides two different approaches to meet the goal of containing the heat from a fire in the compartment of origin as part of compartmentalization. The application is broken down into three different naval ship types;

- Type A- 240 or more embarked personnel, or may carry more than 36 passengers;
- Type B – 60 to 239 total embarked personnel, with no more than 36 passengers; and
- Type C – less than 60 embarked personnel, of which no more than 12 are passengers. [22]

Safety requirements increase with the number of embarked personnel and potential passengers to allow additional safety margins, and also due to the fact that this generally corresponds to an increased size and complexity of the vessel.

Solution 1 is based on SOLAS, and prescribes the fire rating, and thus insulation design, of the boundary based on the function of the two spaces that it separates. If applied, this approach requires additional requirements for smoke control to be applied. Solution 2 assigns a risk and value score to each compartment, and uses that to determine the necessary fire rating at the boundary. This approach integrates the smoke control aspect so it does not need to be applied later in the design process. The specifics between the two approaches are not relevant for the research, except to note that they may result in slightly different results in terms of what insulation rating is required at some boundaries.

In addition to the compartment insulation, the ship is divided vertically into main fire zones. These are generally no bigger than 40m in width or length (but can be extended to 48m to coincide with watertight subdivisions or for large spaces). These fire zones are divided by A-60 (S) class divisions. These vertical main fire zones apply to both solution 1 and solution 2 when determining the fire insulation rating. Further, these main fire zones give the ship three main fire safety sections, allowing safe mustering points during the initial reaction and subsequently response to the emergency.

2.6.2 Impact of SOLAS versus Naval Ship Code standard on the design

In both the commercial marine standard, and the two different NSC approaches, there will be varying levels of fire insulation installed at different divisions, and potentially different smoke control arrangements each affecting the boundary conditions of the fire as well as the conditions in the adjacent compartments. Differences in approach to design across the standards mean that there are differences in the underlying philosophy driving the result. Thus, developing universal, standardized tactics for fire response and decision making is not possible. Instead, it must be particularized to each vessel to directly relate to the actual implementation of the fire insulation.

The work done in this thesis is intended to generate preliminary understanding of the general impacts of fire insulation on compartment boundaries, so that when specific scenarios are being looked at, the context of how fire insulation may affect the fire fighting approach and tactics can be better understood. It is currently assumed that the fire insulation will reduce heat conduction and change the temperature profile on the surface in the adjacent compartment sufficiently to render current tactical decision-making approaches very difficult. However, until the extent of the change is known, adaptations of the approaches are not possible. Thus, the experimental data collected in this work will provide some objective measures to quantify the impact of the addition of fire insulation and examine if there are different indicators that can potentially be used in the fire fighting decision making process.

A key difference in modern vessel design that will not looked at as part of this research is finished surface covering on the compartment boundaries. Commercial finishes for insulation are available. These include a decorative sheet metal facing and other higher end finishes for use on passenger vessels. In naval vessels it is more likely that a finish over the insulation would be a foil or fibreglass. It is unknown if this surface will be painted or re-coated during the in-service period, so it may be useful in future work to expand to look at the specific configurations used on specific RCN vessels, and include the impact of the renewal of the surface finish on initial fire characteristics, particularly if a paint coating is applied and accumulates over time.

2.7 Marine firefighting standard procedures

To close out the background for the present research, it is important to understand some of the fundamentals of fire detection and firefighting in the marine environment. Fire detection provides insight into the fire growth and fire response timelines, while general understanding of firefighting operations is key to determination of the impact of insulation of tactical decision making. Therefore these will form the subject of this section.

The procedures below were taken from several sources, but are largely based on what is described in two publicly available publications. On occasion, the procedures from the RCN are referenced, but only in general terms to allow open publication of the thesis. Specific responses to battle damage would depend largely on the configuration of a specific warship, equipment available and other factors that may be relevant to determining the appropriate tactical decisions. These are not all addressed here, but would form a normal part of the preplanning for different scenarios within the RCN in any case, so are outside the present scope.

2.7.1 Fire detection and alarm

The effectiveness of the fire detection and alarm system on board vessels is a critical component of the overall fire response, particularly as crew sizes are reduced, leading to more compartments primarily being monitored remotely. If the fire is detected quickly, it is more likely to be able to quickly extinguished by personnel using extinguishers and minimizing the overall damage, while maximizing the safe evacuation time for personnel in the vicinity. Conversely, a delayed detection will reduce the safe evacuation time, allow additional time for fire growth and result in more damage before the initial response, and that suppression using portable extinguishers may not be effective, requiring more intrusive methods such as an overhead sprinkler, or manual application of water by an attack team.

The examination of the results includes a time sensitive analysis that breaks down the temperature plot into appropriate intervals for the two-tiered RCN response, and includes an estimate of the detection time to account for the possibility of some fire growth prior to detection. This estimate of the detection time is based on the assumption that the system is fully compliant with the relevant standard. Therefore a brief explanation of which standards apply to ships and how the monitoring system is included below for context.

The requirements for fire detection systems come from standards such as SOLAS or NATO's ANEP 77. Broadly these dictate the number and location of fire and smoke detectors throughout the vessel that are centrally monitored at an alarm panel, typically with a second panel at a separate location for redundancy. Normally the alarm panel is actively monitored by trained personnel, and will include the ability to control ventilation to prevent the spread of smoke, remote control of some fitted fire suppression systems, as well as the ability to monitor for flooding.

Additional fire detection systems may be installed in higher risk locations, such as in the vicinity of propulsion engines or electrical generators. Some modern technological innovations include image processing of digital video feeds to monitor for signs of smoke or fire, as well as increased fire hazards such as a high pressure fuel spray. These systems supplement the basic system but are all intended to allow for quick detection, and thus initial response, to any fire.

Finally, ships are normally crewed and operated 24 hours a day so there is a procedure for reporting when a crew member encounters a fire. This can include a report via radio or using the ship's internal phone system. For the RCN this will include yelling out 'Fire, Fire, Fire' loudly to alert anyone else in the vicinity to help with the response.

In all cases, once the fire is detected, this will raise a general alarm. For the RCN, this will include an announcement by the personnel monitoring the alarm panel over the ship's internal announcement system (referred to as a 'pipe') that includes confirmation that the emergency is a fire (versus a flood or other emergency), the location of the fire alarm on the ship, directions for personnel to respond, and instructions for supernumerary personnel (which is repeated twice). [7] This quickly alerts the entire crew and any other personnel onboard (such as trades people conducting repairs) to the danger, what to do and where the safe locations are. So in addition to directing the correct personnel where to respond, it also directs other personnel in terms of what areas of the vessel need to be avoided during transit to a safe location, so is a critical part of the response.

2.7.2 Initial response

Once a fire is detected by sensors, this will activate an automatic sequence to shut down all ventilation. This will include remotely shutting down fans as well as closing ventilation dampers and other openings to prevent smoke migration throughout the ship. This automatic sequence can also be manually triggered if required.

In the RCN, the initial response is done by the Rapid Response Team (RRT). The composition will vary depending on whether the ship is alongside during working hours, during after-hours, or while at sea, but will be a small team of trained personnel with dedicated roles. Additionally, it will include any trained personnel that are in the immediate vicinity of the alarm, as well as any personnel that discover signs of fire prior to the general alarm. The team will normally vary between approximately 3 and 6 personnel depending on the context. Response time depends on the location on the ship, but would typically be within 2-4 minutes of the alarm, and may be quicker. In comparison to what is outlined in [10] and [11], this is a much more robust response than the typical civilian vessel procedure, which focuses on evacuation of personnel to safety.

The typical member of the RRT will only have the standard RCN uniform as part of their personal protective equipment. This uniform contains a layer of fire resistant Nomex material to provide some basic protection to personnel. Different types of fire extinguishers are located throughout the ship, and each member of the RRT is expected to bring one to the location of the fire alarm. The majority of extinguishers are either Carbon Dioxide or water types, but more specialized extinguishers (such as dry chemical types) will be located in the vicinity if there is a specific fire risk to address.

The RRT has several immediate priorities which include;

- Performing first aid on the fire using extinguishers (if safe to do so) or activating fitted systems (if available);

- Searching the watertight compartment and evacuating any personnel found to a safe area; and
- Closing any doors, hatches and other openings to the compartment to prevent further spread of smoke, and limit the supply of fresh air.

All members of the RRT will have individual training on how to safely enter a compartment and use an extinguisher for first aid to try and put out a fire. Additionally each member of the ship's company completes a detailed on-the-job training package specific to the vessel that requires them to know the ship's layout, the location of all portable fire fighting and other emergency equipment, and how to manually activate the various fitted systems onboard. Regular team training is also conducted to ensure that the RRT can properly work together and understand the roles of others well enough to stand in as necessary. So the general concept of the RRT is to put out the fire before it grows further if possible, evacuate anyone in the area, and limit the fire and smoke to the compartment of origin by closing all openings. Because of the significant amount of individual training as well as team training involved, this represents a large time investment.

While at sea, only a limited number of doors and hatches are allowed to be open, with a focus on doors and hatches below the waterline staying closed to prevent progressive flooding. Because of the increased level of compartmentalization on a warship compared to a standard civilian vessel, closing all the doors and hatches can make it significantly more time consuming to transit the ship. So normally specific doors and hatches along high traffic areas remain open on warships while maintaining some basic compartmentalization, and are only all closed during high threat scenarios. This ensures sufficient safeguards against flooding and similar considerations without significantly impacting movement throughout the ship. This balance allows a quicker response to any emergency alarms, but still maintains sufficient compartmentalization to prevent a wide spread of smoke throughout the ship before the compartment with the fire can be fully isolated.

Alongside the restrictions are loosened as the general risk is decreased significantly. Some doors, hatches and special access panels are potentially being removed or unable to be closed due to ongoing maintenance requiring temporary trunking, wiring or similar interference items across the opening, so the opportunity for compartmentalization may be compromised. Depending on the fire location, the RRT may not have to open a door or hatch to enter the compartment where the fire is located.

In all situations, the RRT will use the procedure described below to ensure that a closed door/hatch is safe to open. Since very few watertight doors and no hatches onboard current RCN ships include a window, there is no way to view the interior of a compartment.

Instead, visual indications such as burnt paint or smoke, along with smells and sounds of smoke and fire may be the only observable signs of an internal fire showing outside the compartment of origin. Thus, using key indicators from the surrounding environment is a critical aspect and important safety factor for personnel during the response.

Both the RCN instructions, as well as the civilian fire fighting references, provide instructions to follow when opening a door or hatch where there is potentially a fire on the other side. Some of the possible signs to look for are listed as discolouration or scorching of paint around the opening or on the door or hatch itself, as well as bubbling, smoking or other surface effects due to heat transfer through the structural steel. For the RRT, instructions indicate checking the door temperature before making the entry decision which includes looking for any of the visual signs described above. If there are no obvious visual signs, the standard procedure is to then verify the door temperature using the back of the hand, starting at a point near the top, where it is anticipated that door will be the hottest, and moving down towards the bottom of the door. Because there is no access to equipment such as a thermal imaging camera during this initial response, this has proven to be an effective way to verify conditions on the opposite side of a steel door in the current context, where there is no insulation on internal doors.

For a guideline, ASTM C1055 further provides an outline of how surface temperatures can be measured by touch, with the data based on previous experimental results on the subject. It suggests a surface temperature between 32-34°C would be warm, 40-42°C would be hot, and approximately 44 °C would be the threshold temperature for pain. [5]

If there are indications the door is hot, it is assumed to be unsafe for the RRT to advance further without first donning proper bunker gear (or turnout gear) (i.e. the protective fire fighter ensemble). If a fitted system is available, they will take the hot door as a confirmation of the presence of a fire and activate it, and then divide up to complete various tasks related to a full fire response. At this point, some crew members will stay on location to begin setting up fire hoses from the nearest station.

If the door is cold, or if it is only warm, there is a procedure for the RRT members to open the door under control, verify it is safe to enter, and then proceed to investigate the watertight compartment to perform first aid on the fire. This will include attempting to put the fire out with available extinguishers if it is safe to do so. This procedure includes a quick initial check with the door only partially open under control, so if the compartment is in an underventilated fire condition the door should be in a position that it can be safely closed before any rapid fire growth can result from the introduction of fresh air.

In practice, the RRT typically responds with a sense of urgency, and from the author's personal experience, proper door procedure is not always followed when there are no obvious signs of fire before opening. After finding the door is cold, it is not unusual for the door to be opened directly and personnel to advance rapidly into the compartment. In terms of both assessment of a fire situation per the above and the urgency of response, the surface temperature profile on the unexposed side of an insulated bulkhead is of significant interest, with a time interval from 0-5 minutes after ignition of a fire being relevant for observations necessary for decision making during initial response. Further, due to the current use of indicators such as discolouration and bubbling of paint on the surface of a door, it is of interest to investigate the response of paint to the temperature levels that are expected to be encountered with fire insulation installed on the bulkhead.

2.7.3 Firefighting Attack Team entry procedures

The second stage of fire fighting is done by a team fitted out in protective equipment, which will include full bunker gear, a self contained breathing apparatus, and a variety of tools. For the RCN team, this will include a ruggedized thermal imaging camera (TIC). This is a common piece of equipment in many land based and marine fire fighting teams that is very useful in low visibility situations to locate the fire as well as find casualties. Technical standards such as NFPA 1801 are available for the performance requirements of the TICs. This standard indicates that the cameras shall include features such as an easy to read interface, large buttons that can be operated with gloves on, and lists shock and other durability requirements, as well as ensuring a camera can effectively operate within the typical temperature ranges experienced by fire service personnel [24]. Due to the prevalence and use of these cameras in the RCN, it was decided to employ them in the present research, and is discussed in further detail in the Experimental Setup section, as well as in the analysis of the results.

For the RCN fire fighting attack team, the TIC is used to image the surface temperature of the entire door via the readout prior to opening a door or hatch. The output includes a heat colour reference bar and upper and lower detected temperatures. The scale automatically adjusts to compensate for the detected temperatures. This gives more detailed feedback to the attack team, than was determined by the RRT, about the surface temperature and any warm or hot spots on the door. In addition to using a TIC, references suggest a variety of other methods that could be used to check the surface temperature, including installation of thermocouples or pyrometers, marking the surface with welder crayons that change colour at specific temperatures, or spraying a short burst of water on the bulkhead and taking note of how rapidly the water evaporates[11]. To date, however, none of these have been adopted for use during fire fighting operations on RCN vessels.

The Attack Team will typically consist of 4 personnel; a nozzle handler, the Attack Team Leader (ATL), a backup, and a hydrant person. The nozzle handler and ATL will advance together, with the ATL having overall control of the team, and instructing the nozzle handler on the water application, and using the TIC to assess the fire conditions. The backup provides assistance with the hose handling and is available for an immediate replacement for the nozzle handler. The hydrant person ensures that both water and foam continues to be available and is responsible for fitting the smoke curtain over the door/hatch once the attack team has entered the fire compartment.

Figure 2.4 depicts the basic route for the attack team into the fire compartment (called the primary zone) from the staging area (located in the secondary zone). As discussed further in the next subsection, manual boundary cooling is used in the compartment above the fire as well as the adjacent compartments (and potentially below the fire) to prevent spread from the thermal transfer through the uninsulated steel structure. To prevent smoke spread from the secondary zone to the remainder of the ship, all doors and hatches within the secondary zone are also closed.

Under the current tactics, prior to opening the door, the fire hose can be used to cool the surface of the door and bulkhead, with the TIC being used to direct and monitor the effectiveness of water application. Once the decision is made to open the door (or hatch), this can be done under control with the door partially opened and the TIC used to assess the interior compartment conditions. This allows the attack team to assess the fire compartment conditions, and if it is too hot, apply cooling water, close the door to allow the water to absorb heat, and reopen to reassess. This can be repeated until the attack team decides it is safe to enter the compartment, at which point the door will be fully opened and the attack team will take the hose into the compartment.

Once the attack team fully enters the fire compartment (or primary zone), and the hose is across the door/hatch, a portable fire curtain is clipped over the open door or hatch coaming to minimize the amount of smoke that will flow into the secondary zone, as well as to limit the amount of fresh air flow into the primary compartment. By limiting access to the primary zone to a single entrance, this minimizes the spread of smoke throughout the ship.

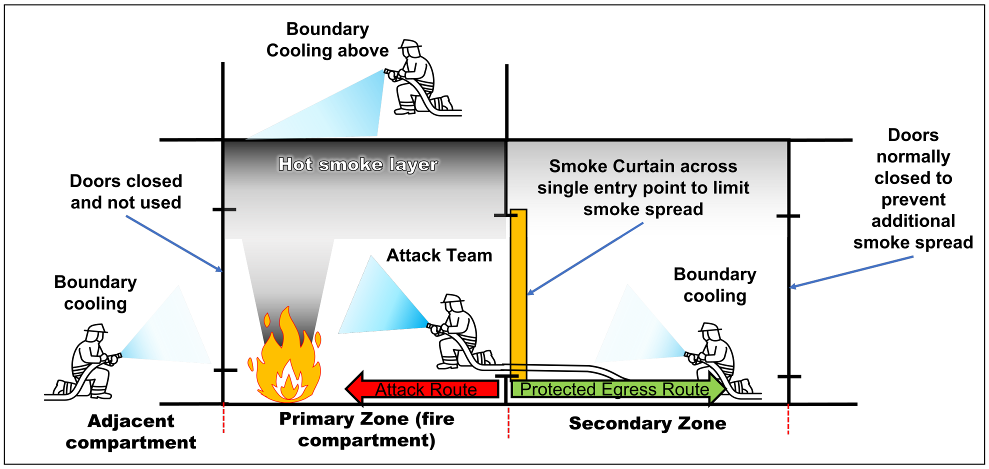


Figure 2.4: Simplified diagram showing basic RCN Attack team route, and boundary cooling locations to prevent spread of fire. Safe egress route is maintained from the primary zone back into the secondary zone for evacuation and casualty extraction.

As can be seen through the above discussion, although current uninsulated steel divisions allow free heat transfer between watertight compartments, they also allow the attack team to assess the fire conditions and obtain a degree of situational awareness prior to breaching into a fire compartment. With the inclusion of fire insulation, direct thermal feedback to the team through the steel structure is expected to be lost. On the flip side, it is anticipated that the addition of insulation will provide greater overall safety on the vessel by providing a passive measure to prevent the heat from the fire from spreading into adjacent compartments. In either case, as long as the attack team can open and maintain a route in the fire compartment back to the entry point, and control the heat/smoke at the entry point, they should be able maintain a safe escape route that can also be used for casualty extraction, which, as shown in Figure 2.4, will be back along the attack team hose into the secondary zone.

In new vessels, a cold door and bulkhead surface may no longer be indicative of a safe condition on the opposite side of the entry point however, depending on the level of fire insulation installed. The bulkhead or door will now be 'thermally thick', and there may be a significant thermal gradient across an insulated wall. In addition, there may well be a time lag between exposure to fire temperatures on one side and signs of heating of the wall on the unexposed side. Given that the unexposed surface temperature can no longer be used to gauge the conditions at the entry or on the interior of the compartment, this change needs to be carefully considered when making tactical decisions and introducing them into current marine fire fighter training.

2.7.4 Fire Boundary procedures

One key fire fighting tactic that has evolved due to current vessel designs where there is no fire insulation on the bulkheads is known as boundary cooling [10]. Typically, this consists of personnel using a fire hose to cool the hot surfaces of the doors or bulkheads and preventing the fire and heat from spreading to adjacent compartments through the steel compartment boundaries. This concept is illustrated in Figure 2.5, which shows a sample compartment layout as well as how the vessel compartmentalization may complicate fire containment.

For external portions of the fire compartment (such as the ship's hull) which is watertight, use of water for boundary cooling is not a concern and can be provided by a fire tug, personnel using a fire hose or other possible sources of water. For internal boundary cooling operations, water will accumulate inside the vessel. This can create stability issues. Therefore during fire fighting operations the vessel is continuously monitored for symptoms indicating a loss of stability (such as the ship is leaning to one side, known as a 'list'). Personnel are trained to use the minimum water necessary for boundary cooling, but if necessary, boundary cooling and other firefighting water usage may need to pause to conduct de-watering operations or otherwise improve vessel stability and prevent the ship from capsizing [10].

For deployment of boundaries, the area directly above the fire is normally the highest priority due to direct flame impingement, the presence of the hot smoke layer at the ceiling and thus the high heat transfer that takes place through the ceiling above the fire. This is followed by cooling of adjacent compartments, and finally cooling the areas below the fire. The extent of cooling may be limited in practical terms by a limit on available personnel/equipment, access routes to the boundaries and other factors. Additionally, high hazards in adjacent compartments may change the prioritization of activities, so in the end boundary cooling is highly dependent on the fire scenario. As such, it is typically part of the pre-planning but remains adaptable to fit a specific context. In the end the decision also relies on information about the temperatures of the surfaces adjacent to the fire, again underlining the importance of understanding potential changes due to the present of insulation on any of the surfaces.

In cases where the fire is too big for an attack team to enter the compartment and a fitted system is unavailable or ineffective for example, limiting the fire fighting efforts to boundary cooling on all sides of the fire compartment may be chosen as the method by which to contain the fire to the compartment of origin. By closing all openings to prevent inflows of fresh air, and cooling the boundaries, the fire will eventually extinguish. Because of the potential for extensive damage within the compartment, this is not the preferred method, but can be effective in maintaining control of a fire and preventing further damage to a ship.

In addition to using boundary cooling to prevent the spread of heat, the personnel at the boundaries are also responsible for monitoring the spread of smoke within the vessel. Smoke may spread due to several reasons, which may include automatic dampers that fail to close, or possibly openings to the compartment that were not reachable, and thus were left open by the rapid response team during the initial response.

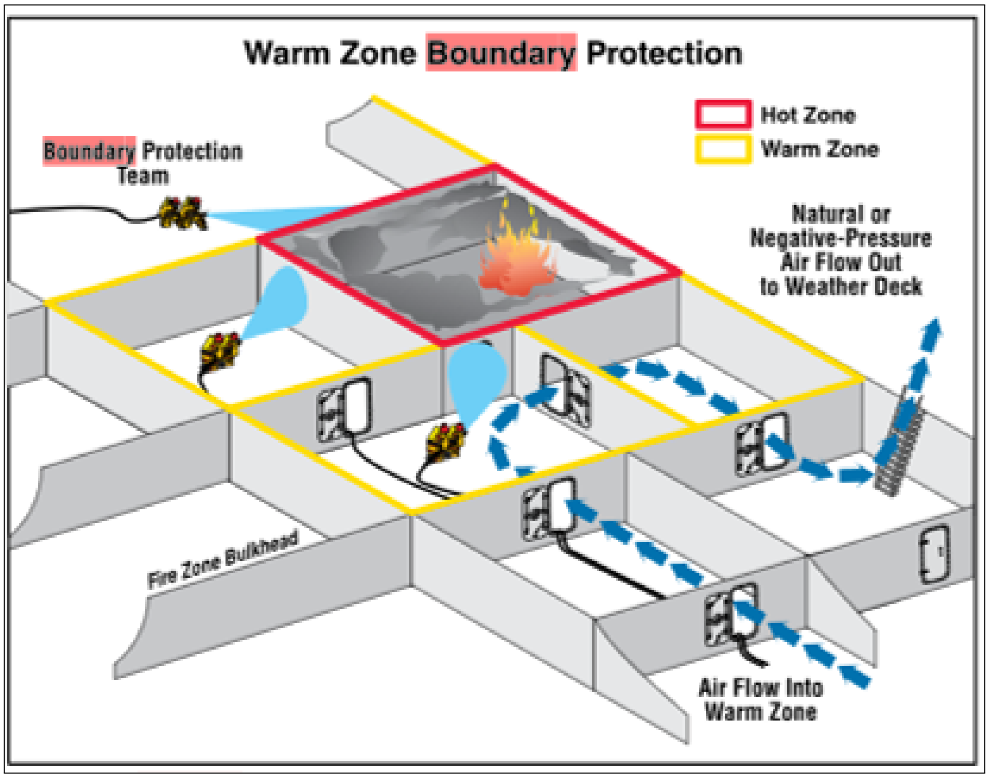


Figure 2.5: Diagram demonstrating possible boundary cooling team deployment locations[11]

In addition to the water application depicted in Figure 2.5 is an airflow. It should be noted that this figure formed part of a larger example used to explain venting techniques for land based fire fighters responding to a ship fire while in harbour. The natural convection exhaust in this example is highly situation dependent and not typically used by the RCN nor incorporated into current tactics so is not considered further here.

Instead, the warm zone depicted in the figure (referred to as the ”secondary zone” in [7]) is closed down and maintained as an air tight boundary to limit the spread of smoke outside the fire compartment. A heat resistant fabric curtain with a centre seam is clamped across the perimeter of the entry point into the fire compartment to limit the spread of smoke and heat through the entry point to this secondary, warm, zone. This procedure means that while the fire compartment may be fully exposed to smoke, the spread to the secondary zone is very limited.

In summary then, it is unknown how the addition of fire insulation may impact fire boundary procedures. Further, it is not clear if applying cooling water to the insulation will impact it's effectiveness as a thermal barrier. Because the fire insulation is normally only installed on one side of the division to create a thermal break, it is also not known if the location of the insulation relative to the fire impacts the ability of the crew to make initial decisions or subsequently, impacts the application of cooling water, or potential generation of smoke from what is usually a painted steel structure.

2.7.5 Fire Overhaul procedures

Once the fire is detected, there are two stages until the fire scenario is fully resolved. The first stage is the immediate actions taken to extinguish the fire at the source, described above. The second stage is known as overhauling the fire, and involves cooling down any hot spots to prevent the from fire re-flashing. Because of the potential for the fire to continue to smolder, this can be an extensive and time consuming process that may involve multiple teams being cycled through.

Overhaul typically involves moving materials out of the way to be able to apply water to any smoldering fuels, verify that there are no fires burning in voids or trunking, and otherwise cooling down any residual hot spots. This tends to be complicated by the density of equipment fitted in the compartments on warships. Nonetheless, once the overhaul is completed and the initial smoke cleared out of the space, ventilation with fresh air will continue until a tenable atmosphere can be restored and verified (known as 'Gas Free'). Once this is achieved, personnel involved in the fire and damage investigation and related repair activities are no longer required to use a self contained breathing apparatus (SCBA) but, depending on the operation underway, may still require other PPE such as coveralls or filtration masks. At present, it is unknown how the addition of fire insulation may impact fire overhaul procedures. For instance, because fire insulation will normally only be installed on one side of a division to create the thermal break, it is not clear how the location of the insulation relative to the fire might further impact fire overhaul procedures. Further, it is possible that fire insulation may need to be removed to complete the overhaul process in which case, the combined thermal, decomposition and water retention profiles of the exposed insulation become important to fire response decisions as well.

The addition of fire insulation is a significant improvement in fire protection on board vessels. At the same time, it changes the thermal characteristics and subsequent characteristics of the fire compartment boundaries. This has implications in terms of conditions and heat transfer in vessel compartments. It also impacts the overall context for the current set of marine firefighting tactics and procedures. At present, however, there is no data available to judge how the temperatures may change, or the implication of any changes on visible heat indicators on the bulkhead and compartment boundaries, on potential changes in production of off-gases from bulkhead paint, or other important processes particularly in more realistic, less severe fires than those used in certification testing. Therefore, this research is tailored to better quantify and understand the broad implications of thermal differences between bulkheads with and without fire insulation. By using a representative, well instrumented test bulkhead that includes some structural features representative of a bulkhead on a naval vessel, with controlled fire exposures, it is aimed to better evaluate how fire scenarios and current marine firefighting tactics may be affected by the use of insulation required under the new SOLAS regulations. This was complemented with a series of bench scale tests aimed specifically toward looking at the interactions between the insulation and painted surfaces on the steel bulkhead under exposure to heat. Details of the experimental set-up, methods test fires and instrumentation are outlined in Chapter 3, followed by results of both sets of tests and their implications on naval fire fighting operations in Chapter 4. Finally, Chapter 5 contains concluding statements and avenues for future work arising from this thesis.

Chapter 3

Methodology and Experimental Design

3.1 Overview of experiment design

Experiments in this research were designed to improve understanding of the wall temperature profiles on the unexposed side of an insulated steel wall and their impact on fire fighting decision making over the course of a realistic fire scenario. Large scale compartment tests, combined with small scale bench tests, were designed to mimic typical thermal exposures on a compartment bulkhead during a realistic fire scenario. An overview of the experimental approach is outlined in this section, with additional details of each part of the experiment discussed in subsequent sections of this Chapter.

The design of the Navy bulkhead test specimen used in the large scale tests includes several features that simulate common structural features of the bulkheads on RCN ships such as a pipe penetration and a simulated door mounting arrangement, in addition to being constructed with standard structural stiffeners and plate thickness as required to comply with IMO testing protocol. The test specimen is mounted in the existing wall fire test unit at the University of Waterloo fire research laboratory. The test unit is a modified sea container, subdivided to include an instrumentation area, a fire compartment, a mounting frame with standardized connecting points, and a rear compartment that allows the unexposed side of the test specimen to be monitored.

The existing thermocouple arrangement in the wall fire testing unit could be used, with some additional sensors added to monitor the conditions at specific points of interest on the test specimen developed for this research. Characterization fires from previous research and other lessons learned around the ventilation conditions in the wall test unit location were used to select an appropriate fuel load and configuration for the research objectives.

Along with the video data, instrumentation in the wall test unit provided continuous monitoring of both the fire compartment and unexposed wall temperatures, which provided a baseline to analyze the potential impact to normal RCN firefighting tactics and decision making processes at different time periods during the fire event. The fire insulation has already proven to be an effective thermal barrier in terms of the PASS/FAIL temperature criteria assessed through IMO testing. This research however, provides time resolved temperature data from the start of the test through to end of the test, with sufficient granularity to help make informed assessments of the existing fire response tactics, with quantitative data to support changes to those tactics, RCN fire response decision making processes, and for use in the training that underpins both items.

A Thermal Imaging Camera (TIC) is used to capture Infrared images of the unexposed side of the test specimen at set intervals to provide an overall view of the temperature profile across the entire wall section during each experiment. In addition to supplementing the temperature data from the thermocouples, these images mimicked the infrared images that would be seen on the display of a hand-held TIC that is part of the standard fire fighting equipment used in the RCN. Thus, they are useful for explaining the results and also for training of RCN personnel. Further, they provide additional benefit to the experimental setup by identifying gaps in the insulation or other unintended shortcomings in the installation and mounting arrangement, thus improving the experimental configuration and results in subsequent tests.

Due to the lack of baseline data on the performance of fire insulation with painted surfaces, uncertainty around the impact of paint on the fire scenario, and general practical considerations around applying/renewing the paint coating between successive experiments, it is decided not to apply IMO FTP compliant paint on the test wall in this research. A high temperature paint is used on the exposed side to provide a uniform surface emissivity and protect the steel from corrosion, but as this is rated for temperatures exceeding the fire conditions, this did not contribute to the fire.

In lieu of applying paint to the test wall, a series of small scale bench tests that mimic the fire scenario exposure were conducted to determine how a painted steel structure might behave under heating, and to what extent smoke may be generated. The experiments include configurations where the insulation is on both the exposed and unexposed side of the painted steel sample. The effects of paint accumulation on both the heat release rate and the smoke generation were studied. These results are intended to provide some preliminary data and verify an experimental procedure that could be used for future studies. Results pointed to areas for more work via both a more detailed bench scale investigation into potential impacts of bulkhead paint accumulation under exposure to radiant heat, and for potentially scaling up the experiments to include medium or large scale testing of painted and insulated wall test specimens under real fire exposure scenarios.

Finally, neither HVAC trunking or electrical cabling penetrations commonly found on ships were included in the design of the test specimen. For the HVAC trunking, this is a practical consideration due to the size of the test specimen. For the electrical cabling, the penetration includes a specialized water and smoke tight cable transit block, and also would introduce additional uncertainty and be a source of smoke generation on the unexposed side of the bulkhead due to the cable insulation, so is excluded from the test specimen design in order that a baseline data set could be developed. Both items are potential areas for additional work, but were outside the scope of the present investigation.

3.2 University of Waterloo wall fire test unit description

The wall test unit at the University of Waterloo consists of a modified 6.1m (20 ft) long ISO shipping container, which is originally developed for the PhD work by DiDomizio and is described in detail in his thesis [8]. A summary of key details related in the present research is outlined here. The wall test unit is based on the ISO 9705 Room Corner Test configuration, which specifies a compartment measuring 3.6m long, 2.4m wide and 2.4m tall [17]. As such, the test unit is built in a standard sea container which is 6.1 m long, 2.4 m wide, and 2.4 m tall, and then modified by a local provider based on custom design drawings. First, the container is divided into three sections; a fire compartment, a transition compartment, and an instrumentation section. Separations were achieved by welding 10 gauge sheet steel (3.57 mm) and 3/16 in (4.8 mm) structural steel tube to the interior of the container [8].

A section view of the wall fire test unit is shown in Figure 3.1, with the remainder of the construction drawings available in Appendix A.

A custom ”wall frame” is welded in place to provide an integrated method for mounting a test specimen, separating the fire compartment from the transition compartment. This wall frame, shown in Figure 3.2, has an opening 75.5 inches wide by 75.5 inches tall by 12 inches deep (1917 mm x 1917 mm x 300 mm). Pre-drilled holes evenly spaced around the perimeter provide standardized attachment points to allow easy mounting of specimen walls for testing, and attachment points for instrumentation. This setup has been used for fire testing of a variety of wall configurations, including standard residential wall configurations using both wood and metal framing with drywall and insulation, and is sufficiently flexible to be easily adapted to other test specimens and experimental parameters.

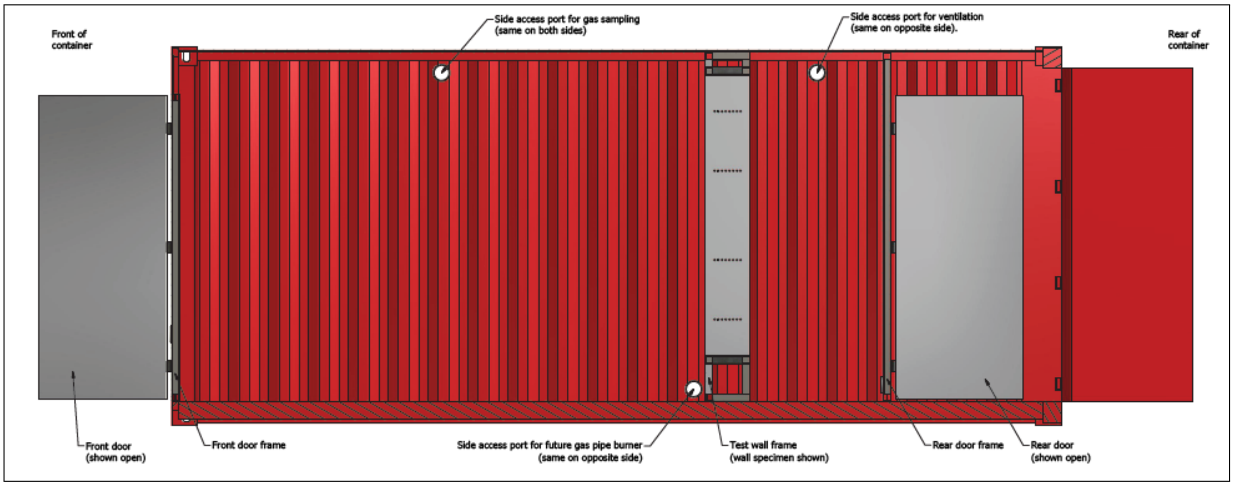
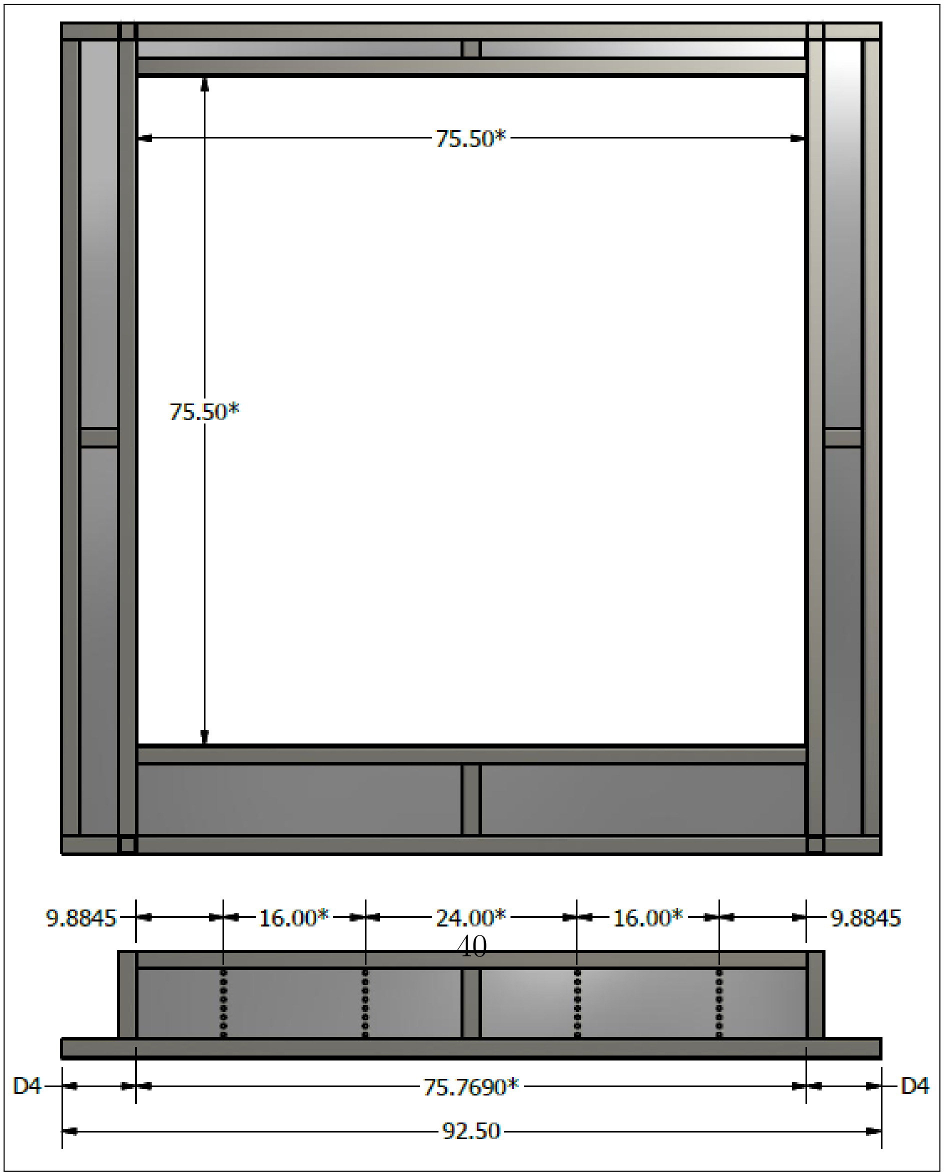


Figure 3.1: Wall test unit side view [8]



In order to provide thermal insulation and to protect the floor, 2.5 inch (63.5 mm) fire bricks were used to line the bottom of the container. In order to protect the fire compartment walls and ceilings, panels made from 1/2 inch (12.7 mm) cement board and 1 inch FibreFrax Durablanket S®refractory ceramic blanket were installed. Panels were assembled using machine screws (8-32 UNC, 2 in (50.8 mm) length), nuts (8-32 UNC, 5/16 in (7.9 mm) drive), and fender washers (3/16 in (4.8 mm) inner diameter, 1 1/8 in (28.6 mm) outer diameter). After assembly the screws extended approximately 1/2 inch (12.7 mm) behind the cement board which created an additional air gap to protect the steel container. Figure 3.3 shows both a front and side view of the panel with Fiberfrax and cement board backing. [8]


(a) Front side. (b) Back side.

Figure 3.3: Insulated panel [8]

For the ceiling installation, 1 5/8 inch (41.3 mm) Unistrut channel is mounted at 24 inch (600 mm) intervals with the panels placed on top. The wall panels were then friction fit behind the ceiling panels, with smaller panels installed on the face of the wall frame. This protects the apparatus and is sufficiently robust to allow for multiple experiments to be performed without requiring the panels to be replaced, while greatly reducing the effect of variations in ambient weather conditions by limiting loss of heat at the boundaries. [8]

Figure 3.4 shows the interior of the fully insulated compartment with a wall test section mounted at the far end. The final internal dimensions of the fire compartment are 138 in (351 cm) long, 90 in (229 cm) wide, and 90 in (229 cm) high. The bottom of the wall frame is 12 in (31 cm) above the brick floor, and the top of the wall frame is 87.5 in (222 cm) above the brick floor, or 2.5 in (63.5 mm) below the ceiling. [8]

Figure 3.4: Panels shown installed in the wall test apparatus [8]

The original door to the fire compartment measured 31.5 inch (800 mm) wide by 78.75 inch (2000.25 mm) tall. During the experiments by DiDomizio [8], it was found that when used as a vent, this did not allow a suitable thermal layer to form and allowed too much heat to escape the compartment. An additional soffit was added to the top of the door opening to reduce the overall door height to 53 inches (1346 mm). [8]

Figure 3.5 shows the reduced height of the door opening when it was propped fully open during experiment number 2. This configuration allows greater heat retention and resulted in the desired compartment temperature profile for the chosen test fire, so is used in all experiments for this thesis work.

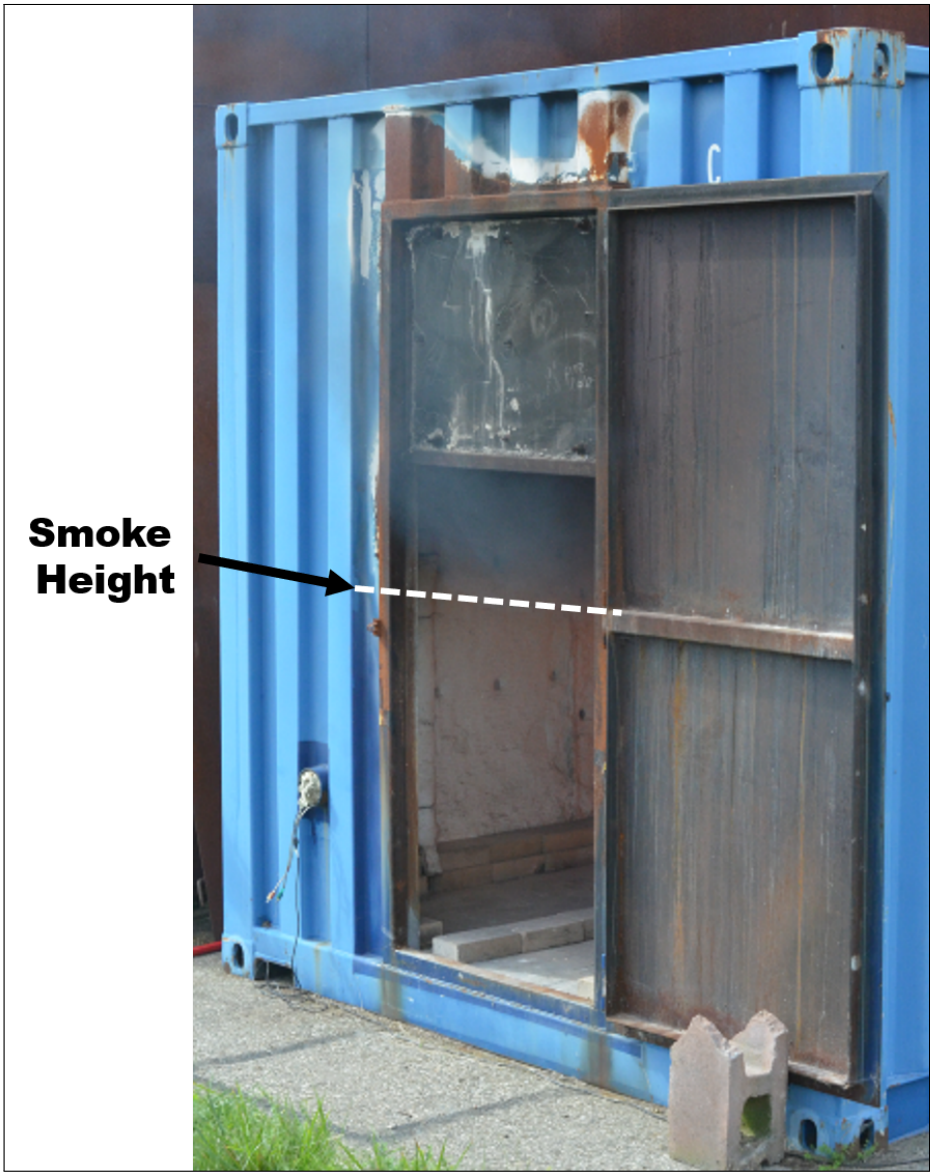


Figure 3.5: Adjusted fire compartment door opening height showing venting smoke during an experiment

3.2.1 Navy bulkhead custom test specimen

A custom wall test specimen is designed for the present research, based on the standard configuration used in the IMO test. It also included some potential features that would be found on a ship. The standard IMO wall test calls for a minimum overall dimension of the test specimen to be 2440 mm wide and 2500 mm tall. [12]. The specimen itself is a continuous panel of steel plating with stiffeners spaced at 600 mm.

Features such as pipe penetrations, HVAC trunking, doors and hatches and wire penetrations are normally tested separately, so one aim of the present custom wall design is to integrate some of these into a representative wall section that has similar features, placed in the same location, as would be the case on a typical Navy bulkhead. Details are shown in Figure 3.6 with full construction drawings for the navy bulkhead assembly included in Appendix A.

Because of practical considerations, the custom wall test specimen for the Navy bulkhead is designed to cover only a portion of the total wall test area available. Figure 3.6a shows the details of the assembly, including the location of the stiffeners, pipe penetration, door features and the effective test area where the insulation is installed.

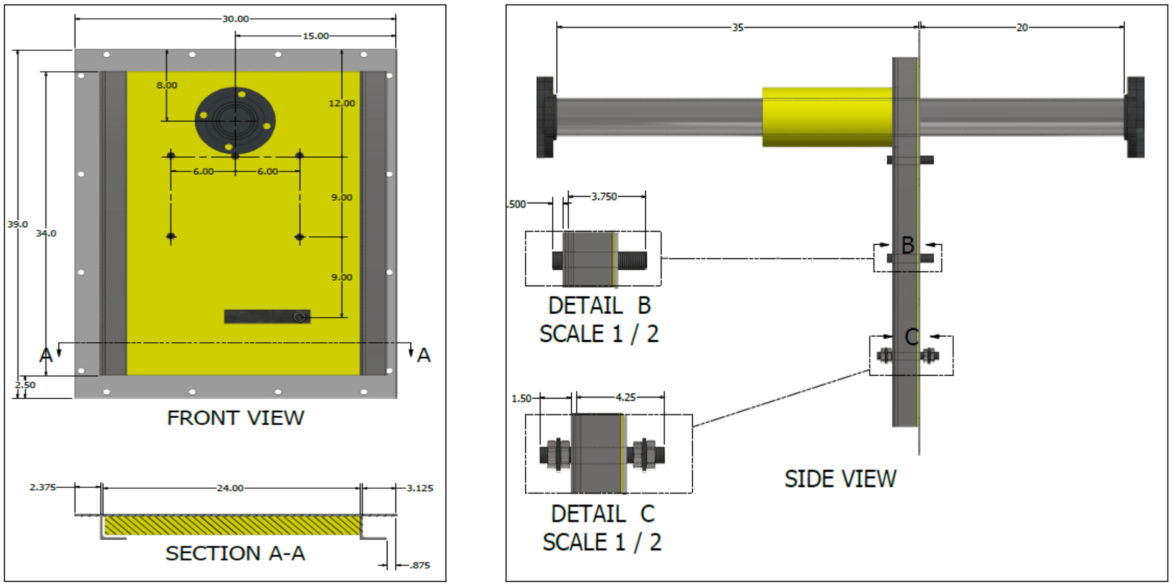
The material specified for the steel plate and the stiffeners is shown in Table 3.1. Locally available steel suppliers primarily used Imperial standards, so material is selected to match the IMO standard as closely as practicable given the differences in specification systems.

Table 3.1: IMO material requirements for standard bulkhead material versus design selection [12]

Item	IMO specification	Design selection
Steel Plate	4.5 ± 0.5 mm	3/16 inch (4.8 mm)
Stiffener	(65 ± 0.5) x (65 ± 0.5) x (6 ± 1) mm L stiffener	2.5 inch (63.5 mm) x 2.5 inch (63.5 mm) x 1/2 inch (12.7 mm) angle bar

The size of the doors into the wall fire test unit as well as the overall weight of the assembled panel were both limiting factors to the final design. Because of the addition of the welded pipe penetration, the width of the panel is limited to 30 in (762 mm) to ensure clearance through the doors. Additionally, the panel is intended to have a total assembled weight of less than 50 kg to allow installation and removal by personnel without mechanical aids, so an overall height of 39 in (990 mm) is selected. As the assembly is going to be mounted onto a 1 5/8 (41.3 mm) Unitsrut frame which is then bolted in place onto the wall frame, this included a perimeter for the bolt attachment points. The stiffeners are a total of 34 inches (864 mm) high and 24 inches (600 mm) apart. The mineral wool insulation comes in a standard width of 600 mm, so the chosen stiffener spacing aided easy installation of the insulation with minimal cutting and thus reduced potential for unwanted air gaps.

The final assembly featured a number of through-panel penetrations, which included a pipe penetration shown in Figure 3.6a, as well as a number of bolts intended to represent door features, shown as details B and C in Figure 3.6b. The pipe penetration is modeled on the IMO pipe penetration test requirements, which specifies that the pipe must project 500 ± 50 mm on both the exposed and unexposed side of the wall [12] with full penetration welding to the wall. The pipe must be suitably blanked off at the exposed end. As shown in Figure 3.6b the pipe projected 35 inches (890 mm) on the exposed side and 20 inches (500 mm) on the unexposed side. The pipe selected is commercially available 3 inch (75 mm) schedule 40 steel pipe, which has a nominal outer diameter of 3.5 inches (89 mm) and a nominal wall thickness of 0.216 inches (5.49 mm). Steel flanges were welded to each end of the pipe and fitted with matching steel blanks to prevent smoke migration during the test.



(a) navy bulkhead assembly front view

(b) navy bulkhead assembly side view

Figure 3.6: Navy Bulkhead assembly showing the front and side view

Finally, the Navy bulkhead test specimen design includes features to represent a typical door onboard a vessel. Because the fire fighting tactics and decision making processes of concern include the decision on whether or not it is safe to open an insulated door or hatch based on assessment of the unexposed surface temperature by either visual indications or using a TIC, the included door features were an important custom design feature. They provided measuring points through which to determine if it might be feasible to use similar features on in-service fire insulated hatches or doors to indicate the possible fire conditions inside the opposite compartment.

Standard watertight marine doors include door 'dogs' which are levers installed around the perimeter that include a wedge that rotates into place and places pressure to seal the door against the frame. An example of this that has been adapted from [11] is shown in Figure 3.7. The door dogs include a handle on both sides of the door, and have a solid metal rod rotating in a gland that penetrates the door. To represent these features, 3/4 inch (19mm) threaded steel rod is welded to the assembly. The threaded rod extends approximately 2 inches (50mm) on the unexposed side, and 2.5 inches (62.5 mm) on the exposed side. This is to ensure that approximately 0.5 inches (12.5 mm) of threaded rod extends past the 50 mm of mineral wool insulation on the exposed side once installed. Additionally, one threaded rod included a handle, so is extended to allow for the securing nuts. The handle is manufactured from standard 2” (50 mm) steel flat bar that is readily available, and cut to an overall length of 10 inches (250 mm).

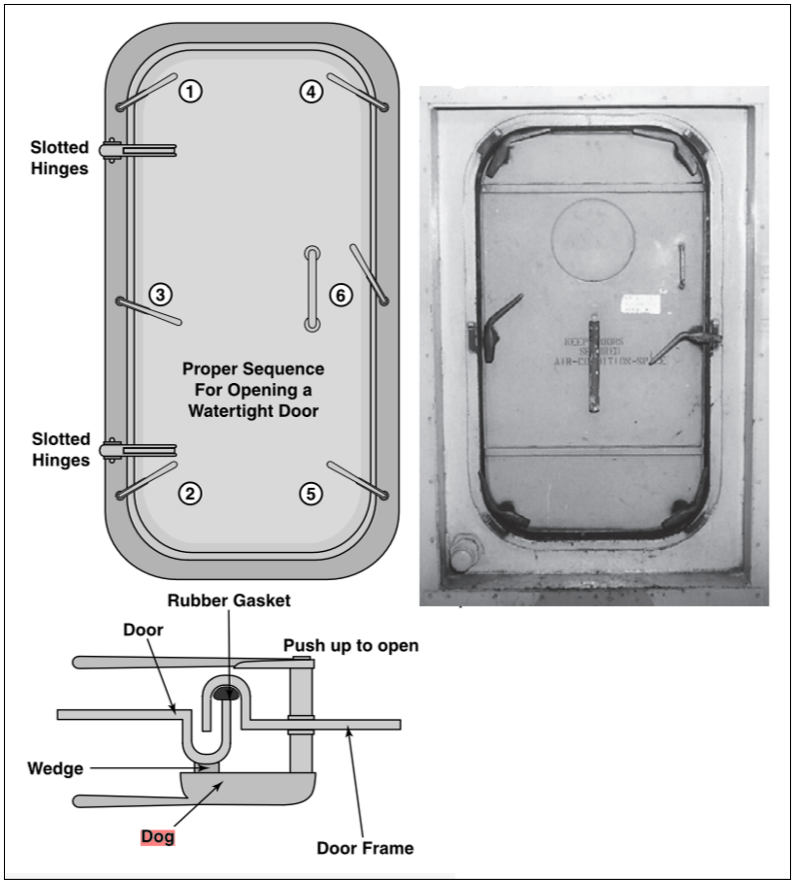


Figure 3.7: Standard watertight marine door configuration adapted from [11]

The custom Navy bulkhead test specimen is bolted onto a 1 5/8 inch (41.3 mm) Unistrut floating frame that is sized to fit in the test apparatus wall frame opening, as shown in Figure 3.8; see Appendix A for details. This includes legs for attachment of the floating frame onto the wall frame via the standard hole locations, and standard Unistrut corner brackets installed with 1/2 inch (12.7 mm) bolts for stability, with a 1/4 inch (6.4 mm) allowance for thermal expansion as well.

To limit heat transfer from the test specimen into the wall frame, a 1/4 inch (6.4 mm) thick strip of high temperature silicon rubber gasket is installed between the wall frame and the floating frame, so the overall test specimen face measured 75 inches (1905 mm) by 75 inches (1905 mm). The remainder of the vertical opening on the floating frame is covered with sheets of 10 gauge (3.57 mm) steel bolted onto the Unistrut frame using 1/4 inch (6.4 mm) bolts (finger tight). This arrangement is rigid enough to support the wall assembly while remaining free to expand under fire loads. It included an additional horizontal support under the section of plate compared to the floating frame used by DiDomizio [8] due to the additional weight of the custom wall panel studied here.

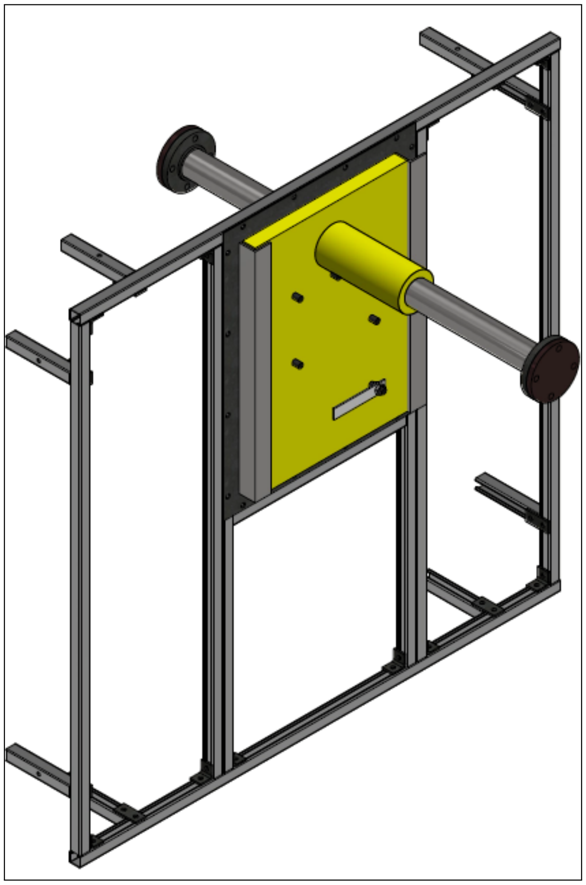


Figure 3.8: Navy bulkhead test specimen assembly bolted onto the Unistrut®frame for mounting on the test apparatus wall frame

Figure 3.9 shows the navy bulkhead test specimen fully mounted onto the Unistrut®frame and attached to the apparatus wall frame with the insulation on the exposed side, which is one of the configurations used for this research. The assembly is designed to be reversible to allow testing with insulation installed on either the exposed and unexposed side. Because the insulation is installed on the same side as the stiffeners to save space, this requires the section to be unbolted and hung facing the opposite direction, with all the thermocouples removed and re-attached to the unexposed side.

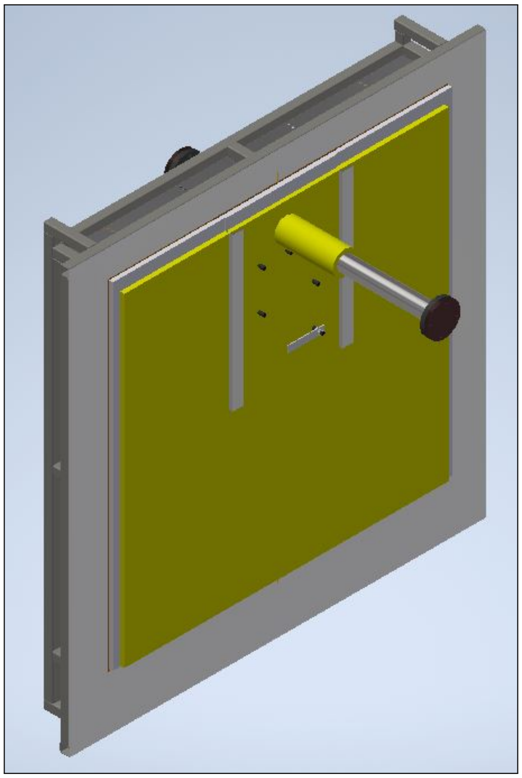


Figure 3.9: Navy bulkhead shown with the test specimen fully mounted with the insulation on the exposed side (test configuration)

Figure 3.10 shows the Navy bulkhead test specimen mounted onto Unistrut®frame in the reversed position and attached to the apparatus wall frame placing the stiffeners and insulation onto the unexposed side. Due to COVID delays and subsequent time constraints, testing of the uninsulated reference wall and the configuration with the insulation on the exposed side (shown in Figure 3.9) formed the scope of the large scale testing. This insulated configuration was chosen because the scenario in which the insulation is exposed directly to the flames in the fire compartment is considered to be the more challenging test condition for the fire insulation while still providing excellent information about heat transfer through the insulated assembly to the unexposed side.

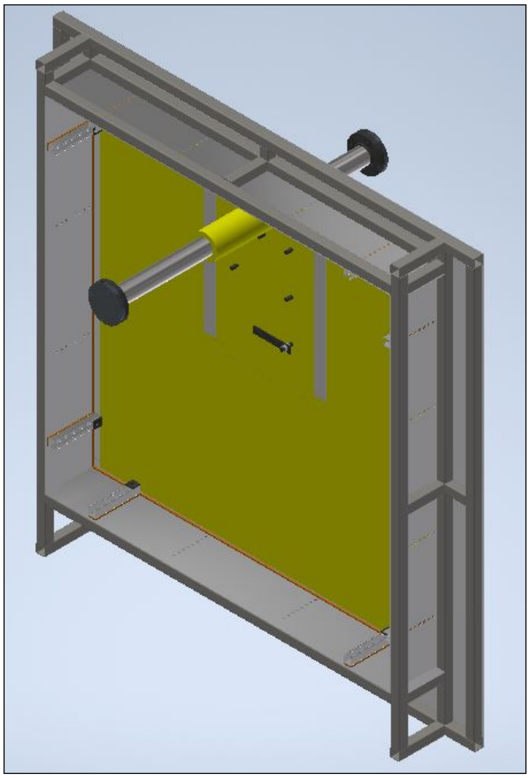


Figure 3.10: Navy bulkhead assembly shown with the test specimen mounted in the reversed position with insulation on the unexposed side (not used in this research)

Test specimen exposed surface preparation

Once all the thermocouples were welded in place to the unexposed side of the wall, the exposed surface of the wall is coated using the same technique employed by DiDomizio [8] to protect the exposed steel surfaces from corrosion between tests, and to ensure a consistent emissivity of the exposed test specimen surface for the reference wall tests without insulation. For this, the steel wall is first prepared with an angle grinder fitted with an 80-grit flap disk, which removed any rust and ensured a consistent surface profile. Following this, the entire exposed surface is treated with four coats of black VHT Flameproof®paint, which is rated for continuous use at up to 704 °C. Paint is applied using the supplied spray nozzle and alternating the angle of application by 90 degrees between coats. This method is found to give a surface coating with a measured emissivity of $\varepsilon = 0.93$ [8]. The coating, as applied, is successful in preventing rust from forming on the exposed wall surface throughout the numerous experiments. This minimized potential sources of error due to varying wall surface characteristics and also prevented degradation of the integrity of the test specimen.

Smoke propagation testing configuration

In addition to the thermal characterizations tests, one set of experiments includes measurement of the smoke flowing between the fire compartment and the transition room via an opening configured to represent a standard open cable transit through a non-watertight bulkhead on a RCN ship.

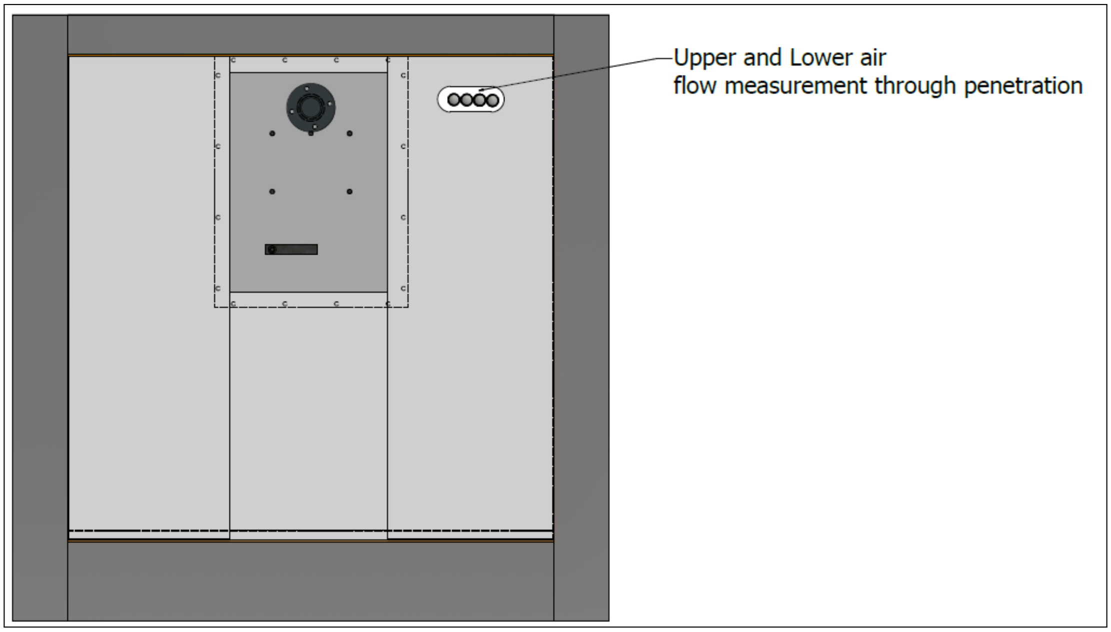


Figure 3.11: Smoke penetration configuration front view

The through wall opening is shown in Figure 3.11. It is located on the upper portion of the right hand steel panel in the wall test specimen (looking into the fire compartment from the outside door). The opening measured 12 inches (305 mm) wide, by 6 inches (152 mm) tall, with a 6 inch (152 mm) radius rounded ends. To represent large gauge electrical cables in a cable tray going through the opening, four 18 inch (457 mm) long, 1 1/2 inch (38 mm) diameter cast iron pipes were sourced locally and hung using a standard pipe hangar to have an equal overhang (approximately 9 inches (229 mm)) into both the fire compartment and the transition compartment, as shown in Figure3.12. This configuration provided comparable geometry to large gauge, high amperage electrical cable typical on a navy vessel while not contributing additional fuel or smoke and hot products that would have complicated the intentionally simplified initial investigations undertaken here.

Figure 3.12: Photo showing actual pipe and pipe hangar configuration at opening from the rear view

3.3 Instrumentation

One main advantage to running a series of comparison tests in the wall unit test apparatus is that, following the initial work to install the desired sensors, they can then be reused with minimal adaptation for a variety of experiments. For this thesis, the setup previously used by DiDomizio for a sheet steel wall is used with minimal changes. In general the test instrumentation consisted of sensors to measure temperature in the fire compartment, surface temperature at key points on the unexposed side, as well the gas flow velocity gas analysis (for CO, CO2, O2 and other key fire gas parameters) for the portion of testing that included smoke propagation between compartments. As discussed below, high definition video as well as IR images were also captured to assist in the data analysis, and also to aid explaining the results to the RCN and potentially to be incorporated into any training updates. The full details of the instrumentation can be found in Appendix B.

3.3.1 Temperature measurement

A summary of the standard temperature data captured in the test apparatus is as follows;

- vertical thermocouple probe rakes were installed in each corner of the fire compartment to measure the compartment and ceiling gas temperatures (four in total),
- several thermocouples were embedded into the wall frame to document the boundary conditions for the test specimen,
- thermocouples were located in the transition compartment to measure the gas temperatures as well as the boundary condition at the rear wall, and
- each of the three vertical sections of the test specimen had 8 thermocouples fixed at standard heights on the unexposed side to measure the surface temperature profile across the wall test specimen [8].

The thermocouples used in the fire compartment to measure gas temperatures (item 1) were assembled using K-type thermocouple cables (20 gauge solid wire, glass fibre and Inconel sheathed, with one duplex pair per cable). For the fire compartment probe rakes, 1 5/8 (41.3 mm) Unitsrut channels and protective ceramic fibre insulation were used mount bead-welded exposed junction thermocouples that extend 1/2 inch (12.7 mm) outside the channel at regular intervals to provide a vertical temperature profile in each corner [8].

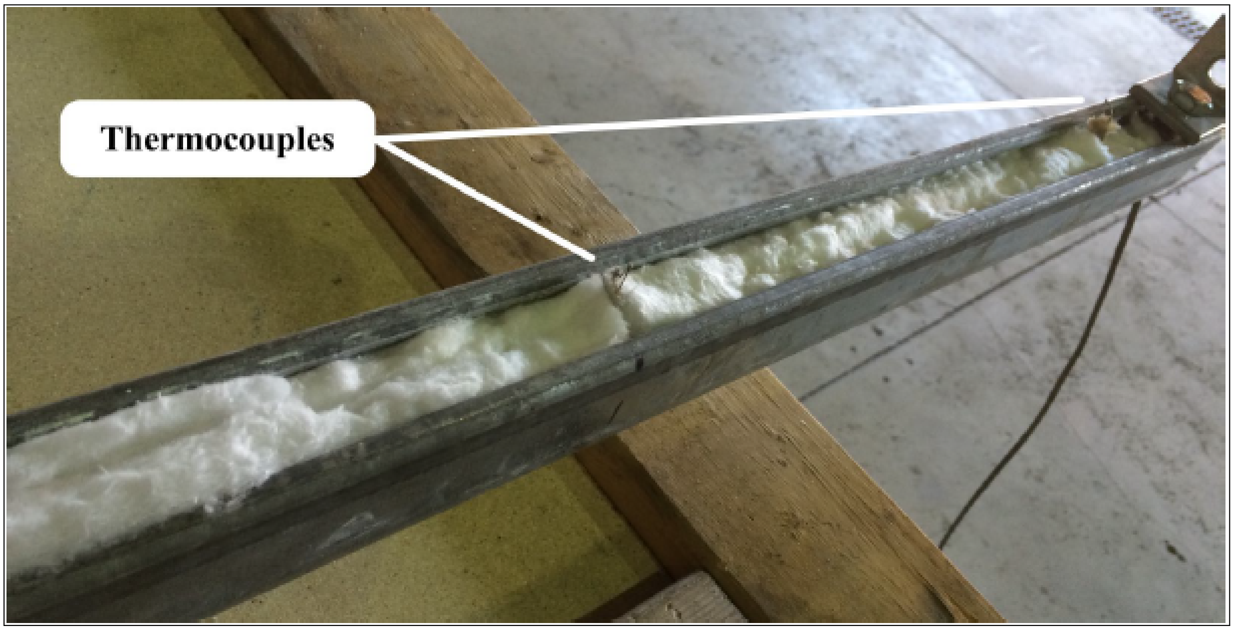


Figure 3.13: Thermocouple probe rake preparation [8]

Seven thermocouples were used in each rake, with an additional thermocouple extended from the top of the rake to the ceiling layer. The four rakes were denoted T1, T2, T3 and T4, with the overall layout shown in Figure 3.14.

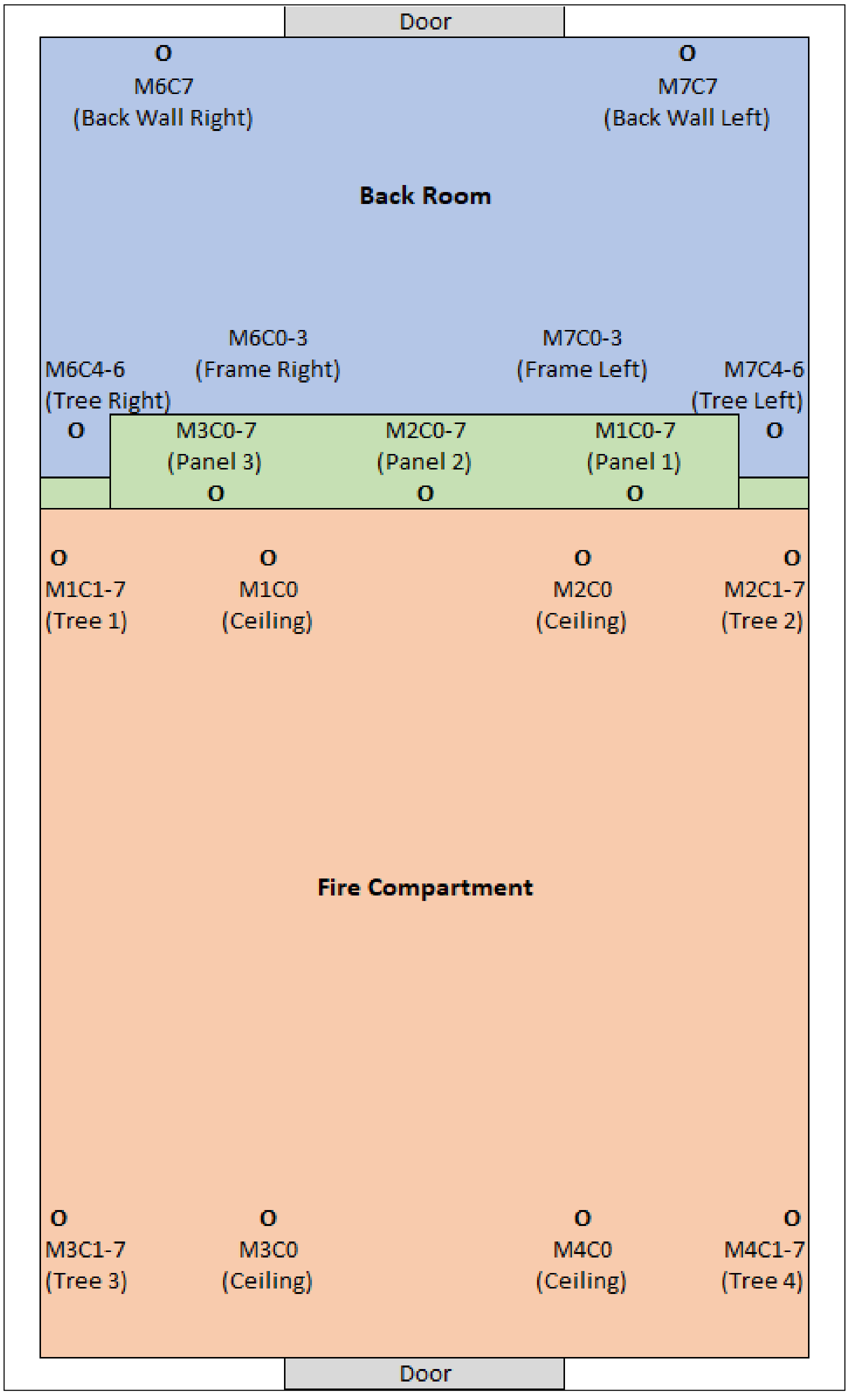


Figure 3.14: Instrumentation overview for the apparatus- top view [8]

The heights of the seven thermocouples for the fire compartment rakes ranged from 12 inches (31 cm) above the floor to 84 in (213 cm) from the floor (or 6 in (152 mm) below the ceiling). The eighth thermocouple is located 2 1/2 in (63.5 mm) below the ceiling and extended 1/2 in (12.7 mm) below the ceiling channel.[8]

(a) Thermocouple probe rake installed in compartment [8]

(b) Thermocouple extension details [8]

Figure 3.15: Details of the thermocouple probe rakes installed in the fire compartment [8]

Overall this gave satisfactory data to describe the fire compartment conditions and to identify if the fire is burning preferentially on one side or the other, or if any prevailing wind or other environmental conditions were affecting the fire. The equally spaced thermocouples on the vertical rakes provided a good measure of the degree of thermal stratification in the compartment without interfering with the gas flow as well.

The level of protection provided by the insulated channel housing the cable runs ensured that the thermocouples could be used for multiple experiments without needing replacement, which would have involved a significant amount of labour.

An additional 16 thermocouples were used to monitor the temperature at various locations on the wall frame and in the transition compartment (items 2 and 3). Eight of these thermocouples were welded to the wall frame itself along the top, bottom and sides to measure conditions at the boundary of the test specimen. Two vertical probe rakes of three thermocouples each were fitted on the outer left and right sides of the unexposed side of the wall frame to monitor the transition gas room temperatures, with the final two thermocouples attached to the back wall of the transition compartment to monitor the overall boundary conditions.

Unlike DiDomizio's [8] experiment, which used a wall comprised of three identical vertical panels 24 in (610 mm) wide and of 18 ga (1.214 mm) sheet steel, for the present experiments the center division is 30 in (762 mm) wide, with the navy bulkhead panel mounted in the upper center portion, and the lower center portion is a separate panel of 10 gauge (3.4 mm) sheet steel. The two side panels (no 1 and no 3) were both constructed of 10 ga (3.4 mm) sheet steel as well, measuring 22 in (558) wide by 75 in (1905 mm) high. The same approach as outlined in [8] is used to measure the surface temperature profiles on the steel panels: that of placing a column of vertically spaced thermocouples along the center of each panel.

Each of the three vertical panels is instrumented with 8 thermocouples, horizontally centered on the panel and with equal vertical spacing between the thermocouples. Thermocouples used for the surface temperature measurement are assembled from 24 ga K-type glass fibre sheathed thermocouple wire, with the leads welded directly to the steel panels. The thermocouples are welded (from the top)at 70.5625 in (1793 mm) above the wall frame continuing downwards to 4.9375 in (125 mm) from the bottom of the wall frame, with an equal vertical spacing of 9 3/8 in (238 mm) between each thermocouple location. Figure 3.16 shows the sensor designation used, along with an overlay showing the approximate location of the Navy bulkhead panel on the overall assembly. The height of each sensor is noted in Table 3.2.

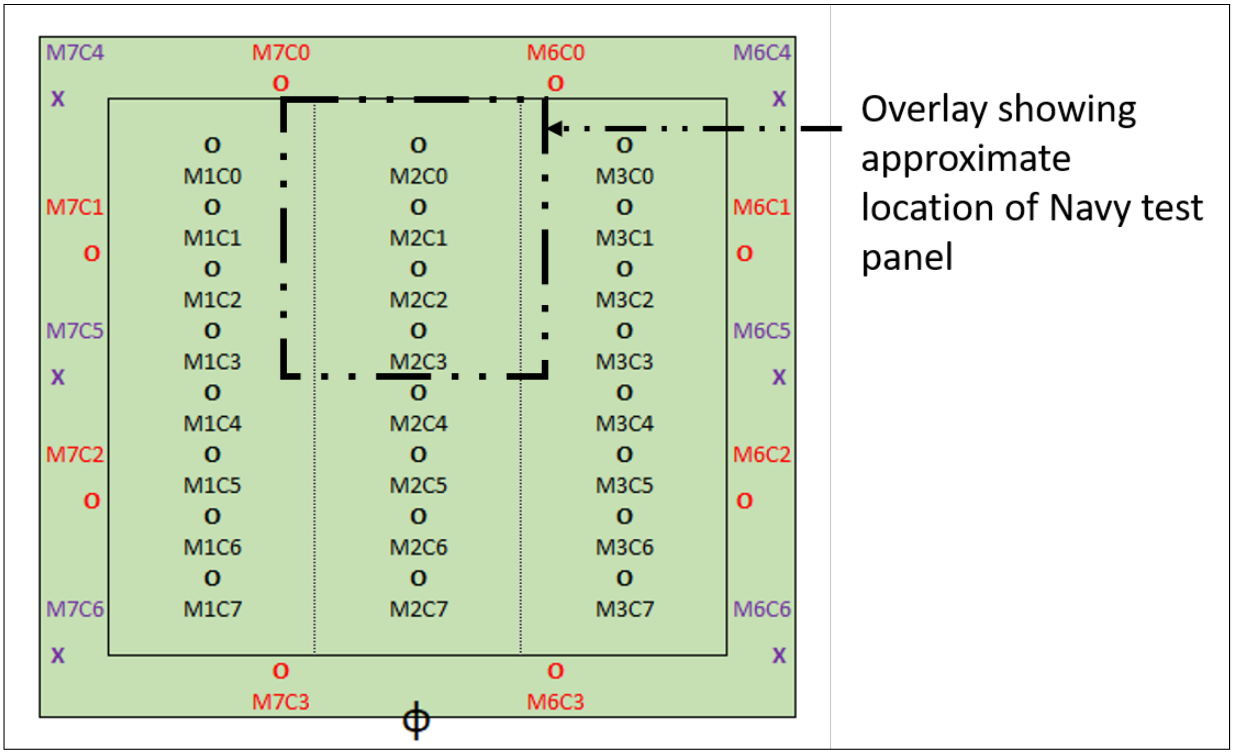


Figure 3.16: Wall thermocouple location- rear view [8] with overlay showing approximate location of the Navy bulkhead test panel

Table 3.2: Steel wall- sensor height positions [8]

LABEL	POSITION	HEIGHT FROM COMPARTMENT FLOOR
P1/P2/P3	0	2097 mm (1794 mm from bottom of wall frame).
P1/P2/P3	1	1859 mm (1554 mm from bottom of wall frame).
P1/P2/P3	2	1621 mm (1316 mm from bottom of wall frame).
P1/P2/P3	3	1383 mm (1078 mm from bottom of wall frame).
P1/P2/P3	4	1145 mm (840 mm from bottom of wall frame).
P1/P2/P3	5	906 mm (602 mm from bottom of wall frame).
P1/P2/P3	6	668 mm (364 mm from bottom of wall frame).
P1/P2/P3	7	430 mm (125 mm from bottom of wall frame).

In addition to the overall surface temperature profile measurements, additional thermocouples were welded to the navy bulkhead panel. The locations are listed in Table 3.3 and shown in Figure 3.17. The sensors required under the IMO FTP are annotated in the table and highlighted in blue in the figure. Under the IMO FTP standard, the Navy bulkhead panel is divided into quadrants, with a thermocouple located at the center of each quadrant, as well as at the center of the panel. A thermocouple is also located along the weld point for each vertical stiffener, at 75% of the total height. Five thermocouples are welded, one to the center of each bolt head, to assess if these points could be used by the fire fighting response teams to better assess the compartment conditions once the exposed compartment boundary surfaces are insulated.

Table 3.3: Description of additional thermocouple locations to measure IMO FTP requirements and other points of interest

Module	Channel	Description
4	0	Bolt 1 (B1, top left)
4	1	Bolt 2 (top centre)
4	2	Bolt 3 (top right)
4	3	Bolt 4 (middle left)
4	4	Bolt 5 (middle right)
4	5	Bolt 6 (handle)
4	6	Bottom left centre (IMO req)
4	7	Bottom right centre (IMO req)
5	0	Left stiffener (upper 75% of length, IMO req)
5	1	top left centre (IMO req)
5	2	pipe, 1 in (25 mm) from wall (IMO req)
5	3	pipe, 4 in (101 mm) from wall
5	4	pipe, 10 in (254 mm) from wall
5	5	top right centre (IMO req)
5	6	right stiffener (upper 75% of length, IMO req)
5	7	centre of plate (IMO req)

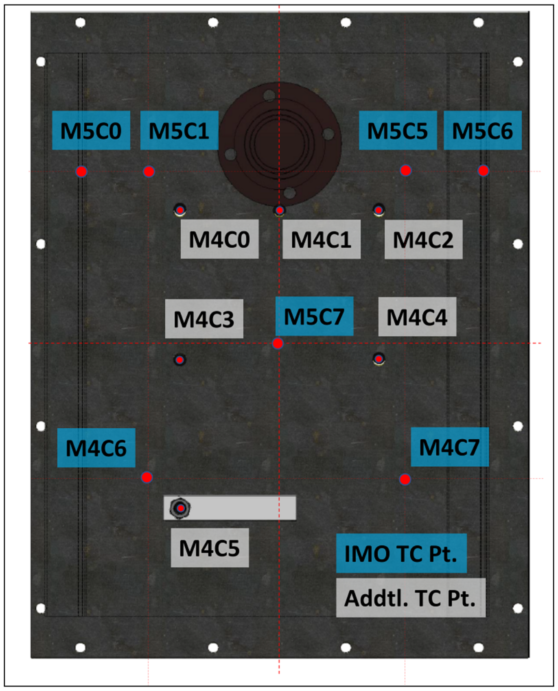


Figure 3.17: Navy Test wall thermocouple location. (IMO required thermocouples indicated in blue)

For the pipe penetration, three thermocouples were welded along the bottom of the pipe as shown in Figure 3.18. One thermocouple is required at 25 mm from the unexposed side of the wall under the IMO testing protocol [12]. Two additional thermocouples were attached at distances of 4 in (101 mm) and 10 in (254 mm) from the unexposed side of the wall along the bottom of the pipe. The three thermocouples on the pipe give a temperature profile along the pipe on the unexposed side during the experiments.

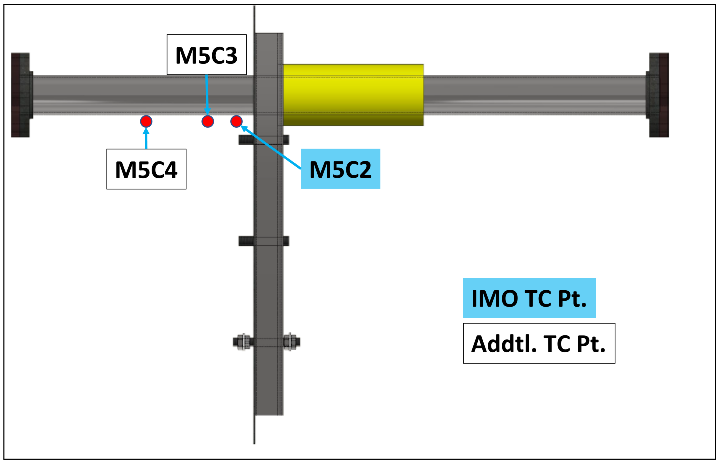


Figure 3.18: Thermocouple locations on the unexposed side of the pipe.. (IMO required thermocouple indicated in blue)

3.3.2 Transducer uncertainty

Type K thermocouples have an uncertainty of ± 2.2°C or ± 0.75% (whichever is greater)[26], with a response time of approximately 1 s at gas flows of approximately 20 m/s [31].

3.3.3 Data acquisition

For data acquisition a National Instruments Compact FieldPoint distributed data logging system is used. The system allows remote placement of the analogue to digital (A/D) signal conversion hardware. Two modular backplanes (NI cFP-1808) in conjunction with a sufficient number of Compact FieldPoint modules to facilitate the required temperature (NI cFP-TC-125) and analog voltage or current (NI cFP-AI-110) measurements are utilized. The backplanes communicate to the local network switch, which uses gigabit Ethernet and a conventional Ethernet protocol to transfer the digitized signals back to a central computer running LabVIEW. Data is collected at 1.125 second (0.89 Hz) increments and saved to Comma Separated Value (CSV) files. All temperature channels are recorded simultaneously. The sampling rate is chosen to ensure to ensure it exceeded the thermocouple response time, which varies depending on the ambient temperature and gas flow rates, but is estimated to be approximately 1 second. [31]

The instrumentation system used in these tests has many advantages including: reduction of the lengths of expensive and exposed thermocouple wire; minimized travel distance of analogue signals for improved noise immunity; and allowance for the controlling and data receiving computer to be located tens of meters from the experiment [31]. The data acquisition wiring, backplanes, network switches and the laptop were all located in the instrumentation compartment, which allows the data to be monitored during the experiment.

3.3.4 Multimedia recording

A QSee high definition digital video recorder (DVR) is used to record several simultaneous inputs from exterior security cameras. These have proven to be cost effective for fire testing due to their low cost and relatively good image resolution. Camera locations and angles were chosen for each test to view both the exposed and unexposed sides of the wall specimen. The fire-side camera (CAM1), is located outside the fire compartment to capture the fire growth and smoke layer development for the main thesis experiments. Generally, the fire side camera is not permanently installed so that it can be removed if thermal failure appears imminent during an experiment. A second camera is located in the transition compartment (CAM2) and is positioned to show the unexposed side of the test specimen during the experiments, looking upwards from near the floor [31]

These cameras provide high definition video but no audio; one area for potential improvement on future experiments may be to include some method for recording the sound levels to allow an objective comparison using decibel level in the transition compartment, as this is another source of information for personnel responding to a fire emergency.

Still images were captured using a Nikon D7000 digital single lens reflex camera set in high quality jpeg mode. These images are used primarily for documenting and explaining the experimental setup, but the camera is also used to capture high definition photographs of specific points of interest during the fire. Using the camera, images could be taken from different angles and areas of focus compared to the fixed high definition video records.

3.3.5 Infrared imaging

A FLIR T650sc handheld infrared camera with a 25° angle lens fitted is focused on the Navy bulkhead panel installation and surrounding frame and used primarily to capture thermal images of the unexposed side of the test specimen. This research grade thermal camera has a temperature range from -40° to 2000 °C, and provides an IR image resolution of 640x480 pixels. The FLIR camera is mounted on a tripod located approximately 4 m from the unexposed wall to ensure all the infrared images captured had the same focal length and angle for comparison purposes. The image capture began after ignition of the test fire and individual frames were captured and stored automatically every 7 seconds which is the maximum framing rate for continuous capture using this model of FLIR camera. Additional infrared images could also be captured upon completion of the main testing from alternate angles to document areas of interest, or troubleshoot heat leakage around the test specimen mounting or the installed insulation. In this respect, the TIC is an extremely useful tool for finding gaps in the test specimen insulation, which would not have been evident based on the thermocouple data or video recordings alone.

Due to the quantity of data contained in combined thermocouple and IR images, data analysis for all tests is focused on the time interval from approximately 5 minutes after ignition until 15 minutes after ignition since that is the period of main concern for the purpose of assessing the potential impact of bulkhead fire insulation on the attack team tactics.

Combined use of the TIC and thermocouple data is chosen for this research since it brought several advantages over using only one of the methods. The thermocouples provided continuous monitoring of wall surface temperatures but only at a set of discrete measurement points. In contrast, the TIC recorded a full IR image of the wall on a longer time scale, at 7 s intervals. Between the two methods, however, there is sufficient data to compare measured thermocouple temperature data to the temperatures captured at the same locations by the TIC camera and make corrections to improve the overall accuracy of the temperature information on the TIC IR image. Even after the comparison, the thermocouple data that is continuously monitoring the unexposed surface temperature is considered more accurate than values obtained using the TIC and will be used as the primary data during discussion. The TIC images, on the other hand are useful for comparison purposes and for explaining local, point thermocouple results in the context of response of the entire assembly to the fire. In all cases, the IR images are useful for providing a quick reference and approximate temperature ranges for visual analysis of the situation, but by correcting the IR image temperature readings they could be used as a second source to verify the information, as well as to get a closer approximation to the surface temperature distribution throughout the portions of the unexposed surface that are not directly monitored by thermocouples.

To accomplish this, image processing is done using the freely available FLIR Tools®software from the TIC manufacturer. This allows the user to edit several parameters on the IR image including the emissivity, relative humidity and ambient temperature, as well as adjust the upper and lower values on the temperature levels, measure specific points of interest, and generate summary reports. The relative values of radiation measured by the camera are primarily emissions from the object, with contributions from reflected emissions and atmospheric emissions from areas with lower ambient temperature. As the temperature and thus radiant emission from the object increases this dominates the signal to the camera. So while atmospheric conditions and other known values can be used to correct the IR images, using a correct value of surface emissivity for the object is critical for getting accurate readings from the IR images. During processing then, the emissivity had to be adjusted to an estimated value for the surface emissivity of the unexposed side of the steel plate, and temperatures determined from the IR image at the approximate locations of thermocouples installed on the unexposed side of the wall were compared against the measured thermocouple temperature values as described below.

In actuality, the unexposed side of the wall did not have a consistent finish or surface appearance, but is generally matte grey, consistent with cold rolled plate steel, although there were some oxidized patches, heat discolouration from welding, and some tool marks. The FLIR user manual provided a wide range of measured emissivities for different varieties of iron and steel, with values of below 0.1 for highly polished finishes, to measurements up to 0.96 for highly rusted red surfaces [14]. In a reference from a different manufacturer, suggested values of emissivity for normal plate steel were in the range of $\epsilon = 0.8$-0.9 [15]. This is lower than the default value for the camera of $\epsilon = 0.97$.

During analysis of the IR images, the measured values for the ambient temperature and relative humidity for the day were first input into the camera software. Key measurement points were then selected from an IR image using the 'spot measurement' tool. This tool places a standard sized circle on the image and outputs a value of the average temperature of that spot. It is chosen because the set sized circle is the same diameter as the bolt faces in the image, which were clearly visible in the insulated bulkhead images, allowing the selection to be reliably compared to that thermocouple measuring point. Other tools were available which included a box, ellipse and line measurement over an adjustable area. These were later used to confirm emissivity settings. Once the spots corresponding to the bolt faces were selected, the emissivity is manually input across a range of values, and the value of average temperature of the spot were compared to the measured values of thermocouple temperature at the bolt head. By trial and error, an emissivity of $\epsilon = 0.85$ is selected as a reasonably representative value to give spot temperature measurements that were within the error range for the measured thermocouple temperatures. Using this value for the emissivity gives measured IR values within 1-2°C of measured thermocouple values in the lower temperature range (for the insulated wall experiments) and within 5-8°C of the measured thermocouple values for higher temperatures of the unexposed steel wall (i.e., in the uninsulated wall tests).

While in this research results and discussion are focused toward comparison of specific temperatures mainly at the thermocouple measurement points, a comma separated value

(.csv) file of the image, that contains IR temperature readings for each pixel, can also be output from the FLIR Tools software [14]. The output temperature values are based on the input parameters used, but would allow a comparison amongst temperatures to be done manually at the pixel level. Here, it is deemed that it would prove a significant challenge to map the specific measuring point to the pixel location, so a method to correlate the points in the IR images to the specific thermocouple location would be required. While it could potentially be facilitated in future by taking some additional reference images, possibly including some kind of locating key (such as a highly reflective point that would be easily distinguishable in the IR image) and using other software tools to assist in the image analysis, the approach described above provides the necessary information within an acceptable range for the purpose intended here.

A second key goal in the research is to gather some data that would be useful for training RCN personnel. The TIC images are a very useful data set for this purpose as they can be readily understood by personnel who are already familiar with use of TIC cameras during fire response operations. It should be noted though that the research images taken during this study use a different colour palette than what is seen in the NFPA 1801 colour palette; for the latter images the lower portion of the temperature scale would be grey instead of blue, with the colour reference bar starting at yellow, transitioning through orange and the highest temperatures in red. [24] Notwithstanding the different colour palette, the TIC images from this research are familiar enough to trained RCN personnel to be extremely useful for demonstrating the practical implications of the fire insulation in terms of changes in surface temperatures at fire divisions.

3.3.6 Additional instrumentation for specific experimental scenarios

In one test, Test number 3 of this series, two standard Underwriters Laboratory (UL) listed battery operated ionizing smoke detectors were purchased from a local hardware store. These featured an 85 dB audible alarm as well as an indicator light. The smoke detectors were used as a trigger in changing the compartment door setting, as might be done in a real fire situation on board a naval vessel. In this scenario, the door to the fire compartment is fully open for ignition and then is closed 4 minutes after detection of the fire as indicated by the audible alarms. The time delay in closing the door is selected based on standard operating procedures on RCN vessels, where the compartment door is closed after evacuation to contain the fire and limit the spread of smoke (estimated as a time delay of approximately 4 minutes). Because the automated fire detection system will also shut all ventilation down (known as 'crashing' the ventilation), it is of interest to study the response of the insulated barrier under this condition since it will limit the fire growth, and thus potentially the maximum hot layer temperatures, by creating an under-ventilated burning condition.

In Test numbers 1 through 4 of this series, it is interest to study smoke propagation into an adjacent compartment through a penetration in the compartment bulkhead test wall. For this experiment, the rear door between the instrumentation and transition compartment is closed to allow any smoke and fire gases to collect in the transition compartment so that the smoke build up and density and gas concentrations could be measured as it flowed from the main fire compartment to the adjacent compartment.

For this test, gas flow velocity measurements were made across the penetration opening using two bi-directional probe transducers. Each probe is centrally located above or below the obstruction provided by the cast iron pipe. The transducer signals were then post-processed to convert the analogue output into gas velocity.

Fire growth, smoke layer development and visibility were captured with a camera (CAM1) placed inside the fire compartment on the left hand side of the door looking upwards towards the opposite corner. This monitored the fire growth over the fuel, the smoke at the opening between the compartments, and a gypsum board painted with black and white checkerboard pattern (described below) which is further used to monitor the smoke layer progression and descent in the fire compartment near the penetration. Smoke flow through the penetration and into the adjacent transition compartment is visualized using a second camera (CAM2) mounted low in the transition compartment and positioned to view the penetration, looking upwards from near the floor.

The smoke layer progression in the fire compartment is monitored using a novel method recently developed at the UW Fire Research Facility by Ellingham [9]. For this, black and white squares, each 305 mm on a side, are painted onto gypsum boards. The boards are mounted vertically in the compartment with a video camera mounted to view each board through the duration of a test. The camera is positioned perpendicular to the painted surface and at a known distance away. The smoke layer progression with time is then visually recorded by the camera, and the depth and thickness of the smoke can be deduced based on detailed analysis of individual images from the recorded traces [31]. This process is followed to capture the data and is not processed as part of this research, but may be of use for future work on smoke progression and penetration using the custom Navy bulkhead test specimen setup.

Concentrations of unburnt hydrocarbons, O_2, CO, CO_2, NO, and NO_2 are measured during the tests using a Novatech P-695 gas analysis system with Servomex Servopro 4900

(IR) and paramagnetic analyzers [31]. The Novatech unit is situated indoors in the main fire test enclosure due to the sensitivity of the components to environmental exposure. A heated sample line is connected to 1/4 in (6 mm) copper tubing that ran along the floor, through the gland of rear wall into the transition room, and is then supported by a vertical stand so that the sampling point is located in the middle of the transition compartment at height of 72 in (1828 mm). This height is set to collect representative samples with which to assess tenability conditions at approximate head height in the transition compartment. To prevent cooling of the fire gases that could lead to condensation in the copper tubing and affect the results, the tubing is wrapped in Fibrefrax insulation along it's length. In this way, sufficient heat is retained in the sampled fire gases as they flow from the transition room along the copper tubing to the heated sampling line and to the analyzers so that no condensation is observed at the connection point between the tubing and the heated sampling line while sufficient gas flow rates were still drawn for the analyzers to monitor the environmental conditions.

The Novatech is connected via an ethernet cable to the local network switch allowing gas concentration data to be captured continuously with the other data by the laptop computer running LabView software. Because the output from the Novatech is a set of analogue signals specific to each measured gas concentration, the Novatech gas sensors were calibrated prior to each experiment. The output of this procedure is a set of calibration curves to determine the concentration of each gas corresponding to a specific analogue signal, as bracketed by zero and a maximum value of concentration. This curve is subsequently applied to the raw analogue output data to calculate the measured value for each gas concentration.

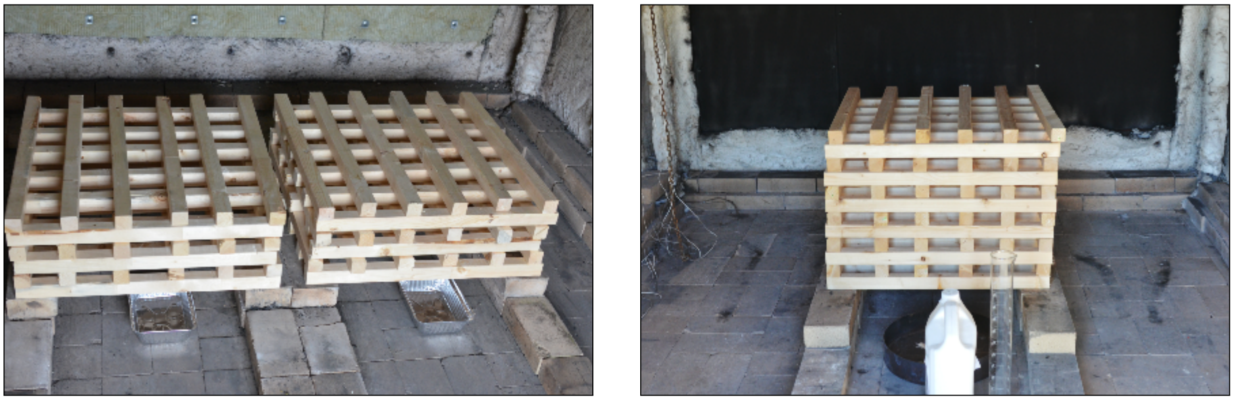
Finally, Gastech®Colour dosimeter tubes (Dosi-tubes) were used to obtain a time weighted average concentration of exposure to CO, CO_2 and HCN in the transition room for the duration of the experiment. The tubes were placed inside the transition room approximately 1 m off the ground along the rear wall beside the closed door leading to the instrumentation compartment. Each tube contains a colour changing reagent that reacts as a specific gas in the hot smoke diffuses through it. The tubes were activated and put in place just prior to lighting the fire and removed from the rear room once the experiment is complete. The time interval for the total exposure time is recorded and the tube is then sealed with tape to prevent further exposure. Because the level of exposure is estimated based on the degree of colour change indicated on the printed scale on each tube, this reading is taken as soon as practicable after the fire and also documented by taking a picture of the tube with the digital camera to refer back to during subsequent data analysis. Using the scale to get the concentration and knowing the time interval allows the time weighted average exposure level to be calculated in part-per-million per hour (ppm/hr), and is a useful comparator against the CO and CO_2 concentrations measured using the Novatech.

3.4 Design fire

Design of an appropriate fuel load and fire is necessary for use in the experiments. The intent is to generate levels of heat flux to the bulkhead that represented fire conditions less severe than the IMO FTP test fire which follows the ISO 834.1 curve (shown previously in Figure 2.1) and also more representative of a real world scenario. A significant amount of work has been done by the Waterloo Fire Research Group by Obach [25], Sheehan [27], and DiDomizio [8] to characterize a variety of configurations of standard wood crib fires, as well as diesel pool fires, for use in the wall fire facility. Different configurations of wood crib fires have been found to typically result in ceiling temperatures between 500 - 600 °C, while the diesel pool fires resulted in ceiling temperatures between 600 - 700 °C.

Based on these previous studies, the laboratory standard wood crib is made from locally sourced 2 in by 2 in (50.8 x 50.8 mm) softwood lumber cut from standard 8 foot lengths (2440 mm). The lumber has nominal measurements of 1.5 by 1.5 inches (34 x 34 mm), and can be either spruce, pine or fir wood (denoted by the ”SPF” designation). Each full length piece is cut into 4 approximately equal length 2 foot (610 mm) pieces. Each row of a crib consists of 6 equally spaced pieces, and the full crib is made of 6 rows of pieces, stacked and with each row mounted perpendicular to the one below. In addition to a single standard wood crib, two configurations made of two wood cribs each were chosen for the present fire tests as shown in Figure 3.19. One consists of two cribs side by side, and the other of two cribs stacked on top of each other. Each crib is raised off the floor using rows of the fire brick to allow a fuel tray to be placed underneath, and also to allow sufficient air flow into the wood lattice structure to feed air into the fire. The fuel load is always centered horizontally in the compartment, and at a spacing of 2 feet (610 mm) from the test wall. For the two side-by-side cribs, a 3 inch (76 mm) spacing is maintained between the two, which is equivalent to the normal gap between each piece of wood in the individual rows, and is intended to allow consistent air flow between the cribs during combustion.

The standard wood crib has been demonstrated to provide uniform and repeatable fire performance while being easy to customize to achieve specific goals. This may include increasing the number of cribs, using different crib layouts within the compartment and generally adapting the overall configuration to the situation at hand. Because it is made of standard construction lumber that is readily available, it is a versatile and effective fuel load that can be adapted to fit a wide range of experimental goals while being repeatable enough to be scientifically valid.



(a) Two wooden cribs in a side by side (SBS) configuration in the wall test unit

(b) Two stacked cribs stacked configuration in the wall test unit

Figure 3.19: Compartment temperature comparison - single wood crib versus two wood cribs

Three different fuel load configurations were tested during the experiments; a single crib, two cribs (stacked) and two cribs side-by-side. This is based on previous work by Obach[25] using a free-burn setup under a large scale calorimeter, which demonstrated that a single wood crib has a peak heat release rate (HRR) of approximately 250 kW, while use of two cribs effectively doubles the peak heat release rate to approximately 500 kW. The experiments. As can be seen in Figure 3.20, when using two wood cribs, the growth and decay rate is similar for both the stacked and side-by-side (SBS) configurations. The two stacked cribs configuration has a longer sustained peak HRR compared to the two side-by-side configuration, so both were included to verify how that impacted fire compartment temperatures and thus thermal exposure conditions on the wall.

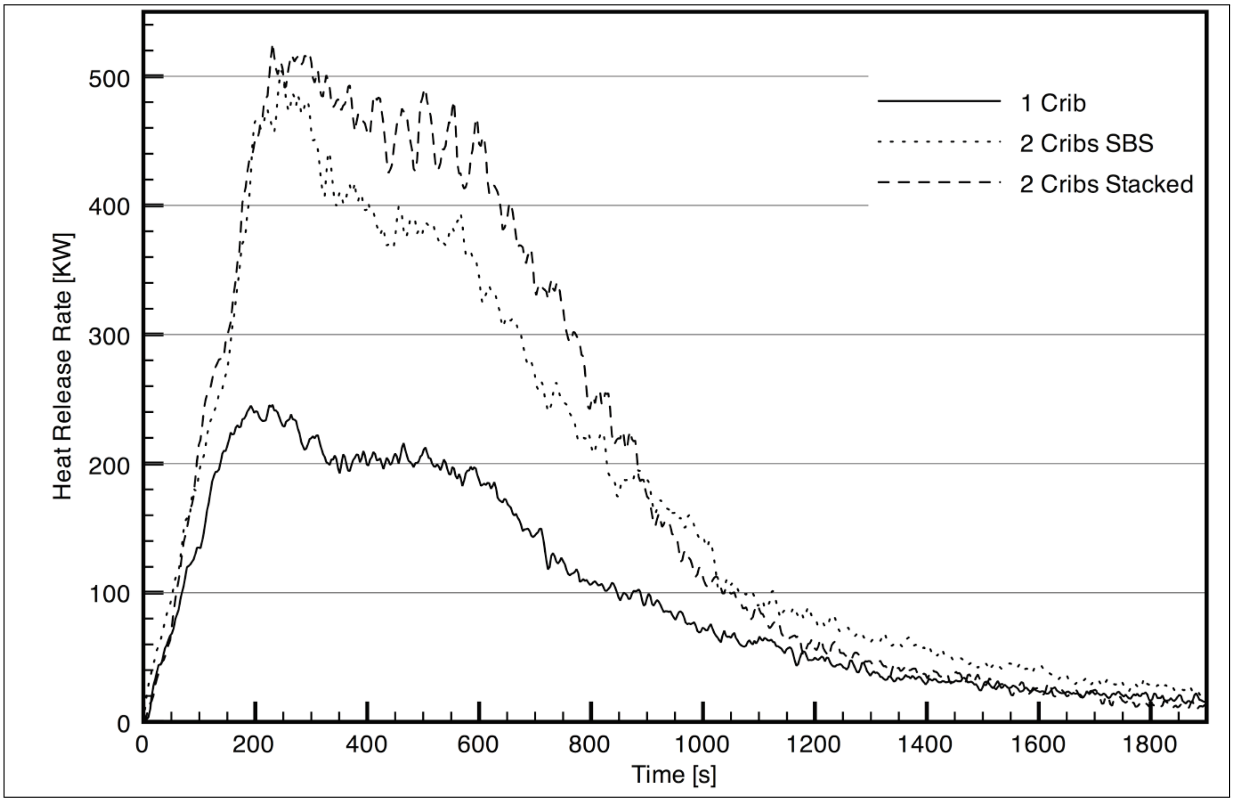


Figure 3.20: Heat Release rates for different wood crib configurations (adapted from [25])

In terms of the duration of the fire, DiDomizio [8] had characterized several wood crib configurations that would have resulted in similar temperatures to the two crib configurations but with a longer duration of that temperature. Because the focus for this thesis is to determine what the potential impacts of insulating the bulkhead might be on tactics used during the initial response as well as the initial breach of the fire compartment, the first 10-15 minutes of fire exposure after ignition is of most interest. Thus, the two crib fire which peaked at approximately 10 minutes after ignition and remained at the peak for 2-3 minutes before decaying is deemed to be suitable, with no significant advantage gained with a longer duration peak heat release rate.

For tactics where a longer time interval may be appropriate, such as boundary cooling, the wood crib configuration chosen can be easily adopted using a series of two SBS wood cribs arranged along the length of the fire compartment as shown in [8].

3.4.1 Starter fuel

For the majority of the testing, methanol is used as the starter fuel, and is not considered to be a significant contributor to the overall fire heat release rate. The exception is in Test 4, where acetone is substituted for methanol. This significantly contributed to fire heat release during the initial 30 seconds of fire growth, and can be seen in the measured results. Based on this result, acetone is not used for any further experiments.

For both the single and double stacked wood crib configuration, a single steel tray with 200 mL of the starting fuel is used, and is placed directly on the fire brick floor, along the center line of the compartment under the front of the crib. For the two cribs side by side, a tray is placed under each crib, with 150 mL of starter fuel in each (for 300 mL total). For safety, the trays were filled partially exposed from the wood crib to allow access, then moved into the final position. The fuel is then lit from the front of the crib (nearest to the door) to allow a direct egress path if required.

For the single tray, an 8 inch (203 mm) round steel tray is used. For the two crib side by side configuration, two 4 inch x 6 inch (101 mm x 106 mm) aluminum trays were used. In both cases, the fuel burned for approximately 30-40 seconds, and this is sufficient to ignite the wood crib and allow a sustained burn to develop which then grew to fully consume the fuel. The two different configurations of starter fuel pan are shown in Figure 3.21. The chosen configuration meant that the wood crib combustion is initially biased towards the front side of the fire compartment (away from the test wall) but because the wood is well conditioned, the fire spread evenly across the fuel load. This method proved to be a safe and repeatable method for igniting all of the test fires.

(a) Fuel tray configuration - single and two stacked wood crib configuration

(b) Fuel tray configuration - two side by side wood cribs

Figure 3.21: Fuel tray configurations used

3.4.2 Additional sources of variability in the wood crib fuel load

When using construction lumber, one factor to consider is that 'softwood' consists of several different species of wood. While all have comparable mechanical performance, there may be additional variability in porosity and other factors that need to be adjusted for when comparing results from different experiments. For example, the density of Douglas fir can range from 430 to 480 kg/m ^{3} and southern pine can range from 510 to 580 kg/m^3 [18].

An additional step of verifying the moisture content using a meter along with weighing the wood cribs helps to further identify sources of experimental error in situations where full conditioning is not possible. To more accurately measure the moisture content of the wood used in the present tests, a Powerfist®pin-type digital moisture meter is used. This device is rated as having a resolution of 1 % and is accurate to ±2 %.

The fully conditioned wood used in the tests is purchased as a batch locally in mid 2019, and each wood crib had an approximate weight of 12.5 kg at 0% moisture (known as the oven dry wood weight). The partially conditioned wood, weighing 15.5 kg per crib, is purchased as a batch in mid 2020, and when adjusting to remove the measured moisture content of 10-12 %, the oven dry wood weight would be between approximately 13.8 and 14.1 kg. This means the wood purchased in 2020 is about 10 % denser than that from 2019, which can result from normal variation in density within the same species of wood, or possibly is due to the two batches being of different species of softwood.

The same conditioned wood type is used for the comparison test of surface temperatures on the unexposed side of the uninsulated wall test specimen against the insulated wall test specimen. Therefore both the moisture content and the differences in the two different 'batches' of lumber do not contribute to uncertainty, and comparable fire growth and decay rates are used in the results.

3.5 Mineral wool insulation details

For the experiments, two different types of mineral wool insulation were used. Several key parameters for each are outlined in Table 3.4. The first product, the JM-Minwool 1200 board, is an industrial product meant for high temperature insulation. It has broadly comparable technical specifications as the Rockwool marine insulation. This product is locally purchased and is readily available in a number of thicknesses, including the 50 mm thickness used here to match the marine A-15 insulation installation.

The second product, Rockwool Searox SL 620, is a mineral wool insulation that has been fully certified under the IMO fire testing protocol to meet the A-15, A-30 and A-60 requirements. This product is only available in the local area by special order, but is kindly donated to support this research by Rockwool Technical Insulation, with sufficient material for complete coverage of two full test wall specimens with some remaining for bench scale testing.

Table 3.4: Mineral wool insulation properties

Insulation	Maximum Service Temperature	Thermal Conductivity
JM-Minwool 1200 board	650 °C	0.35 W/m K (ASTM C518) [19]
JM-Minwool 1200 pipe	650 °C	0.35 W/m K (ASTM C518)[20]
Rockwool Searox SL620	750 °C	0.35 W/m K (EN 12667) [16]

Additionally the 330 mm section of pipe in the wall on the exposed side had to be insulated to be compliant with the IMO FTP pipe test protocol. The JM-Minwool 1200 mineral wool industrial pipe insulation is readily available locally and because of the small amounts involved in the testing, it is not practical to source a matching A-15 certified pipe insulation. With the Minwool product having a service operating temperature of 650 °C and comparable thermal conductivity to marine insulation, this is used throughout the experiments. The insulation is replaced following each test, but no obvious damage or other significant changes to the appearance or physical properties were observed, so the use of the JM-Minwool 1200 insulation is not thought to be a source of any uncertainty in the testing.

For follow on experiments, if a higher peak temperature and/or a longer peak temperature duration are planned, JM-Minwool 1200 may not be completely suitable, but is acceptable for exposure during these specific fire compartment conditions.

Insulation mounting

The insulation is mounted in accordance with the manufacturers instructions found in the Rockwool Technical Guidelines [16]. These are based on the IMO requirements, and use a 3 mm steel pin and a 38 mm steel washer to secure the insulation in place. The pins were fixed at a maximum distance of 300 mm, and followed the pattern in Figure 3.22. The steel pins were welded onto both the steel plate and the sheet metal sections, with approximately 25 mm of the pin extending past the insulation once installed.

This securing method is found to be effective for both the JM Minwool 1200®board and the Rockwool SeaRox SL 620®board insulation.

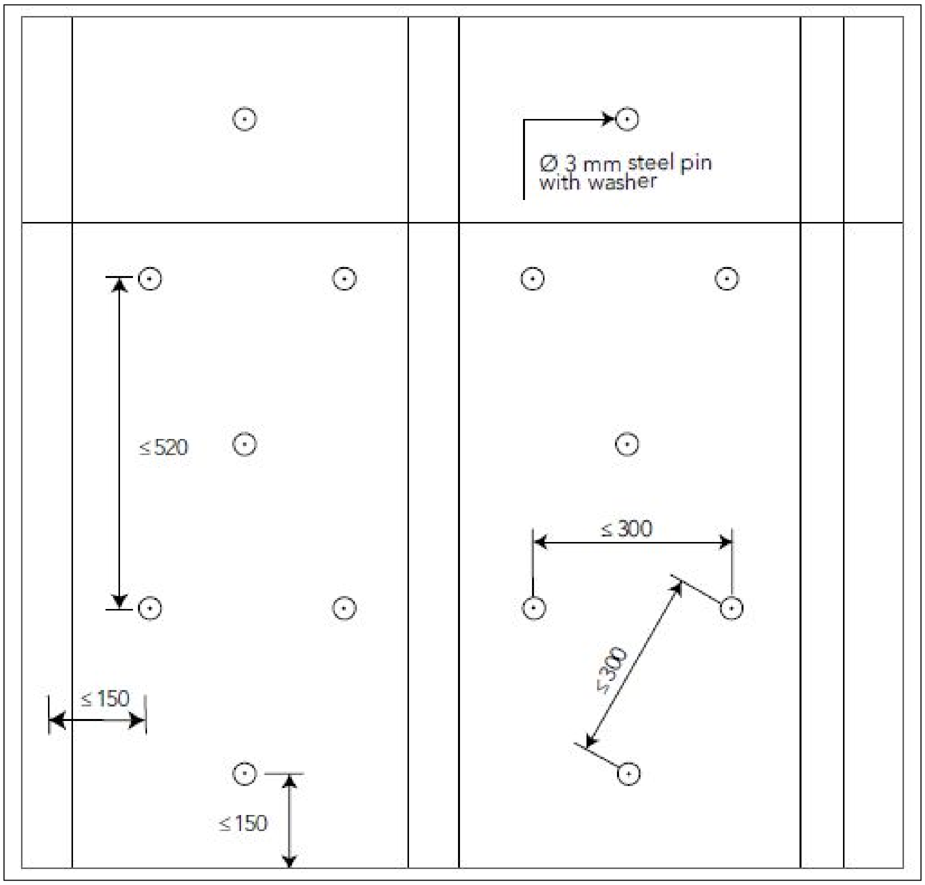


Figure 3.22: Rockwool A-15 diagram showing standard location for the mounting pins [16]

For the JM Minwool 1200®pipe insulation, the product is rigidly formed and is selected to fit onto the outer diameter of the pipe. The IMO requirements for the pipe insulation require it to cover a length 380 mm from the steel plate. The 50 mm thick wall insulation is trimmed to fit around the diameter of the pipe. A 330 mm section of mineral wool pipe insulation is cut to size, and fit around the exposed section of pipe to meet the IMO requirement. Steel mechanic wire is used to ensure the pipe insulation stayed in place, without compressing or otherwise distorting the mineral wool. This is sufficient to keep the insulation in place for the duration of the tests without any gaps.

Following each experiment, the wall and pipe insulation is removed and replaced using the same procedure described above.

With the stiffeners not running the full vertical height of the wall, a small discontinuity approximately 6 mm in width and 25 mm in height above and below the stiffener is noticeable as a hot spot on the TIC images during the initial testing with JM Minwool 1200 product. Initially it is attempted to fill this air gap by cutting insulation to fit, but this is found to be difficult to cut accurately and maintain the shape over the full thickness due to the fibrous nature of the insulation. Therefore, some 3/8 inch (9.5 mm) high temperature fibreglass rope gasket material is sourced locally. This product is rated for continuous use at up to 538 °C, and is easy to cut to size to fill the gap without compressing the adjacent insulation. This is then covered over with small pieces of mineral wool insulation to maintain the 50 mm thickness in that area. This is found to be an effective way to create a uniform surface and eliminated the hot spots. Because the stiffeners normally extend from the floor to the ceiling, in a normal installation these discontinuities would not exist, so this is particular to the test specimen and insulation mounting arrangement used for testing, and would not be found on a ship.

3.5.1 Measurement of wood crib heat of release Rate in the wall test Unit

During modeling work as part of the smoke propagation study, it is observed that the free burn Heat Release Rate (HRR) for two wood cribs side-by-side reported by Obach[25] is not consistent with the fire growth parameters seen in the wall unit tests, and gave significantly different thermal conditions compared to the experimental results.

An experiment is performed to measure the HRR of the two wood cribs side-by-side in the wall test unit to confirm the value for this study. The uninsulated navy composite wall test specimen is in place, with the same wood crib layout and distance from the wall used. The two wood cribs used for this test had an initial mass of 24.87 kg, compared to the initial mass of 28.96 kg in [25], so there will be some differences in the data as a result of normal variations in the wood density and species, with the wood used for the wall fire HRR test having a density of approximately 85% of the wood used for the free burn testing in 2010/2011. Two load cells were used to capture the mass loss rate of the wood cribs. Using the measured mass loss rate from the experiment, the HRR in the wall test unit is determined using Equation 3.1;

$$HRR(kW) = \dot{m} * \Delta H_{c,eff} \tag{3.1}$$

where the Heat release rate is in kilowatts, $\dot{m}$, the mass burning rate, is in kg/s, and $\delta H_{c,eff}$, the effective heat of combustion, is in kJ/kg.

In calculating the HRR, the following value from Obach is used [25];

$$\Delta H_{c,eff} = 14,800 kJ/kg$$

.

This resulted in the HRR curve shown in Figure 3.23 for what is measured in the wall test unit with a peak HRR of approximately 482 kW, compared to the peak HRR of 504 kW obtained in [25]. Because there is a difference in the wood density used in the two tests, with approximately 15% less mass of fuel for the wall test unit HRR, this introduces some variation in the fire growth rate and peak HRR value. However, the trend in the HRR curve is consistent with other observations that the growth rate is slower for the wall unit fire, which also had a peak HRR with a longer duration and that decay rates were similar between the fires.

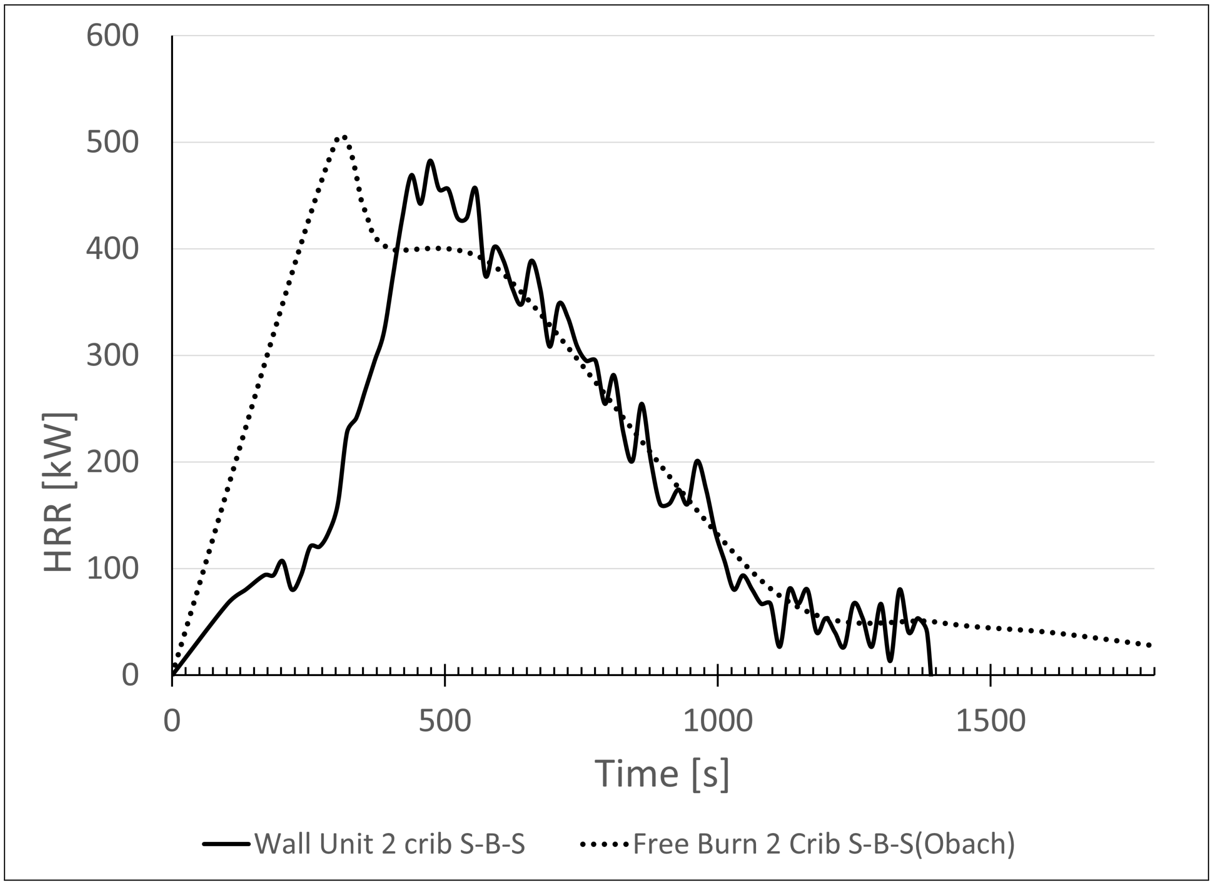


Figure 3.23: Measured HRR from the wall fire test unit with 2 crib side-by-side configuration, compared to free burn HRR from [25]

Due to time limitations, modeling of the insulated wall test with the measured HRR for the two crib side-by-side fire configuration is not undertaken, but this may be of use for future work.

3.6 Small scale testing performed to quantify impact of paint coatings in real fire scenarios

Given that part of the initial fire response on board a naval vessel includes evacuating the space and containing the smoke, it is important to understand how paint on wall and hatch surfaces may negatively impact the safe egress time by decreasing visibility (and tenability, if toxicity data is available) and adding to the fuel load for the fire. Understanding the surface temperature at which the paint begins to off-gas, where visible signs of heating such as bubbling or scorching of the paint occur, and when ignition of the paint occurs is important for both understanding what various visible indicators may mean when deciding to enter a compartment, and for evaluating how the addition of fire insulation over a painted surface may impact smoke generation in adjacent compartments and thus current boundary tactics in the RCN.

During the full scale experimental planning it is observed that although all steel surfaces on ships are coated to prevent corrosion, structural testing is typically done with plain steel. Under the IMO FTP there are standard test requirements for the coatings to certify that they meet flame spread, smoke generation and toxicity limits. This approach makes sense from a certification point of view, but means that any testing to simulate a real environment is missing a potentially significant element, as paint is ubiquitous in every compartment and would contribute to the smoke generation, toxicity and fire load in the fire environment.

Prior to considering including the paint coatings in future full scale testing, a procedure is developed to test the paint coating according to IMO FTP requirements but using the lab equipment available. The method is extended further since paint testing is normally done at only the original paint coating application thickness, but in reality multiple coatings are applied throughout the life of the ship so it is of interest to also determine how paint build up might affect the overall results. In consultation with the paint coating experts in the RCN [2], then a protocol is developed to properly measure and document multiple coats of paint on a test sample, with a target thickness provided based on their experience in the paint build-up seen on a 25 year old vessel. For this, a target thickness for multi-year paint of 18 mils (450 microns) is used, which is approximately 3-4 times the total thickness of 3.1-5.6 mils (78-141 microns) for the initial application of 1 coat of primer and 1 coat of finish applied in accordance with the manufacturer instructions (see more detail below).

One of the paint coating systems that is approved for use on RCN vessels is used for these experiments in order to obtain results that were relevant for use in RCN compartment fire modeling. This ensured results were relevant to this research, but also for future research tailored for the RCN. Because the paint coating system is a commercially available product with an IMO FTP certification, the results may also be relevant for general marine fire fighting research.

Materials were donated by International Paint, and consisted of the Interprime 234 prime coat and the Interlac 665 gloss finish. For coating applications, the manufacturer specifies a finished dry film thickness range, and the corresponding wet film thickness. It is important to follow the correct paint application process in the present work, as too little film thickness would not represent proper protection of the steel substrate, while a coating that is too thick would not properly cure and bond to the substrate.

During normal paint application work in the RCN, quality control checks are carried out by inspectors certified by the National Association of Certification Engineers (NACE). All surface preparation is done to the Society of Protective Coatings standards (SSPC, previously named the Steel Structures Painting Council). For paint film thickness, the manufacturers guidelines are followed, and can be verified using both wet film gauges as well as dry film gauges. Thus, the recommended dry film thickness from the manufacturer instructions for both the primer and finish coatings used in this research are found in table 3.5 below.

Table 3.5: Summary of paint coating dry film thickness from manufacturer's instructions ([4] and [3])

Paint Coating	Dry Film Thickness	Purpose
Interprime®234	1.5-3.6 mils (38-91 microns)	alkyd primer
Interlac®665	1.6-2 mils (40-50 microns)	gloss enamel finish

Test samples were prepared using plain steel test coupons onto which the target thicknesses of paint had been applied. Each steel coupon is a standard 10 cm x 10 cm piece of 12 gauge sheet steel (2.5 mm thick). The coupons were prepared using sand paper, using the SSPC-SP2 (surface preparation hand tool cleaning) standard as a guideline. Coupons that included a welded pin for later combined paint and insulation testing were prepared using a hand grinder to remove any weld slag and used the SSPC-SP3 (surface preparation power tool cleaning) standard as a guide.

Target thicknesses of paint were then applied, using one coat of primer and either one or multiple coats of finish (with appropriate cure time in between coats), until the average dry film thickness is within the target range when measured using a hand held ERAY A770 digital paint thickness gauge. This multipurpose gauge has a range of 0 to 2000 microns (0 to 78.7mils) and comes with dual probes to use either the magnetic induction or eddy current principle to measure a coating thickness on ferrous or non-ferrous substrates. The unit comes with standard thickness foils to allow for both zeroing and multipoint calibration and is considered accurate to ±2.5 % of a micron.

To obtain an average dry film thickness (DFT) of the paint on each coupon and account for surface variations, 5 readings were taken each time; one at the center and one near each corner of the coated specimen. Combined with the measured weight of the steel coupon, the weight of the cured primer, and the weight of the cured top coat this gives sufficient measuring points to account for variation in the paint application between samples while allowing for comparison between results.

Once the steel coupon is prepared, the following steps were taken to build up the paint thicknesses necessary to estimate performance with multiple coatings;

1. Steel coupon weighed;
2. following manufacturers instructions, one coat of Interprime®234 is applied and allowed to cure;
3. coupon with primer weighed and DFT measurements taken;
4. following manufacturers instructions, a coat of Interlac®665 is applied and allowed to cure;
5. DFT measurements of the total coating thickness were taken to check against the target final thickness;
6. additional coats were applied, cured and measured until the target is reached;
7. final test sample is weighed; and
8. following the test, the sample is weighed to determine overall mass loss.

By using this procedure, industry best practices for paint application were followed in a lab setting, which ensures consistency and repeatability. After the paint is applied, separate samples were tested in the smoke density chamber to obtain estimates of smoke generation potential and thus potential smoke density arising from painted surfaces and in the cone calorimeter to obtain an estimate of the heat release rate from the paint. By recording the mass of deposited primer and paint on the steel and the mass remaining following combustion, sufficient data should be collected to be used for estimating potential contributions and for modeling any additional heat load from accumulated paint to the fire environment if scaled up to a full compartment scenario. By using different target thicknesses to simulate the gradual buildup over the life of the vessel and comparing results against the PASS criteria of the IMO FTP testing and the baseline initial test application, over the longer term the data could be used to evaluate the impact of paint buildup on fire growth and factors such as smoke production, toxicity, tenability conditions and fuel load as paint accumulates in the compartment over the service life of a vessel.

If significant, this could change the fire risk analysis of specific compartments over the life of the vessel, with consideration given to changing the management and tracking of the application of paint coatings, particularly in accommodation areas, where painting may be done for quality of life reasons to 'freshen up' the compartments, instead of as part of normal coating maintenance and repairs necessary to prevent corrosion.

3.6.1 Multi year paint accumulation - Cone Calorimeter testing

In a second phase of development of experimental methods to measure the contribution of paint inside that compartment during a fire, a cone calorimeter test is conducted on a steel sample coated with multi-year paint accumulation to obtain basic fire parameters such as heat release rate, while also monitoring the surface temperature of the steel coupon. When combined with the smoke density chamber results, this data provides a baseline for estimating how multiple layers of paint may contribute to a compartment fire scenario, and how important considerations such as fire load, smoke generation and visibility will be impacted during the life of the vessel.

A cone calorimeter from Fire Testing Technology that complies with the ASTM 1354 standard is used in this second set of experiments. The cone calorimeter heater consists of a heating coil wound into a conical shape. The voltage is controlled to produce a constant irradiance onto the surface of a test sample. The sample is placed on a load cell a known distance from the heat source, so that the mass loss rate can be measured during the experiment. Exhaust gases are collected and analyzed to provide time resolved measurement of oxygen, carbon monoxide and carbon dioxide concentrations. The oxygen consumption and mass loss rate data are then used to calculate the heat release rate from the sample as a function of time.

For consistency with the sample irradiance used in the smoke chamber testing, an incident heat flux of 50 kW/m^2 is also used in these tests. The height of the sample is adjusted to maintain a separation of 50 mm from the heat source, with the calibration of the incident heat flux done for this separation. A 10 cm x 10 cm, 3.5mm thick steel coupon is used as a substrate and prepared with the same procedures described above to achieve a final dry film thickness on one side of the steel coupon that corresponds with the target dry film thickness chosen to correspond with multi-year accumulation of paint. The painted side of the coupon is then exposed to the incident heat flux and mass loss, heat release rate, smoke production rate and CO levels (as a percentage) determined as functions of time after the start of exposure.

A thermocouple is attached to the unexposed side of the sample as shown in Figure 3.24, where the thermocouple wire is visible on the left hand side of the picture underneath the exposed steel coupon. The thermocouple output is captured using the same data acquisition system used in the large scale experiments. A sampling interval of 1125 ms is selected to follow the thermocouple response to heating of the sample. Because the steel used as a substrate is 3.5 mm thick, it can be considered thermally thin, and thus the measuring point can be used as an indicator of the surface temperature on the exposed side of the sample as well.

The correlation between measured temperature and visual characteristics of the exposed paint provides important threshold values for use by fire fighting teams looking for visual cues that might be observed on the unexposed side of a watertight bulkhead to help determine whether or not there is a fire on the opposite side. There is no data currently available related to the temperatures at which off gassing and smoke production from paint layers begins, or if those temperature threshold values are affected as multiple coats of paint are applied during the life of the ship.

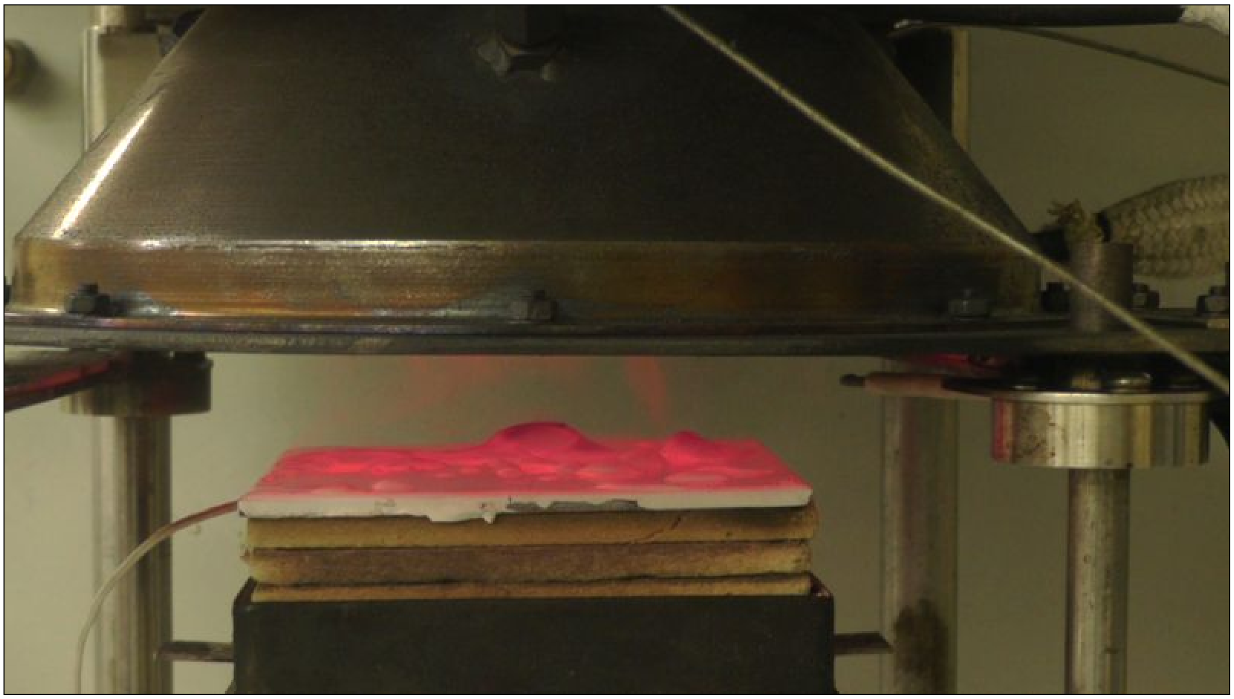


Figure 3.24: Cone calorimeter painted steel coupon test- 50 kW/m^2 exposure with additional thermocouple installed

Finally, digital photos were taken to document key events during the test, such as visual indications on the paint from heat exposure (discolouration, bubbling et cetera), indications of off-gas or smoke generation, ignition and combustion.

3.6.2 Fire insulation orientation to fire - cone calorimeter test

The final set of small scale tests were designed for a preliminary investigation of the response of a painted steel surface that is then covered in fire insulation. This combined test system is anticipated to be the usual combination found on bulkheads on board naval vessels. Since fire insulation is designed to act as a thermal break, it is only typically installed on one side of the fire division, unless the structure is critical and will therefore be protected totally from heat exposure to prevent structural failure. In the typical installation, the fire insulation is installed on the same side as the structural reinforcement (such as the stiffeners) to make efficient use of the available space. Because fires can occur on either side of the fire division, two different fire exposure scenarios exist, with a simplified diagram of each scenario shown in Figure 3.25;

1. The insulation is on the unexposed side of the bulkhead (in the adjacent compartment), so the painted steel is directly exposed to the fire, with significant heating to the paint on both sides of the bulkhead; and
2. The insulation is on the exposed side of the bulkhead (in the fire compartment), so the painted steel surfaces are not directly exposed to the fire resulting in limited heating of the paint.

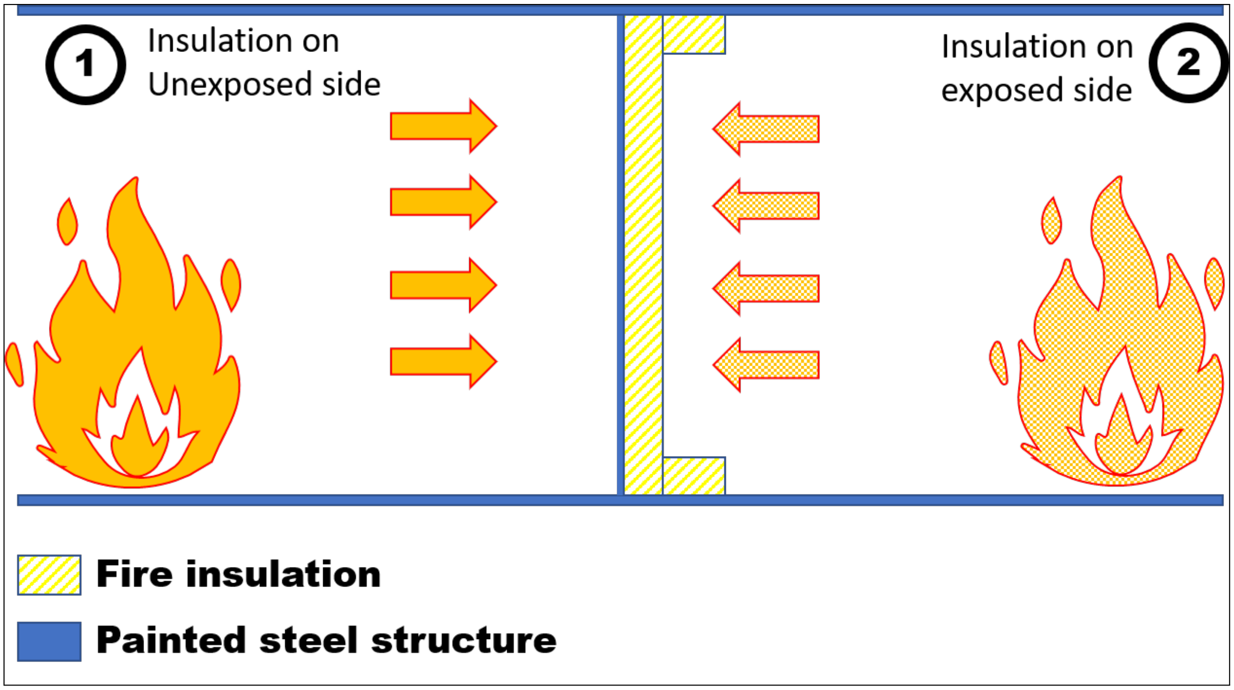


Figure 3.25: Simplified diagram of two possible fire exposure scenarios for the painted steel structure at the bulkhead with fire insulation installed

From a thermal break perspective, it does not matter which side the insulation is on (relative to the fire), but the location of insulation does affect the degree of heating the steel structure will undergo. When the additional factor of a painted steel structure is included, the two insulation configurations outlined above may have very different implications, as which side the insulation is mounted on will potentially determine whether the paint on a bulkhead off gasses, produces smoke or burns.

In designing these experiments, the first focus is to gain an understanding of the behaviour of the paint on the unexposed surface of a bulkhead insulated on the fire side so that results could be used in conjunction with the large scale experimental results. As discussed in Section 3.5, the test wall used in the large scale tests had insulation exposed to the fire (Tests 7-10) and surface temperatures were measured on the unexposed side of the bulkhead. Those results, when combined with these small scale results that include a painted surface, will aid in understanding, and possibly allow estimation, of the amount of off gassing and smoke generation that will occur in the compartment adjacent to the fire. The information can be used to inform review of compartment entry procedures, boundary cooling tactics, and general smoke control approaches on ships fitted with fire insulation.

This configuration is tested initially at large scale since the insulation acts to protect the painted steel surface from exposure to the fire. In contrast, for a scenario that has the insulation protected from direct flame impingement since it is mounted on the other side of the steel structure, the paint on both sides of the steel will experience significantly higher heat exposure during the fire. Therefore, this second configuration is also included in the small scale study to provide preliminary data and insight into how the behaviour of the paint will change in this situation. Results were then also included in the overall review of fire fighting tactics, and also examined for how this insulation configuration might impact compartment tenability. If the results show, as anticipated, that the location of insulation impacts compartment tenability and smoke generation during a fire, this will provide important data for consideration in situations where it is critical that a compartment on board ship is kept free of smoke during a fire.

Previous work by Nagy[21] investigated the thermal properties of mineral wool insulation for modeling purposes, and included an experimental setup for using the cone calorimeter to measure temperature profiles through a layer of insulation when exposed to a constant heat flux. A variation of this experimental setup is used again in the present study though with the steel coupons, the maximum weight on the load cell of 2.3 kg (approximately 5 pounds) is the limiting factor for the experiment design. Nonetheless, the two experimental configurations were tested and are shown in Figure 3.26 and Figure 3.28. The conical constant heat source of the cone calorimeter again provided a uniform surface heat flux to mimic the fire exposure.

One configuration is constructed with the insulation exposed to the heat flux (so the painted steel is shielded), and another where the painted steel is directly exposed to the heat flux (and the insulation is heated via conduction through the steel). For this, two

10 cm x 10 cm, 3.5 mm thick steel samples were prepared, each with a 3 mm pin located on one surface. Paint coatings were applied to what would be the unexposed sides of the steel in accordance with the manufacturers instructions to replicate an initial application of 1 coat of primer and one finish coat. This approach is taken to establish a baseline behaviour for a single layer of paint instead of immediately investigating samples coated with the multi-year paint accumulation used in the previous small scale tests. Pieces of Rockwool SeaRox 620 SL mineral wool insulation, 50 mm thick, were then attached to each steel sample using the pin to make a configuration that meets the A-15 fire division rating. A ceramic backer is placed underneath the sample to protect the cone calorimeter from damage and the insulation-steel composite samples were exposed to a 50 kW/m^2 incident heat flux under the cone calorimeter for consistency with the other small scale tests. The height of the sample is adjusted to maintain a separation of 50 mm from the heat source, with the calibration of the incident heat flux done for this separation.

Thermocouple data is captured following the standard procedure already described, and is combined with the results of from the cone calorimeter software to provide the mass loss rate, heat release rate, painted surface temperature and insulation bulk temperature results.

Finally, digital photos were taken to document key events during the testing, such as visual indications on the paint from heat exposure (discolouration, bubbling et cetera), indications of smoke, and any combustion.

Figure 3.26 is the test setup used for the scenario 1, which places the insulation on the unexposed side of the steel structure. From the perspective of the unexposed side, the painted surface is underneath the insulation, but is subject to the full heat exposure, so is likely to reach combustion temperatures and generate smoke behind the insulation. A thermocouple (labeled as TC0) is placed at the center of the unexposed steel plate to measure the surface temperature of the painted steel, with another thermocouple (TC1) placed at the center of the insulation, at a height of 25mm to monitor the insulation bulk temperature.

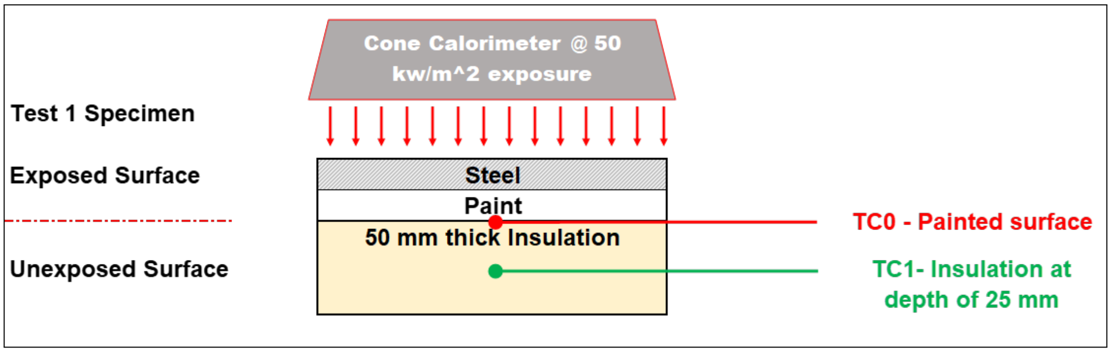


Figure 3.26: Insulated cone test - scenario 1 schematic

Figure 3.27 shows the actual experimental setup for a scenario 1 configuration, where the steel is directly exposed to the heat source, and the paint and insulation on the unexposed side. The two thermocouple wires are visible on the right hand side of the photo, with the protective ceramic backing, metal sample holder and the scale for monitoring the mass loss also visible.

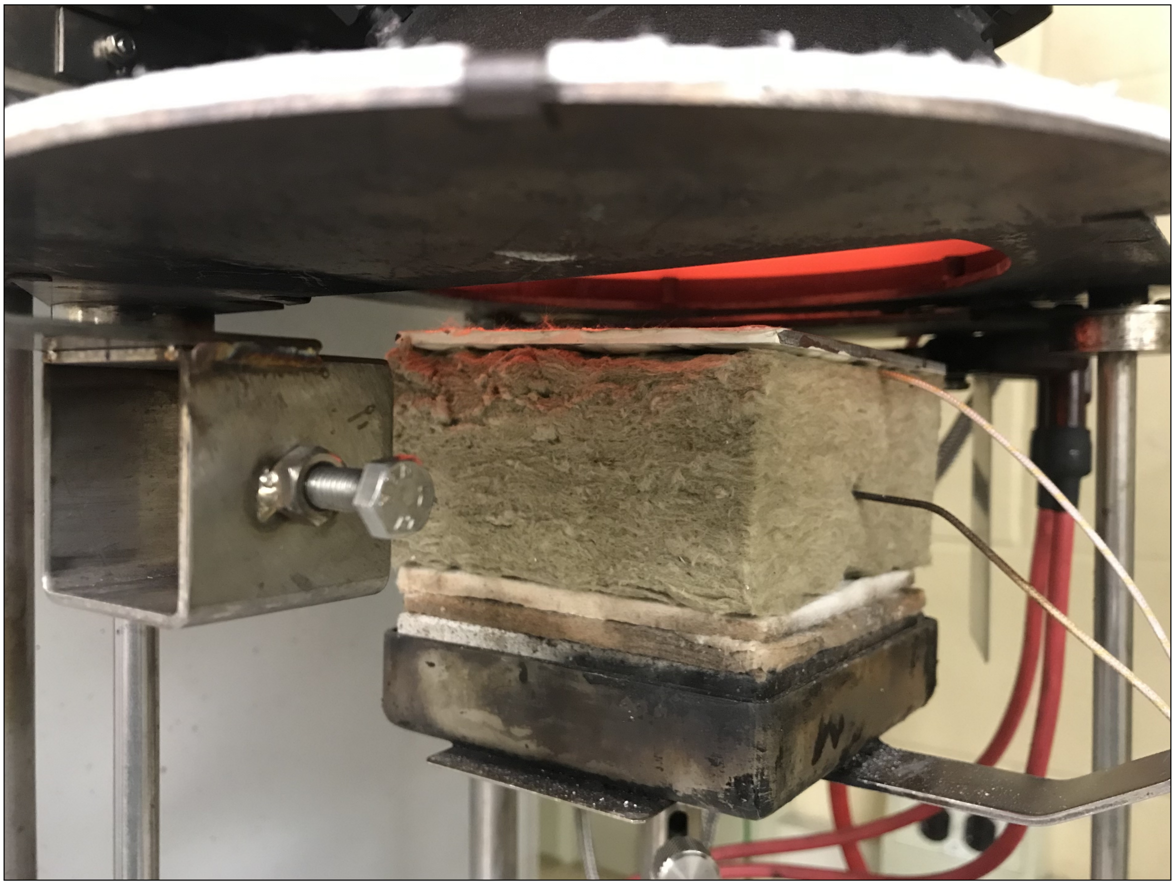


Figure 3.27: Insulated cone test- scenario 1 test setup

Figure 3.28 is the test setup used for scenario 2, which places the insulation on the exposed side of the steel structure. From the perspective of the unexposed side, the painted surface is visible, and is protected from the fire exposure by the insulation. A thermocouple (labeled as TC0) is placed at the center of the insulation, at a height of 25mm to monitor the insulation bulk temperature, with another thermocouple (TC1) placed at the center of the steel plate to measure the surface temperature of the painted steel.

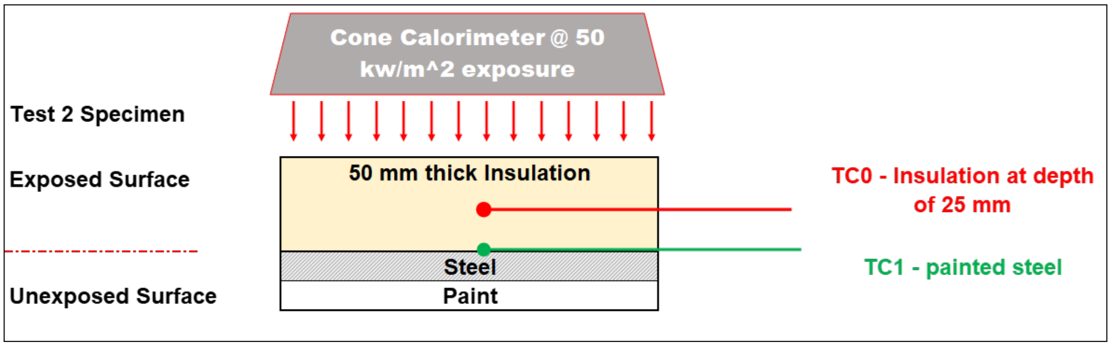


Figure 3.28: Insulated cone test - scenario 2 schematic

These experiments provided preliminary data on how painted surfaces with insulation will potentially interact with heat exposure if incorporated into future full scale testing. They can also be combined with the multi-year paint results to estimate the impact of accumulated paint on a compartment fire environment when both sides of the steel structure are painted.

With extension, a data set such as this should also be useful to provide more realistic modeling of ship fires by contributing to the understanding of surface temperatures where paint will become involved in a fire, and how that involvement potentially impacts visibility and compartment tenability. This aspect is not typically incorporated into fire safety design considerations or compartment fire models, and thus underestimation of actual conditions in a real fire may result. If this potential exists, safety margins around safe egress routes may need to be increased in the design phase to take into account the known issue of accumulation of paint over the service life of a naval vessel

3.6.3 Multi year paint accumulation - Smoke Density Chamber testing

Because accumulation of paint on the bulkheads, deckheads and other painted surfaces in a compartment is common during the service life of a vessel, it is of interest to develop experimental methods to measure the contribution of paint inside that compartment during a fire. In the first stage, testing is conducted to validate a procedure for, and conduct a preliminary investigation into, the impact of paint layers on smoke density and toxicity. For this, an existing smoke density chamber is instrumented with gas sampling tubes and used to estimate a selection of gas concentrations and overall smoke density that resulted from the paint on a steel specimen coated with paint to a thickness representative of multi-year paint accumulation.

The testing is done using a standard Smoke Density Chamber from Fire Testing Technology, which is compliant with both the ASTM E662 and ISO 5659 standards (used in the IMO FTP standard [12]). A painted steel coupon is prepared in accordance with the procedure described above. The incident heat flux for testing is determined based on measurements of heat flux determined by DiDomizio[8] in full scale wood crib wall fire experiments. Using a steel wall test specimen, he collected temperatures and other data, such as the heat lost at the boundaries, and used them to develop a 2 dimensional mathematical model to calculate the heat flux on the wall surface. Test 3 from DiDomizio [8] used a fuel load closest to the fuel load arrangement used for the large scale experiments in this research and the calculated heat flux to the wall is between 30-55 kW/m^2. Based on these results, a constant incident heat flux of 50 kW/m^2 is selected for the smoke density chamber testing conducted here.

Gastech®Colour dosimeter tubes (Dosi-tubes) tubes for two target fire toxicants, CO and HCN, were left inside the smoke chamber to obtain approximate time weighted measurements of the generation of both of those byproducts during paint combustion. The IMO FTP includes a procedure to identify and estimate concentrations of gas in the smoke during evacuation using a Fourier transform infrared spectroscopy (FTIR) apparatus that meets ISO 19702 requirements to conduct the gas analysis. An FTIR apparatus is not available, is costly and requires significant skill to operate, so it is decided to try dosimeter tubes in this initial study. Because the temperatures in the chamber exceed the normal operating temperatures for the chosen Gastech tubes, the level of accuracy of the results is difficult to estimate, but would be useful to investigate in conjunction with the FTIR results toward future refinement of the method. If the dosimeters can provide even an approximate measure of concentration of key gases in small scale tests, they may be a useful and versatile tool for monitoring in large scale fire testing as well, particularly in areas where digital sensors may fail due to the harsh environments in large scale fire experiments.

Due to constraints on time and lab access, only one thickness of paint is investigated in the present case. In future testing, varying both the paint thickness and the incident heat flux would give a better data set for integration with modeling or comparison with large scale test results. The experimental results for both the large scale testing and the small scale bench tests are discussed in Chapter 4. The large scale experiments include the characterization testing used to determine the baseline thermal exposure conditions of the wall under different fuel loads, and selection of the fuel configuration to achieve the desired conditions for the final testing of the fire insulation. The large scale tests of the fire insulation included test wall with both industrial mineral wool insulation and with

IMO A-15 certified mineral wool insulation. The industrial mineral wool testing provided insight into how to refine the installation and configuration of the test wall assembly, while the IMO A-15 certified mineral wool tests provide data that can be directly correlated to possible fire scenarios on RCN vessels where IMO certified fire insulation is used.

The small scale test results are also presented and discussed in Chapter 4, with discussion of the impact from multi-year paint accumulation in a fire scenario and the impact of the location of the fire insulation relative to the heat source on painted structures. The large and small scale results are then combined in a discussion of how this may impact current naval fire fighting operations and training.

Chapter 4

Results and Discussion

4.1 Overview

This chapter contains results of the large and small scale tests conducted using the methods and test procedures outlined in the previous chapter. For understanding the experimental setup in terms of the RCN terminology, the fire compartment is the primary zone, while the intermediate compartment would be the direction that the emergency response is approaching from. From this perspective, the temperatures and any other indications that could be observed from the unexposed side is what is used to inform the decisions made by personnel as part of the emergency response.

In the first section, data from four characterization tests that were completed as part of the design fuel load selection are presented and discussed. Because this portion of the testing included features in the test wall aimed toward study of smoke propagation from the fire compartment into the transition compartment to support other research objectives, the smoke propagation and atmospheric monitoring results are briefly presented.

In the second section, results from the final characterization tests using the design fuel load with the test specimen configured to support the final Navy bulkhead test requirements are presented and discussed. Because of time and logistic limitations during the testing period, this includes examination of the impact of using fully conditioned wood (with 0% moisture content) versus partially conditioned wood (6-8% moisture content) on the thermal exposure conditions for the test wall.

In the third section, the results from the four insulated steel wall tests are presented and discussed. These include two tests using an industrial mineral wool insulation with partially conditioned wood for the fuel, and two tests using an IMO certified insulation product with fully conditioned wood for the fuel. The marine grade mineral wool insulation is installed in accordance to the A-15 certified configuration, with the industrial wool insulation installed using the same thickness and installation procedures for consistency and comparability between results. A brief explanation of how the test results may compare to a real shipboard fire is included for context.

The fourth section provides an analysis of the impact of adding fire insulation to a bulkhead by comparing the results from the uninsulated test to the insulated wall tests. This comparison includes looking at both the general results as determined at the standard

IMO certification test points on the plate and the pipe penetration, as well as at additional key monitoring points where thermocouples are fitted in the test system.

The fifth section presents and discusses the results from the small scale testing on painted steel surfaces. These preliminary results provide some insight into how the insulation will interact with the painted steel surfaces, at what unexposed surface temperatures the paint will exhibit visual cues of heat exposure and begin to generate smoke, and how accumulation of paint over the life of the ship may change the fire properties of the coating. In addition to being of value for this thesis, further development of these results can be used to modify the experimental design in this work to safely include paint in the insulated test wall experiments, as well as be used as an input to improve the modeling of shipboard compartment fires.

In the sixth section, the results of both the large scale testing with the insulated wall and the small scale paint testing are combined and used to analyze how this new design requirement may impact RCN firefighting tactics and decision making processes. Because the RCN uses a two-tier fire fighting response, the analysis is broken down into the relevant time intervals for both the initial first aid response, and the follow on response by the fully equipped attack team and boundary cooling efforts. This includes recommendations for possible changes, and notes areas where additional work would be required to fully understand the potential implications so that any future changes to safety critical procedures are evidence based. This section includes a demonstration using readily available material and equipment that could potentially be used in fire fighting training to show how effective the fire insulation is when introducing the topic to RCN personnel. A brief commentary is included on how these results may be of interest for land based fire fighters responding to a shipboard fire for context as well.

4.1.1 Data reduction

Before presenting the detailed results, it is important to note the general procedure for data reduction that was used in presenting the results. For the temperature plots, each data point shown is an average between the temperatures measured on thermocouple trees on the left and right hand side of the test wall (Tree 1 and Tree 2 respectively). Each thermocouple tree consists of 7 sensors equally distributed vertically from a height of 0.3 m from the floor to 2.13 m from the floor, with an additional thermocouple located near the ceiling. By taking the average reading between the thermocouples at each height, any variations in measured temperature between the two sides due the impact of the prevailing wind (which created some preferential burning generally observed on the right hand side of the fire compartment, looking in from outside) are averaged out.

The Navy bulkhead test specimen is largely symmetrical, with symmetrical thermocouple measuring points on the same points on the unexposed left and right hand panels of the wall. There was no significant difference evident in the experimental temperature data between the two sides. Therefore, the average gas temperature at the wall, as determined above, is thought to be a reasonable measure to represent the thermal exposure at the wall face. It is therefore used in the discussion of the experimental results in which the differing fuel loads were compared.

Although the test data typically captured between 25-30 minutes of data, only the first 15 minutes after ignition (or 900 s) is shown in the temperature plots, as this covers the period of interest for the RCN fire fighting response time. The full results, including the separate thermocouple tree temperature plots for each experiment for the full time period of the tests are available in Appendix C.

For the video images captured, the High Definition video feeds from camera 1 in the fire compartment (CAM1) and camera 2 in the transition compartment (CAM2) are taken from a synchronized playback of both digital files with no manipulation or colour correction applied.

All IR images were adjusted using the method described in the previous chapter with a standard emissivity of $\epsilon = 0.85$. This brings the measured temperatures in the IR images to within 1-2 °C of agreement with the point measurements from the thermocouples in the lower temperature range measured on the unexposed side for the insulated wall tests, and within 5-8 °C at the highest temperature measured on the unexposed side in the uninsulated wall tests.

4.1.2 Potential area for experimental improvement- audible indication of a fire

Because the high definition video did not include any audio capture, the analysis of the experimental results does not include discussion of any audible indications. During the series of experiments, the fire could be heard to be burning from the transition compartment, and subjectively was quieter with both the industrial mineral wool insulation and the IMO A-15 insulation installed. This is consistent with the product specifications, which include sound reduction measurements of 45 dB for the Rockwool Searox 620 SL product when the A-15 compliant solution used for this experiment is installed on a 6mm steel bulkhead, and up to 51 dB on an A-60 compliant bulkhead [16].

Because no objective evidence is available to confirm the subjective impressions, the noise levels from the fire that were audible on the unexposed side will not be discussed during the detailed analysis of the result. However, in addition to the tactile and visual indications from an adjacent compartment when looking at the surface on the unexposed side personnel may get during a fire response, hearing a fire and smelling smoke are both key indicators as well, especially during the initial RRT window when personnel have minimal protective equipment, outside a fire resistant uniform.

Some subjective commentary on the noise levels is therefore included in the sixth section of the analysis of the results, where the overall implications for the RCN fire fighting tactics are discussed. This may be an area of possible improvement for future experiments to expand on this work, by including a method to monitor the sound level in the adjacent compartment, allowing the fuller picture of all the indications available to personnel responding to a possible fire. For a comparison to a real shipboard fire, this objective measurement could then be compared against the normal ambient noise levels on a ship.

4.2 Initial characterization testing

4.2.1 Overview

Four characterization tests were carried out as summarized in Table 4.1. In addition to verifying the instrumentation and validating previous fire compartment temperature profiles found in [8], [25] and [27], these tests were also conducted to monitor gas concentrations, temperature, and gas flow through an open penetration into the transition compartment. For each test, the door between the transition compartment and the instrumentation compartment was closed, with an opening in the test wall used to simulate a cable penetration on a non-watertight bulkhead on a ship. The configuration and additional instrumentation is fully described in the previous chapter. The smoke propagation data itself is not relevant here, but is used to support other research which includes the development of a computer model validated by experimental data.

The fuel load for Test 1 consists of a single wood crib, where Test 2 used 2 stacked wood cribs, allowing comparison of both the compartment temperature profiles, as well as the resultant tenability conditions in the transition compartment under well ventilated fire conditions, achieved by leaving the door to the fire compartment fully open. Test 3 includes a trigger event which corresponds with RCN tactics to confine the fire compartment after the initial investigation, with the door to the fire compartment being closed at 4 minutes (240 seconds) after the smoke detector activated, which results in underventilated fire conditions in the test compartment. Test 4 is a repeat test of a fire fueled by a single wood crib to include gas monitoring equipment which was not available for Test 1. Since the smoke propagation data is not directly relevant, tests 1 and 4 data sets are instead used to provide additional information on thermal exposure of the test wall as related to choosing a design fuel load and configuration for the final experiments.

Table 4.1: Characterization Test Overview

Test	Date	Description
1	1 March 2020	*Fuel:* Single wood crib, 60 cm from wall. 200 mL of methanol for starter fuel. *Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment closed. No gas monitoring in transition compartment.
2	18 September 2020	*Fuel:* Two stacked wood cribs, 60 cm from wall. 200 mL of acetone for starter fuel. *Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment closed. Gas monitoring installed in transition compartment.
3	22 September 2020	*Fuel:* two side-by-side wood crib, 60 cm from wall. 200 mL of methanol for starter fuel. *Initial Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment closed. Gas monitoring installed in transition compartment. *Event:* Door closed at 270s from ignition (240s after activation of smoke detectors in compartment) to measure underventilated conditions in transition compartment.
4	25 Sept 2020	*Fuel:* single wood crib, 60 cm from wall. 200 mL of methanol for starter fuel. *Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment closed. Repeat of Test 1 with gas monitoring installed.

4.2.2 Characterization test results

Test 1 - single wood crib fuel load

In Test 1 using a single wood crib, the average wall gas temperature increased until reaching a peak temperature range between 250 - 370 °C at approximately 360 seconds after ignition, as shown in Figure 4.1. This peak temperature is maintained for approximately 300 seconds, and then begins to decay. The interface between the hot layer and the cool layer is between 1.5 m and 1.2 m from the fire compartment floor, as measured by the vertically spaced thermocouples.

The door to the fire compartment was closed at approximately 20 minutes after ignition; this did not impact the test results as only the first 15 minutes are relevant for understanding the impact on RCN fire fighting tactics and the fuel load was fully consumed by this point.

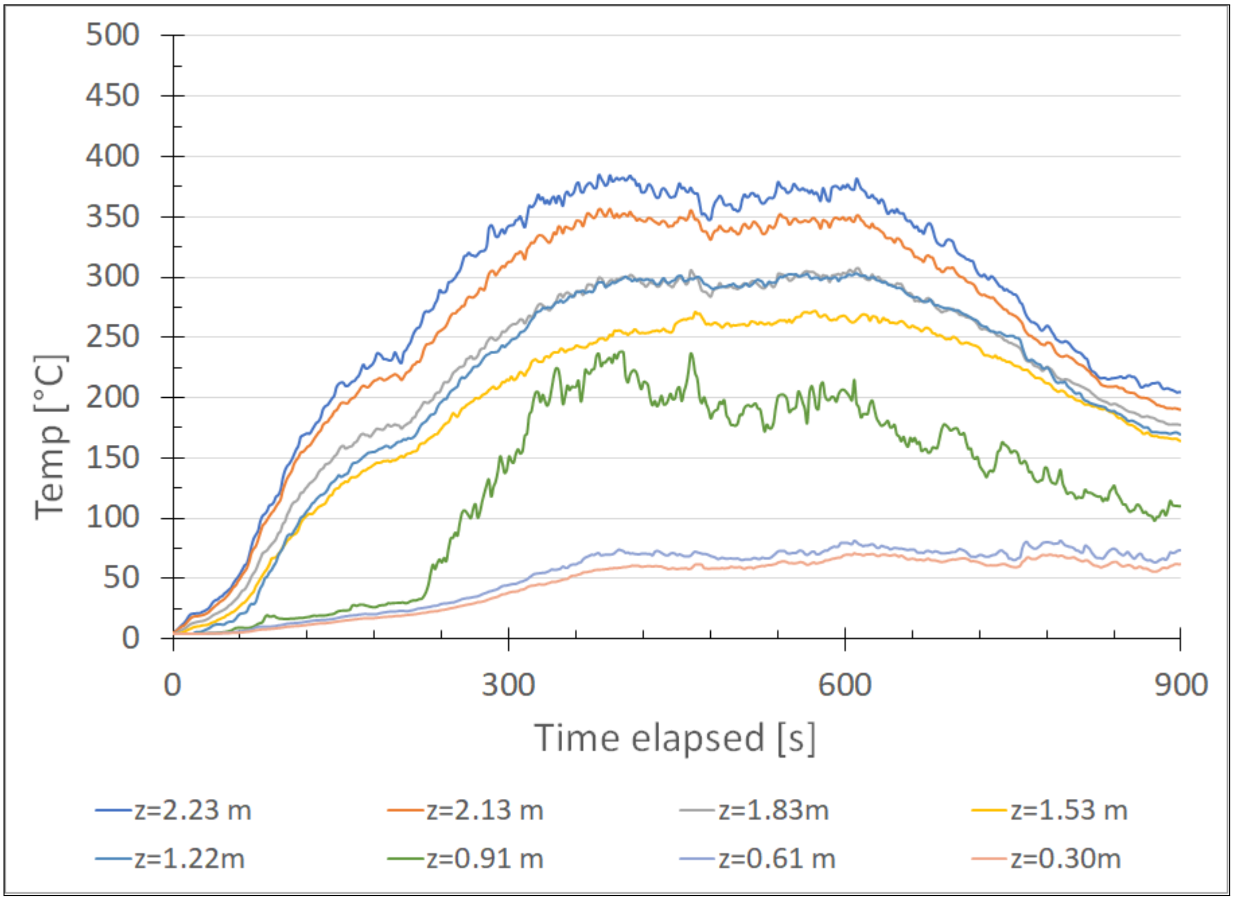


Figure 4.1: Test 1 fire compartment average wall gas temperature

Test 2 - Two stacked wood crib fuel load

In Test 2 using two stacked wood cribs, the average wall gas temperature increased until reaching a peak temperature range between 425 - 600 °C after approximately 600 seconds from ignition, as shown in Figure 4.2. This peak temperature is maintained for approximately 150 seconds, and then begins to decay. The interface between the hot layer and the cool layer is at approximately 1.5 m from the fire compartment floor, as measured by the vertically spaced thermocouples.

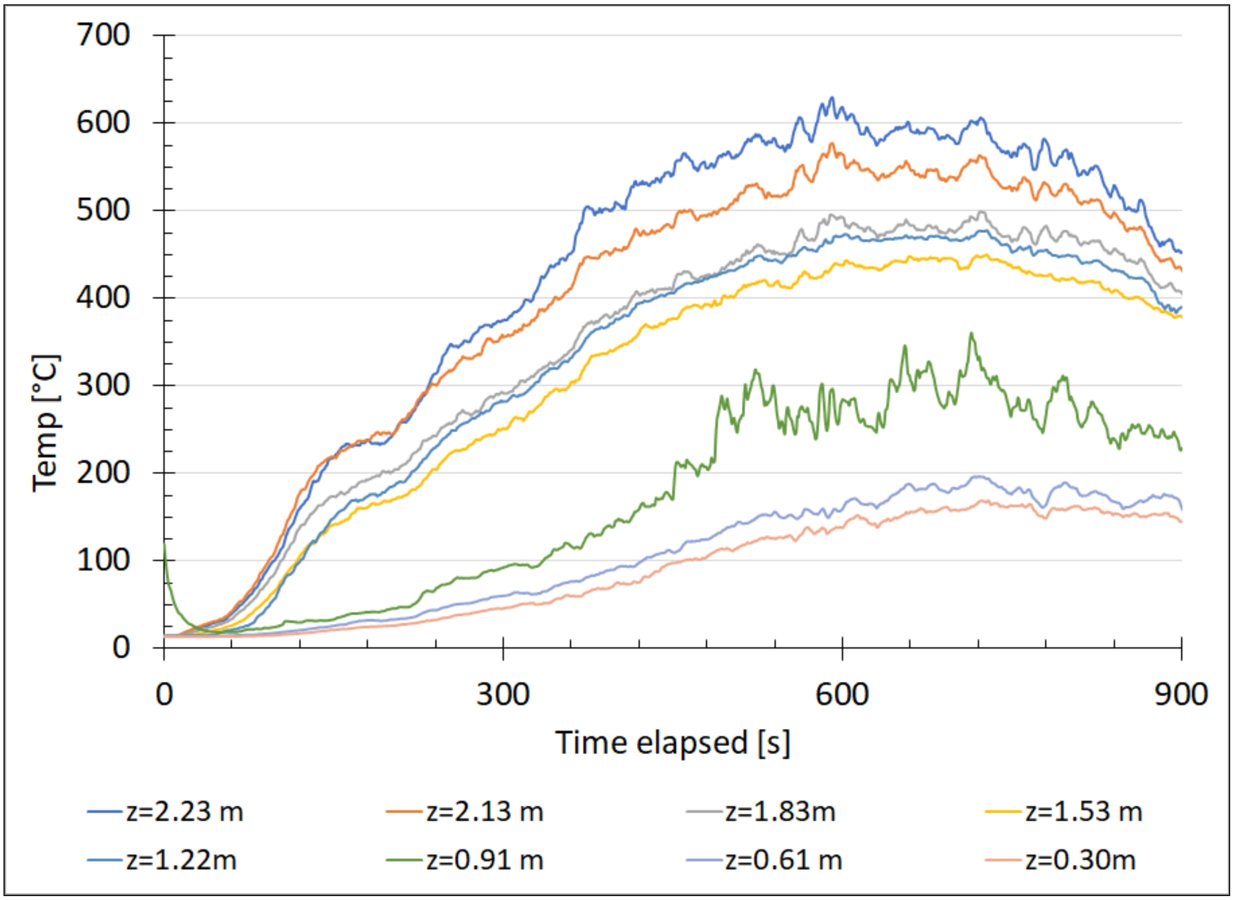


Figure 4.2: Test 2 fire compartment average wall gas temperature

During the steady burning portion of this test, the constant flame height was nearly at the height of the compartment, with some intermittent direct impingement along the ceiling as shown in Figure 4.3. Although the ceiling is adequately protected by the ceramic fibre insulation and cement board backing panels, this direct flame exposure would reduce the lifespan of the panels, with no benefit to the test results. Therefore, in order to protect the test apparatus, a side-by-side two wood crib fuel load was used for subsequent testing.

Figure 4.3: Photo of flame impingement on the ceiling with the two stacked crib configuration during Test 2

During Test 2, the video camera in the fire compartment (CAM1) failed due to exposure to the high fire compartment temperatures at approximately 11 minutes after ignition, as shown in Figure 4.4.

Figure 4.4: Photo showing damage to CAM1 from fire compartment conditions during Test 2

Therefore, cement board was used to fabricate a box for the camera to provide additional protection for tests 3 and 4 since it was important to maintain a consistent camera angle that included the checkerboard since it was also being used to estimate the fire compartment visibility via the method developed by [9]. The additional protection, shown in Figure 4.5 is successful in protecting the camera for tests 3 and 4, which have lower compartment temperatures. Tests 5 and onward do not include a requirement to track the smoke development in the fire compartment as part of the experiments, so CAM1 is re-located to a position outside the test apparatus. This still provides a view of the fire development but significantly reduces the thermal exposure to the camera and prevents unnecessary equipment damage.

Figure 4.5: Photo showing additional camera protection used for tests 3 and 4

Test 3 - Two side-by-side wood crib fuel load with restricted ventilation

For test number 3, two smoke detectors are installed and used as a triggering event to close the door to the fire compartment. Since this test represented a compound, but more realistic, fire scenario, an overview of the experimental results and the thermal exposure conditions at the test wall is described first and followed by additional details of the triggering event and compartment visibility.

One smoke detector is placed in the fire compartment and the other is in the transition compartment. The door to the fire compartment is closed four minutes after the trigger event (i.e. activation of either smoke alarm). The four minutes is intended to represent the estimated time it would take after activation for the space to be evacuated and confined after the initial response by the RRT. As can be seen in the temperature plot of 4.6, the fire self extinguishes and smolders until the compartment is reopened under control, at which point the fire re-flashes, and continues to burn until all fuel is consumed.

The temperature plot for Test 3 is shown in Figure 4.6; this Figure uses a 3000 s elapsed time instead of the standard 900 s range due to the unique nature of the test. The gas temperature at the wall reaches a temperature range between 350 - 475 °C until the fire self extinguishes at 320 s. The interface between the hot and cold layers was located at approximately 0.91 m from the floor during the growth phase. The dropping smoke layer can be seen in the sudden sharp increase between temperatures measured at 0.61 and 0.30 m from the floor respectively. The fire re-flashing is shown in the sudden temperature increase at 2100 s, and the interface between hot and cold layer can be seen to be reestablished between the thermocouples located at 0.91 and 0.61 m from the floor, as indicated by the 100 - 150 °C difference between the temperatures at those two locations.

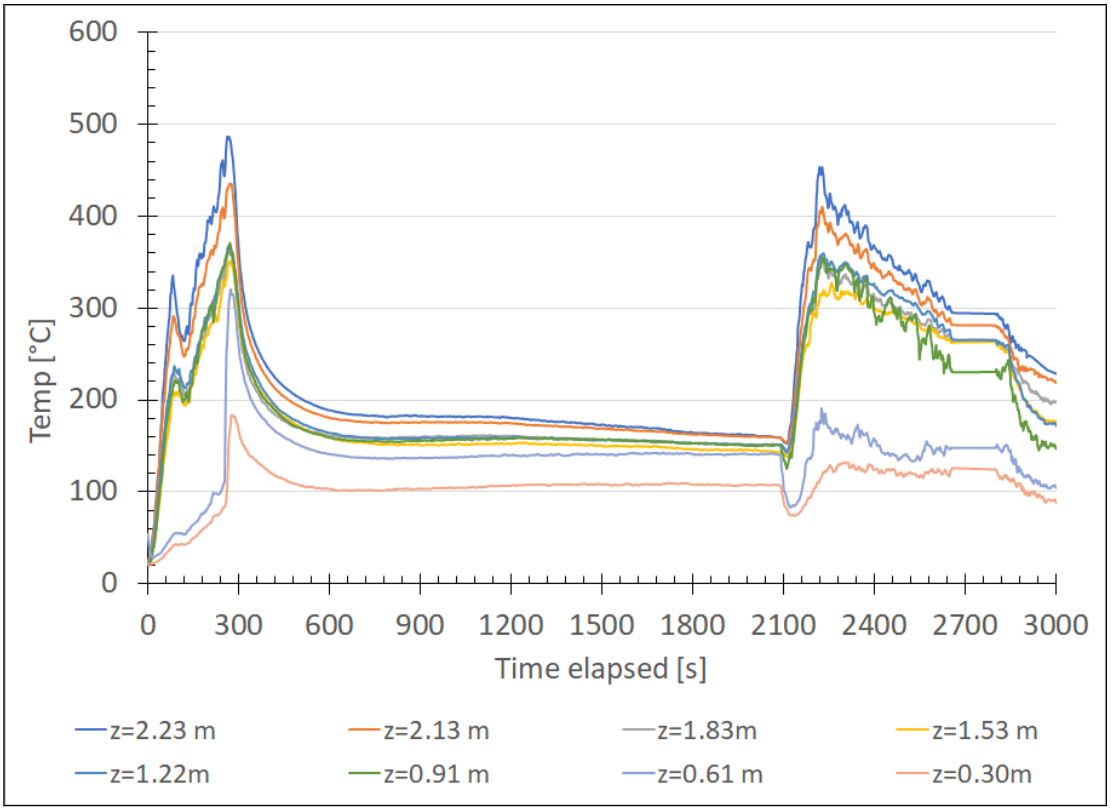


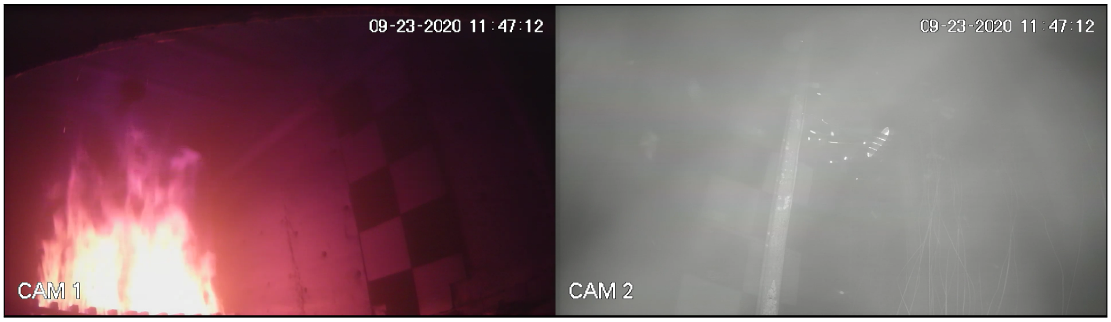
Figure 4.6: Test 3 fire compartment average wall gas temperature

The smoke detector in the main compartment is co-located with a checkerboard used to monitor the visibility in the compartment at a distance of 600 mm from the wall. The smoke detector in the transition compartment is mounted on a bracket connected to the specimen mounting frame, and is located approximately 600 mm from the checkerboard panel, and equidistant between the back of the specimen mounting frame and the rear wall of the transition compartment. Figure 4.7 shows screen captures from the video footage for Test 3, which shows the smoke alarm on 'CAM2'. Due to the camera location for CAM1, the smoke alarm in the fire compartment is not visible within the field of view, but the indicator light is visible in the image on the CAM2 feed and could be used to verify the timing of detector activation on completion of the test.

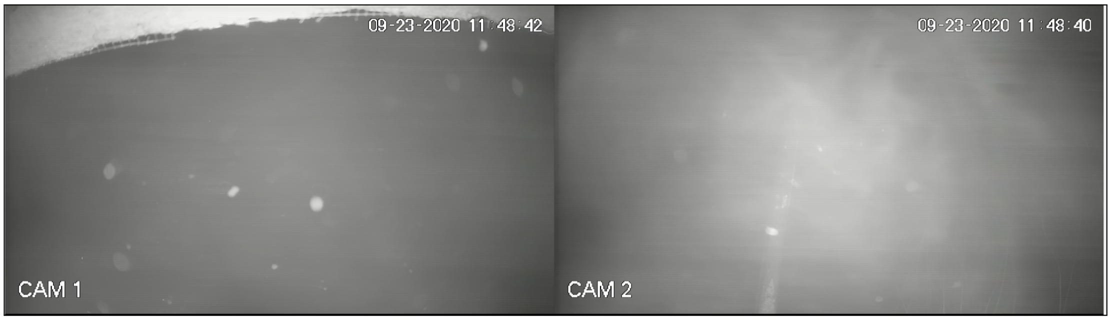
Figure 4.7: Video capture of Test 3, with smoke detector shown mounted in the transition compartment

In Test 3, the smoke alarm in the fire compartment activates approximately 10 seconds after ignition, with the smoke alarm in the transition compartment activates approximately 15 seconds after ignition. Therefore the door to the fire compartment is closed at 250 seconds following ignition. Prior to the fire compartment door being closed, smoke is observed venting out the top half (approximately) of the door opening. The compartment temperatures very quickly decrease as the fire dies down, and the smoke layer is observed to very quickly drop towards the floor, resulting in almost zero visibility in both the fire compartment and the transition compartment. In the video stills included in Figure 4.8 the fire growth and decay as the fire becomes under ventilated can be observed, along with the rapid loss of visibility in both the fire compartment and the transition compartment.

(a) Test 3 video output at t= 3 mins



(b) Test 3 video output at t= 4.5 mins (20 s after door closed)



(c) Test 3 video output at t= 8 min

Figure 4.8: Test 3 video capture showing fire underventilating and visibility loss following door closing

The fire then continues to smolder, and because the fire compartment is well insulated, the temperature remains steady with smoke being seen to escape both around the fire compartment door, and around the closed door between the transition compartment and the instrumentation compartment.

As the fire does not fully self extinguish and a significant amount of smoke continues to be generated from the smoldering fuel, it is decided to re-open the fire compartment door to protect the instrumentation from damage from the smoke. Therefore the door is re-opened (under control, by trained personnel in bunker gear) approximately 2100 seconds after ignition. The fire quickly re-flashes and burns until all the fuel is consumed. Compared to Test 2 in which the wood cribs are stacked one on top of the other, the side by side wood crib configuration in Test 3 is observed to have a wide cross section of the flame, resulting in a more even thermal exposure of the wall test specimen. The flame average flame height before the door is closed is estimated at approximately 1.2m, with intermittent flame height estimated at 1.5 - 1.8m. As well as the more uniform wall exposure, this results in the pipe still seeing intermittent direct flame impingement without risking excessive wear to the ceiling insulating panels.

Figure 4.9: Photo showing representative flame height of the two SBS crib configuration

Test 4 - single wood crib fuel load

In Test 4 using a single wood crib (to repeat the Test 1 configuration with the gas analyzer in place), the average wall gas temperature increased until reaching a peak temperature range between 250 - 370 °C after approximately 360 seconds from ignition, as shown in Figure 4.1. This peak temperature is maintained for approximately 300 seconds, and then began to decay. The interface between the hot layer and the cool layer is between 1.21 m and 0.9 m from the fire compartment floor, as measured by the vertically spaced thermocouples. Some variability in the interface height was seen during this test, and was due to shifting wind directions during the tests affecting air movement in the fire compartment.

The door to the fire compartment was closed at approximately 20 minutes after ignition; this did not impact the test results as only the first 15 minutes are relevant for understanding the impact on RCN fire fighting tactics and the fuel load was fully consumed by this point.

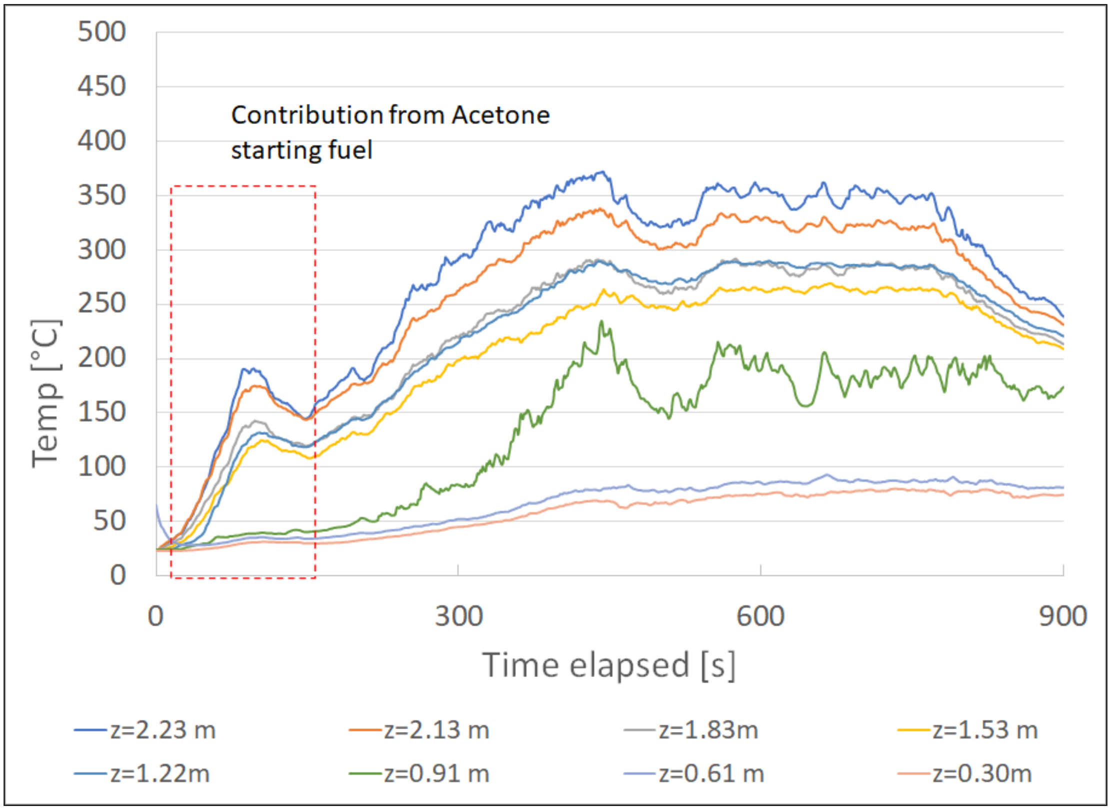


Figure 4.10: Test 4 fire compartment average wall gas temperature

4.2.3 Design fire selection

Compartment temperatures obtained during the single crib and two stacked crib fires are shown in Figure 4.11. To simplify the data, the average wall gas temperature readings taken from the thermocouples at 2.13m from the floor is shown for the hot layer, with the temperature readings from the thermocouples at 0.61m from the floor used to represent the cold layer.

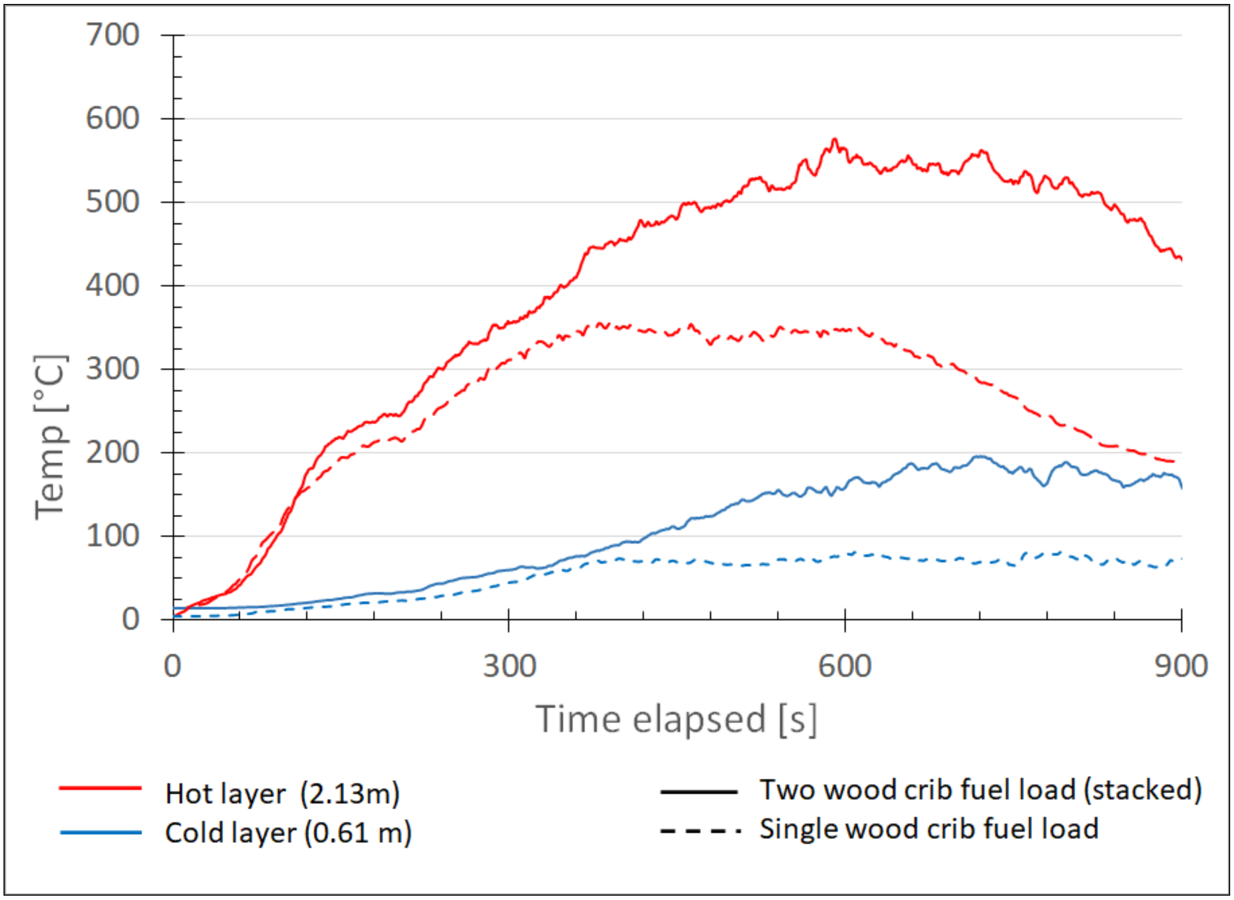


Figure 4.11: Temperature plot comparison between single wood crib fire (Test 1) and two stacked wood crib fire (Test 2)

Both fuel loads show a similar initial growth rate, but rapidly diverge starting at approximately 90 s. The single wood crib fuel load hits a peak gas temperature of approx 350°C at 360s, maintains that gas temperature until 600 s, and begins to decay. The two wood crib fuel load peaks at approx 550 °C at 600s, maintains this temperature until approximately 720 s, then begins to decay. At the end of the 15 minute time interval, the single wood crib gas temperature is only 200 °C, compared to approximately 450 °C for the two crib fire.

Based on the increased maximum temperature across the steady burning portion of the fire, a two wood crib fire was selected for the design fire. Because of the concerns about direct flame impingement damaging the wall test unit apparatus, the side-by-side configuration was selected over the two stacked wood crib configuration. This has the added benefit of having a wider flame cross section and is expected to give a more even thermal exposure across the face of the wall test specimen.

In the characterization testing, the two wood crib fuel load undergoes sufficiently rapid growth to expose the test specimen to temperatures that exceed 200 °C during the response interval characteristic for the RRT, and in the 400-500 degree range during the AT response time interval. The peak temperature is maintained for several minutes before beginning to decay, with hot layer gas temperatures still in excess of 400 °C at the end of the 900 s time period that is of interest to the RCN for understanding the potential impact of fire insulation on fire fighting tactics and decision making processes. Because the IMO A-15 fire insulation is typically meant to contain spaces with moderate fire risks, these gas temperatures are reasonable representations of a fire scenario for a compartment that requires this level of fire insulation under the regulations.

Because the test wall configuration used for this portion of the experiments includes an open penetration, additional characterization testing using the two side-by-side wood crib configuration is conducted to provide data to compare against the insulated wall testing since that wall did not incorporate any opening. Results of these additional tests are presented as results for tests 5 and 6, with the test specimen being reconfigured to seal the opening, and the gas monitoring instrumentation removed to avoid interfering with the field of view required to capture the IR images of the unexposed side of the wall with the TIC.

Applicability of chosen design fire to future insulated steel wall testing

The present results outline the choice of a design fire for the present investigation into thermal response of a wall insulated to an IMO certified rating of approximately A-15. In future work involving compartment fire testing of walls constructed to higher ratings of IMO certified fire insulation, such as A-30 or A-60, a longer fire duration or higher gas temperatures may be desired as being more realistic of the fire threat in those compartments. It was demonstrated by DiDomizio [8] that the duration of the peak compartment fire temperature could be increased by using a larger array of wood cribs arranged in a line, with a small air gap between the cribs to allow air circulation. By lighting one set of wood cribs, the fire will then slowly spread along the array and result in a longer sustained peak temperature.

To increase the peak gas temperature on the other hand, a different fuel source could be used. Using a similar compartment configuration, Sheehan [27] demonstrated that by using a diesel pan fire ceiling temperatures approaching 700 °C are achievable. Because a major fire risk on ships is a class B fire with marine diesel as a fuel source, this may be a better alternative for testing A-60 insulation under realistic fire conditions, as this is the required level of fire insulation for machinery spaces and other such high risk areas.

4.2.4 Smoke propagation and gas analysis test results

The raw results of the smoke propagation testing, including the output from the Novatech gas monitoring system for the experiments are included in Appendix B, though a detailed analysis is outside the scope of this thesis. For each test, the gas monitoring system output measurements of the total unburned hydrocarbon concentrations (in ppm), the NO, NO_2 and NO_x concentrations (in ppm) as well as the concentrations for CO (ppm and %), CO_2 % and O_2 %. As can be seen from Figure 4.12, in Test 2 the O2 levels decreased as the fire peaked, and recovered to normal atmospheric levels as the fuel was consumed, with the CO2 levels having an inverse growth and decrease that corresponded to the oxygen consumption. The CO production stayed low throughout, showing high combustion efficiency, with the peak coming at approximately 1200 seconds when nearly all the fuel was consumed and the fire was just smoldering. This is also confirmed by the low amount of unburned fuel measured by the total hydrocarbon measurements. These results gave a good overview of the combustion efficiency of the fire as well as the compartment tenability, and thus will be useful for ensuring the repeatability for experiments with these ventilation conditions and as data for comparison to results of models of smoke through penetrations on board naval vessels.

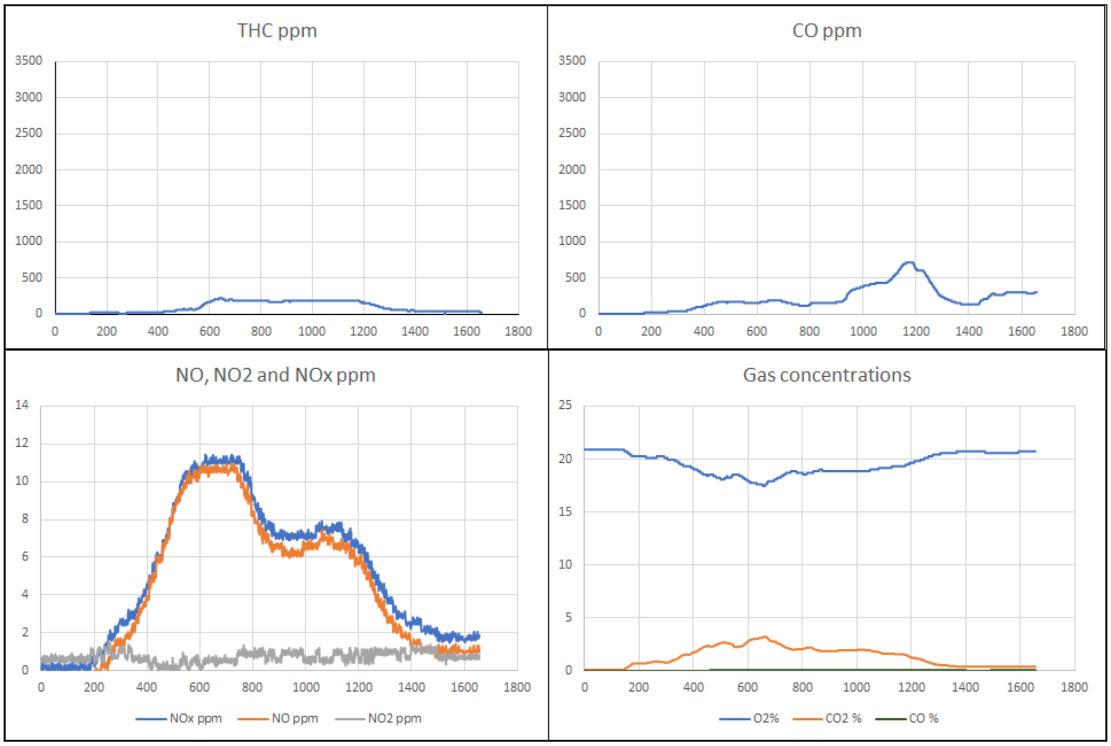


Figure 4.12: Test 2 fire gas analysis summary

For contrast, in Test 3, where the fire compartment door was closed at approximately 2 minutes to create an under ventilated condition to simulate the common navy tactics to evacuate and confine the compartment, and shows how that effects the compartment tenability, as well as saturates the atmosphere with unburned fuel, which can lead to extreme fire phenomena when the compartment is breached if the appropriate cooling tactics are not employed In this case, both the total unburned hydrocarbon and CO measurements exceeded the max span point for the sensors. On the video, the smoke layer in the compartment dropped to the floor with very limited visibility, although the fire did self extinguish at approximately 4 minutes after ignition. So while this negatively affected both tenability and visibility in the fire compartment, it successfully limited fire growth and compartment temperatures. This data will be useful for comparison against the model of fire development and smoke penetration on board naval vessels, and to help design future experiments to better represent naval compartment fires.

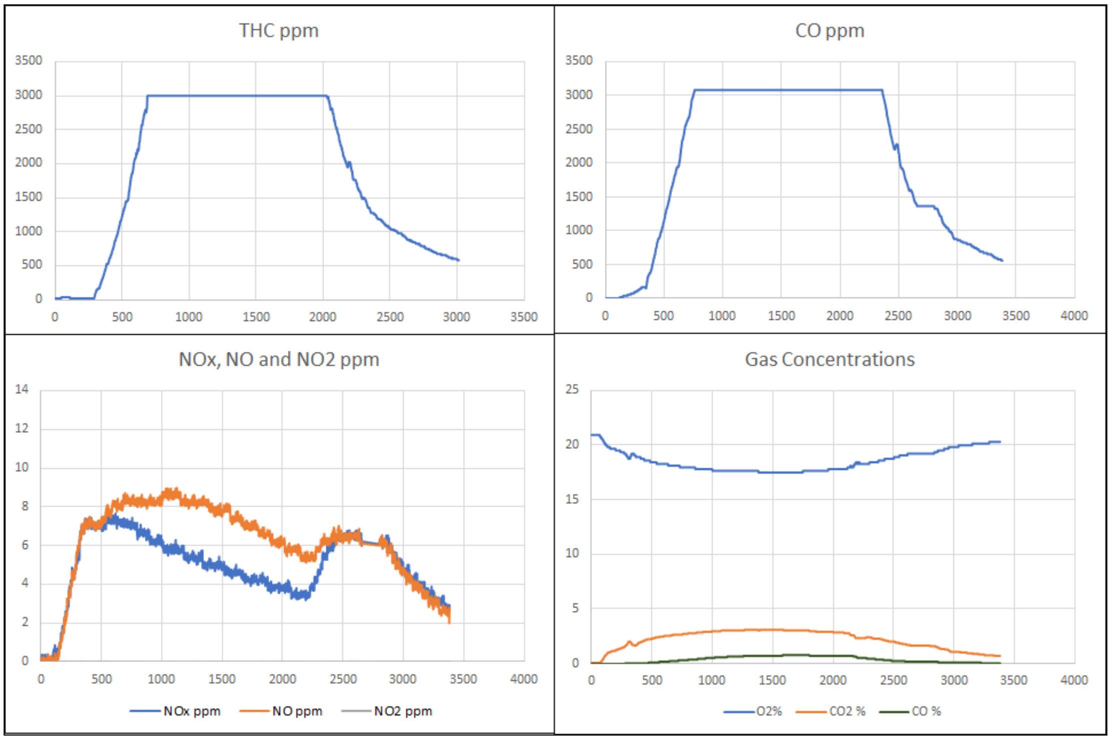


Figure 4.13: Test 3 fire gas analysis summary

It is recommended that for future testing of underventilated fires that a different span gas be used to increase the calibration range for the CO ppm and the THC ppm measurements.

A more complete analysis of the smoke propagation results is completed separately in a report prepared for Defence Research and Development Canada by Ahmed and Devaud, but is not publicly available at the time of this publication.

4.3 Navy bulkhead characterization tests

4.3.1 Overview

An summary of the fuel loads used and the wall insulation installed is provided in Table 4.3. Because of time and schedule restrictions caused by the COVID-19 pandemic, insufficient wood that had the 16 week conditioning routine was available at the time of testing to complete all the tests as well as other concurrent experiments for other work at the research facility. Both fully conditioned and partially conditioned fuel loads were characterized in tests 5 and 6 with the Navy test wall assembly installed in the wall mount unit.

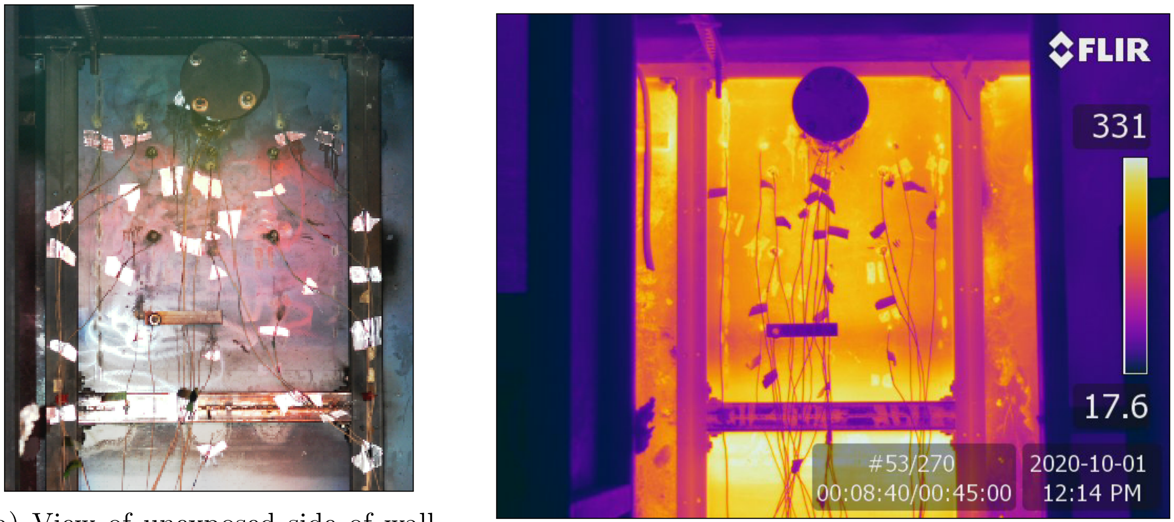
For each test presented below, the data will include the average fire compartment gas temperature at the wall, which is obtained by taking the average value of thermocouples at the same height from the front left and right thermocouple trees (Tree 1 and 2 respectively). The second graph presented is the unexposed wall temperature on the plate, which is derived from the evenly distributed centerline vertical thermocouples on each steel panel. Because only the upper portion is composed of 4.5mm plate with the ship features, only those relevant signals are used, with the specific signals described in Table 4.2.

For the insulated wall testing, a summary of all the key data, chosen based on the IMO standard, for temperatures on the plating, penetrations and piping are presented in the respective sections.

Table 4.2: Description of data signals used for the unexposed wall temperature graphs

DAQ	MODULE	CHANNEL	HEIGHT FROM COMPARTMENT FLOOR
2	2	0	2.08 m (1.79 m from bottom of wall frame).
2	2	1	1.83 m (1.55 m in from bottom of wall frame).
2	2	2	1.62 m (1.32 m from bottom of wall frame).
2	2	3	1.38 m (1.08 m from bottom of wall frame).

Infrared images of the unexposed side of the wall are taken through the rear door of the transition compartment as described in Section 3.3.5. Because there is not insulation on the steel wall for the initial tests, the lab camera is initially placed a safe distance away to prevent damage, and also to allow the full upper half of the wall to be captured in the picture. The IR images are taken in 7 second intervals, with the temperature range selected beforehand. A photograph of the unexposed side of the wall, taken from outside the container with the same approximate field of view as that for the IR camera, as well as a sample IR image is shown in Figure 4.14. The silver tape shown is high temperature duct tape rated for 220 °C. It is used to help secure the thermocouple wires in place and route them so that they do not obscure any key point of interest in the IR images. The tape is also highly visible in the IR images, so is later trimmed back and otherwise re-positioned to limit interference with the surface temperature readings on the IR image as well.



(a) View of unexposed side of wall as seen in the Infrared images

(b) Sample infrared image from Test 6 @ 13.5 min

Figure 4.14: Unexposed wall view and sample IR image

For test 5, a temperature range with a maximum of 160 °C is inadvertently chosen, so the IR images for that test are fully saturated after the unexposed side of the steel plate reached that temperature and thus are not usable past that time. For the remainder of the tests a higher temperature range is selected. This issue is a function of the camera software, which locks the camera into the selected temperature range for the time automated photographs, as it would otherwise automatically reset to a suitable range for each individual photo. This would not normally be an issue with TICs used by emergency services as they are required under the NFPA 1801 standard [24] to automatically adjust the temperature scale based on the temperatures detected in each image.

A summary of the fuel loads and wall configurations used in Tests 5 through 10 is contained in Table 4.3. As explained above, the same two side-by-side (SBS) wood crib configuration is used for all of the Navy bulkhead tests. For these initial tests, the cribs are positioned 609 mm (24 inches) from the steel wall. This spacing is not changed when the mineral wool insulation is installed on the wall, so for the tests using insulated steel walls (Tests 7-10), the distance to the face of the insulation from the wall is approximately 22 in (559 mm).

Partially conditioned wood was used in the wood crib fuel loads for tests 5 as well as Tests 7 and 8 with the industrial mineral wool insulation installed. Test 5 is used with Test 6 (fully conditioned wood) to compare the impacts of wood conditioning on the overall compartment fire test environment. Tests 7 and 8, the other two tests fueled by partially conditioned wood, are run mainly as final verification checks that all sensors and data capture systems are working and that the user of the TIC has adjusted all the settings to gather good infrared images on the unexposed side of an insulated wall. Fully conditioned wood is then used in the wood crib fuel loads for tests 9 and 10, in which the steel bulkhead is fitted with the Rockwool SeaRox SL 620 insulation, which conforms to the IMO certified A-15 insulation installation.

Table 4.3: Summary of fuel load configuration for the Navy bulkhead test specimen

Test	Fuel Load	Weight of fuel load	Insulation
5	*Fuel:* two SBS wood cribs, 60 cm from wall. 200 mL of methanol for starter fuel *Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment open.	29.898 kg (partially conditioned, 6-8% moisture content)	no insulation
6	*Fuel:* two SBS wood cribs, 60 cm from wall. 200 mL of methanol for starter fuel *Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment open.	22.937 kg (fully conditioned, 0 % moisture content)	no insulation
7	*Fuel:* two SBS wood cribs, 60 cm from wall. 200 mL of methanol for starter fuel *Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment open.	29.977 kg (partially conditioned, 6-8% moisture content)	50mm of JM Minwool 1200
8	*Fuel:* two SBS wood cribs, 60 cm from wall. 200 mL of methanol for starter fuel *Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment open.	29.694 kg (partially conditioned, 6-8 % moisture content)	50mm of JM Minwool 1200
9	*Fuel:* two SBS wood cribs, 60 cm from wall. 200 mL of methanol for starter fuel *Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment open.	22.569 kg (fully conditioned, 0 % moisture content)	50mm of Rockwool SeaRox SL 620 (A-15)
10	*Fuel:* two SBS wood cribs, 60 cm from wall. 200 mL of methanol for starter fuel *Ventilation:* Door to fire compartment open. Door between instrument compartment and transition compartment open.	22.993 kg (fully conditioned, 0 % moisture content)	50mm of Rockwool SeaRox SL 620 (A-15)

4.4 Characterization tests for the Navy bulkhead assembly

Tests 5 and 6 were run to verify and compare the fire parameters for the two side-by-side wood crib fuel configuration, and to determine differences between the partially and fully conditioned wood on the fire growth and peak gas temperatures at the test wall.

4.4.1 Test 5 results

Test 5 is fueled by two partially conditioned wood cribs (m= 29.898 kg) in the two crib side-by side configuration. Average gas temperatures at the test wall and unexposed plate temperatures are plotted in Figure 4.15. The peak values of average gas temperatures at the wall are reached at approximately 15 minutes after ignition, with the hot layer temperature varying between 400 - 500 °C.

On the unexposed side of the wall, the peak temperature measurement on the center line of the plate is reached at approximately 20 minutes after ignition, and varies between 300 - 330 °C. The two upper thermocouples (z= 2.08 m and z= 1.85 m in Figure 4.16) are located above and below the pipe penetration. The pipe itself has a significant thermal mass, and is welded on both sides of the plate, with the weld bead adding to the local metal thickness in the area. Since the temperatures measured by these upper thermocouples are actually lower thn those of the lower two thermocouples, it appears that the pipe acts as a local heat sink, but then also slows cooling of these areas as the fire dies down and compartment temperatures fall.

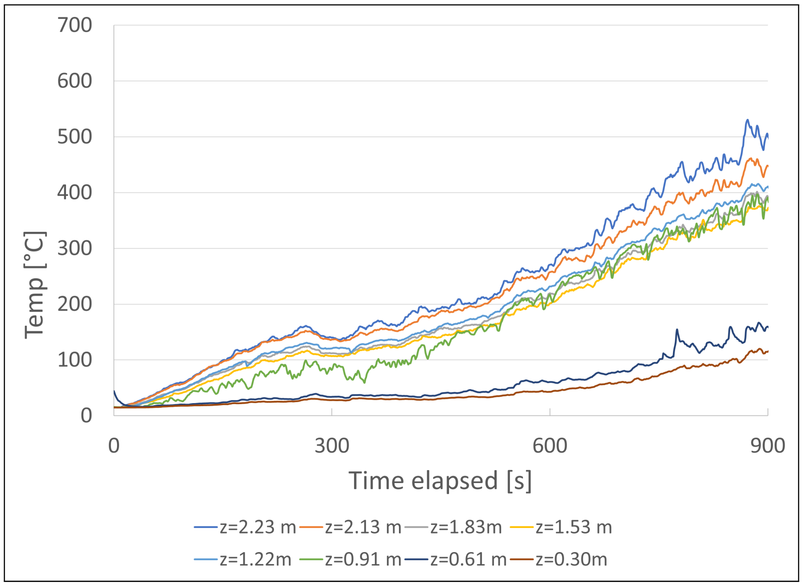


Figure 4.15: Test 5: Fire compartment average gas temperature at the wall test specimen

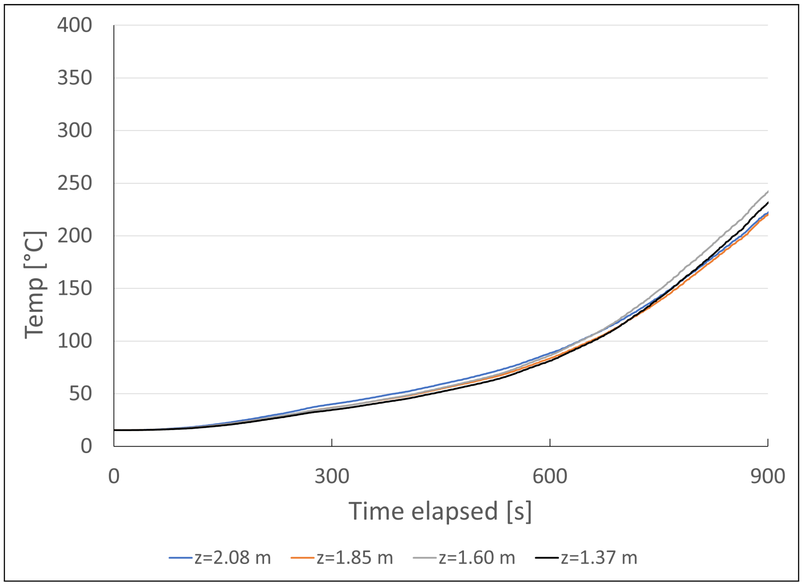


Figure 4.16: Test 5: Unexposed side centerline plate temperature

At the peak of the fire growth, it is observed, and shown in the image in Figure 4.17, that the intermittent flame height is high enough to directly impinge on the exposed section of piping, but not the ceiling. This is desirable for the insulation tests in terms of assessing the effectiveness of the pipe insulation from preventing heat transfer along the piping, and also in terms of protecting the ceramic insulation and cement board protective panels mounted on the ceiling of wall test unit from excessive wear.

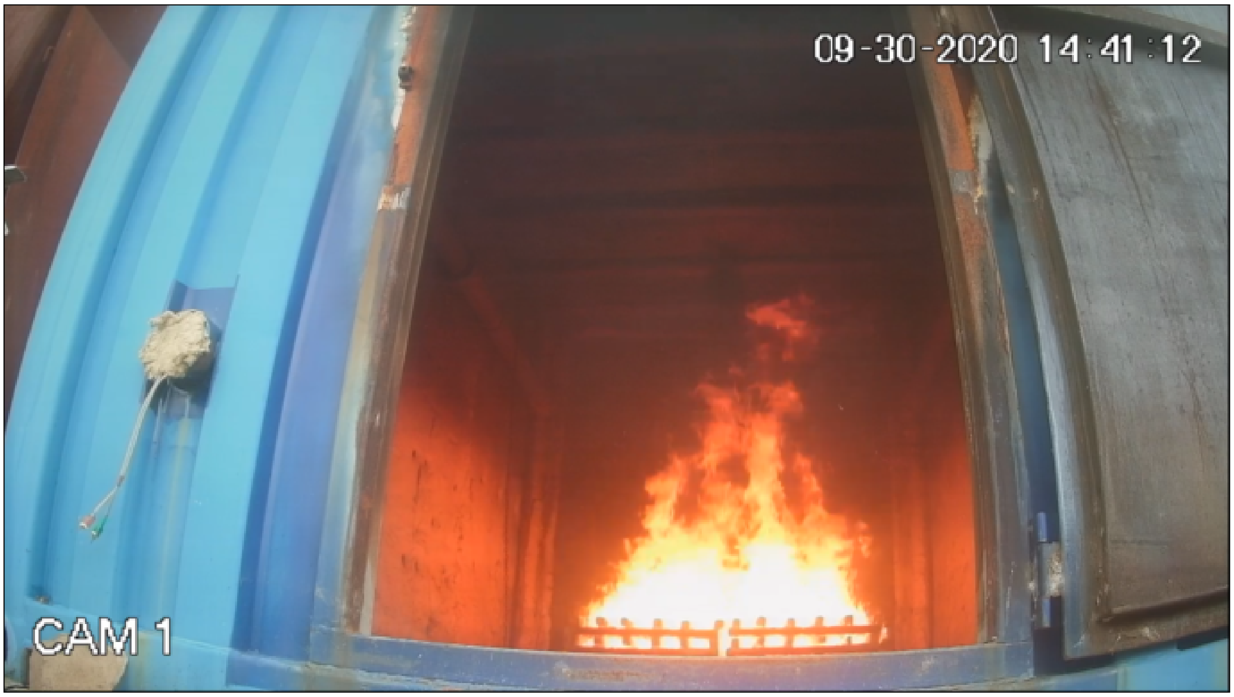
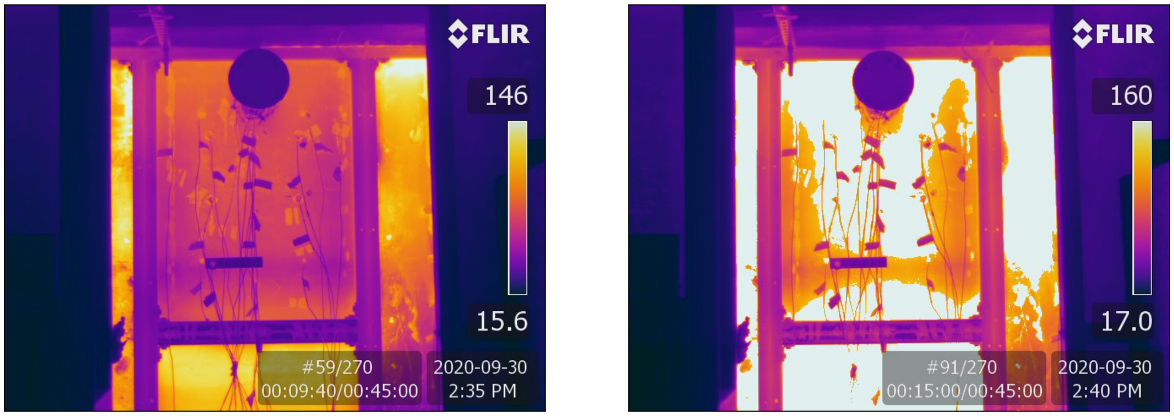


Figure 4.17: Test 5: Video still at t=15 min looking into the fire compartment

Figures 4.18a and 4.18b illustrate the impact of the upper limit on the IR camera being locked at 160 °C for this test. In Figure 4.18a, taken at 10 minutes after ignition, the images are beginning to saturate on the thinner sheet in the side and bottom panel. By 15 minutes after ignition, as shown in Figure 4.18b, the IR images are mostly saturated, and thus unusable, on the navy bulkhead portion of the test wall.



(a) Test 5: IR image at 10 minutes; upper portion of side panels has begun to reach the upper limit of the selected temperature range

(b) Test 5: IR image at 15 minutes with most of the surface fully saturated and exceeding the selected temperature on the IR camera

Figure 4.18: Test 5 sample IR images

This test does identify, however, that the thermocouple wiring is clearly visible in the IR images with the labels showing as cold spots through most of the image. To correct this prior to the insulated wall tests, the labels are removed from the thermocouples and the wiring re-routed where possible without damaging the sensor to prevent interference with later image analysis to extract wall temperature data.

4.4.2 Test 6 results

Test 6 is done using fully conditioned wood (m= 22.937 kg) in the two crib side-by side configuration as fuel. The peak gas temperatures at the wall are reached at approximately 8 minutes after ignition, with the hot layer temperatures varying between 400 - 550 °C, as shown in Figure 4.19. On the unexposed side, the peak temperatures on the center line plate measurements are reached at approximately 15 minutes after ignition, and vary between 320 - 350 °C, and is shown in Figure 4.20.

Compared to the compartment temperatures shown in Figure 4.15 for the partially conditioned fuel load in Test 5, those in Figure 4.19 for Test 6 demonstrate the faster fire growth rate resulting in higher gas temperatures measured at every height for a fully conditioned fuel load.

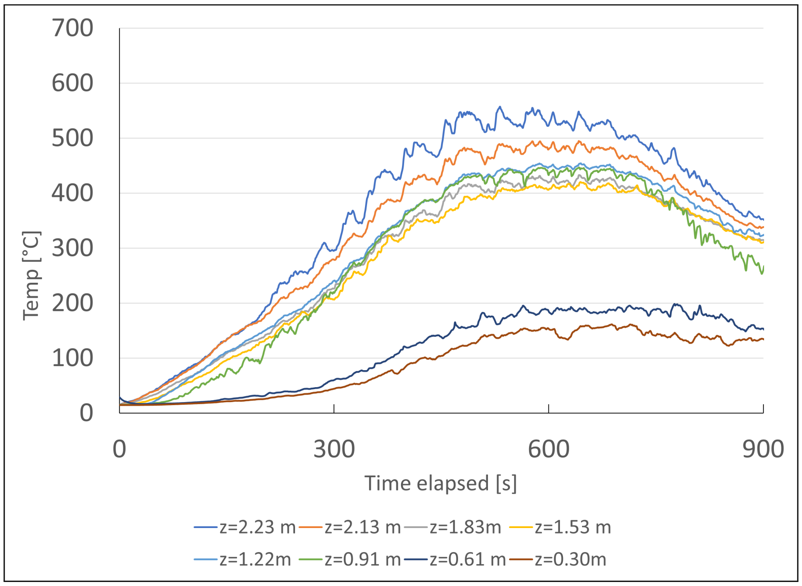


Figure 4.19: Test 6: Fire compartment average gas temperature at the wall test specimen

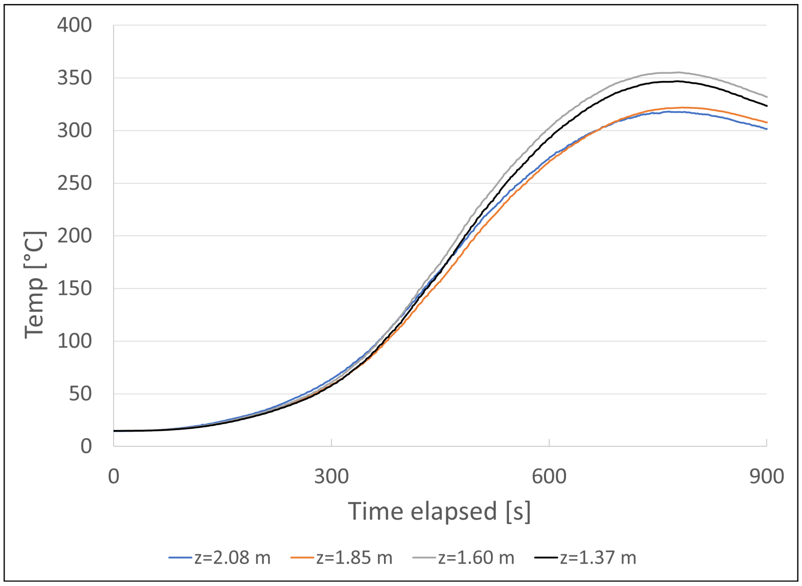
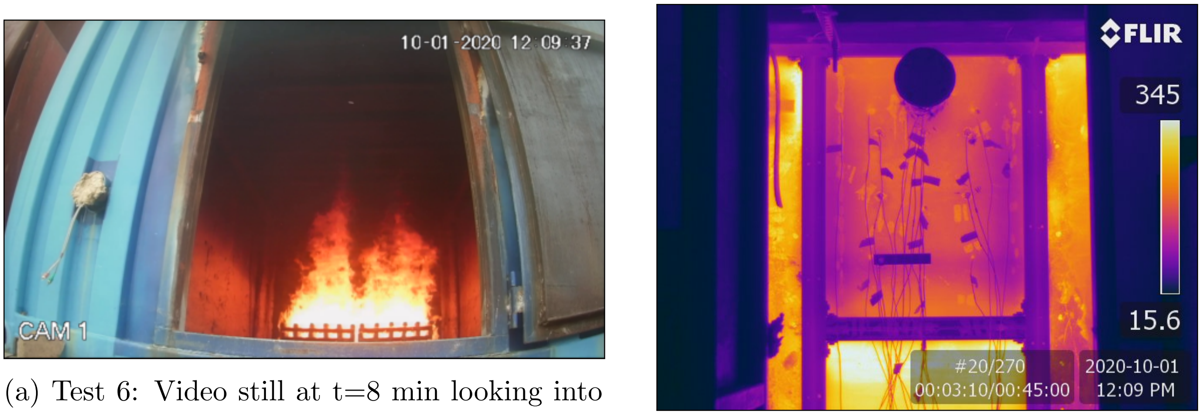


Figure 4.20: Test 6: Unexposed side centerline plate temperature

A still image from the video and the IR image from the peak of the fire at 8 minutes from ignition is shown in 4.21. The thinner sheet metal in the side and bottom panels is hotter than the thicker plate used on the navy bulkhead assembly. Some cooler areas are also evident in the vicinity of the stiffener and below the pipe penetration. The weld point near the L shaped vertical stiffener is warmer than the surrounding plate due to conduction from the face, with a local cooler zone in the shadow of the stiffener face. This is because the stiffener would act to both disrupt the local air flow and lower the convective heat transfer efficiency, as well as prevent the radiation from reaching the plate directly.

Similarly to Test 5, Figure 4.20 illustrates that the temperature readings on the unexposed side of the test wall immediately above and below the pipe penetration are lower than on the plate below, with the IR image also showing a cooler portion of the wall below the pipe.



(a) Test 6: Video still at t=8 min looking into the fire compartment

(b) Test 6: IR image at t= 8min

Figure 4.21: Test 6: Video still of fire compartment and IR image at t=15 min

At 15 minutes after ignition of the wood cribs, nearly all of the fuel load is consumed (Figure 4.22), which is also the case for tests 9 and 10 which also used the fully conditioned wood. The compartment temperature remains between 200-300 °C due to the amount of retained heat and decreases only slowly even though the fire is significantly smaller in size. Interestingly, the unexposed side temperatures of the non-insulated panel only peaks at 15 minutes after ignition, before beginning to cool. This indicates the system lag as a result of thermal inertia of the test wall itself, as well as because the fire compartment is significantly insulated so the only boundary heat transfer is through the test wall and via the open door to the fire compartment. Normal fire fighting efforts would include cooling of hot surfaces in the vicinity, which would eliminate this effect, but may not be effective with insulation installed. This research did not include this aspect of the firefighting tactics but is recommended to be part of future work to understand how the insulation impacts existing overhaul and boundary cooling procedures.

Figure 4.22: Test 6: Video still at t=15 min looking into the fire compartment

4.4.3 The impact of wood sample conditioning

To ensure consistent results, the standard protocol for testing with the wall fire test unit is that, once the fuel wood is cut to length, it is conditioned for at least 8 weeks in a room where the temperature is maintained between 20 and 22 °C and humidity is limited to 35 %. Then, just prior to the experiment, the wood required for that test is taken out and weighed before assembling the crib(s) for the test. This procedure resulted in standard wood crib weights of approximately 15 kg each. [25]

Under the initial timeline, there is sufficient conditioned wood available, with lead time to other experiments to allow replacement wood to be cut and conditioned. Due to COVID-19 restrictions shutting the research lab for approximately six months, requiring these experiments to be run concurrently with others this is no longer feasible, so early tests are used for sensitivity testing on the effect of wood fuel conditioning time and moisture content on fire compartment temperatures.

Even regular construction lumber is kiln dried, and generally protected from the elements to prevent warping or other deformation before sale. Upon receipt at the lab, multiple measurements were taken of numerous pieces of the as-bought lumber. Typical moisture content of the wood is measured between 10-12 %, with minor variations along a standard 8 foot length, as well as among different pieces within a bundle.

Following two weeks of conditioning as described above, moisture content is measured within the 6-8 % range, with the quantities required for a wood crib weighing between 15-15.5 kg. For comparison, the preconditioned wood that had an additional 72 weeks of conditioning measured 0 % moisture and weighed approximately 12.5 kg per wood crib.

Results of the characterization tests for both partially conditioned and fully conditioned fuel loads (test burn 5 and 6 respectively) are shown in Figure 4.23. The impact of the wood moisture content is illustrated in these plots. In both tests, the peak ceiling temperature is in the 520 - 540 °C range. However the fully conditioned wood cribs reached that peak temperature at approximately 10 minutes after ignition, where the fire fueled by the partially conditioned wood cribs hit the peak temperature between 15-16 minutes. This is consistent with the additional moisture in partially conditioned wood slowing down fire growth as the water would absorb some of the energy released as it evaporates during the growth. In either case, the wood is dry enough to not interfere with combustion once the wood crib is fully involved so temperature do reach comparable peak values.

Due to overall time constraints and the observed differences in fire growth rates and compartment temperature evolution with time between the partially and fully conditioned wood cribs, it was necessary to decide on which wood would be used as fuel for which of the remaining tests for this research. There was sufficient fully conditioned wood to complete only two full tests using two side by side wood cribs as fuel. At the same time, two different types of mineral wool had been sourced in sufficient quantities to do a set of repeat (two) tests with each for four remaining experiments in total.

Since the industrial grade insulation will not be a candidate for use in insulating bulkheads on board naval vessels, it was decided to conduct those two tests fueled by partially conditioned wood cribs to verify data capture (thermocouples, video and TIC cameras) before final tests to be conducted with the test specimen insulated using the SeaROX marine insulation. In addition, the industrial insulation is locally procured and readily available so is an excellent candidate material for troubleshooting experimental design. In contrast, the marine grade, A-15 certified insulation is a special order material with an extremely long lead time, so it is important that the setup is well documented with any shortcomings addressed before the limited quantities of marine insulation are used in the final tests.

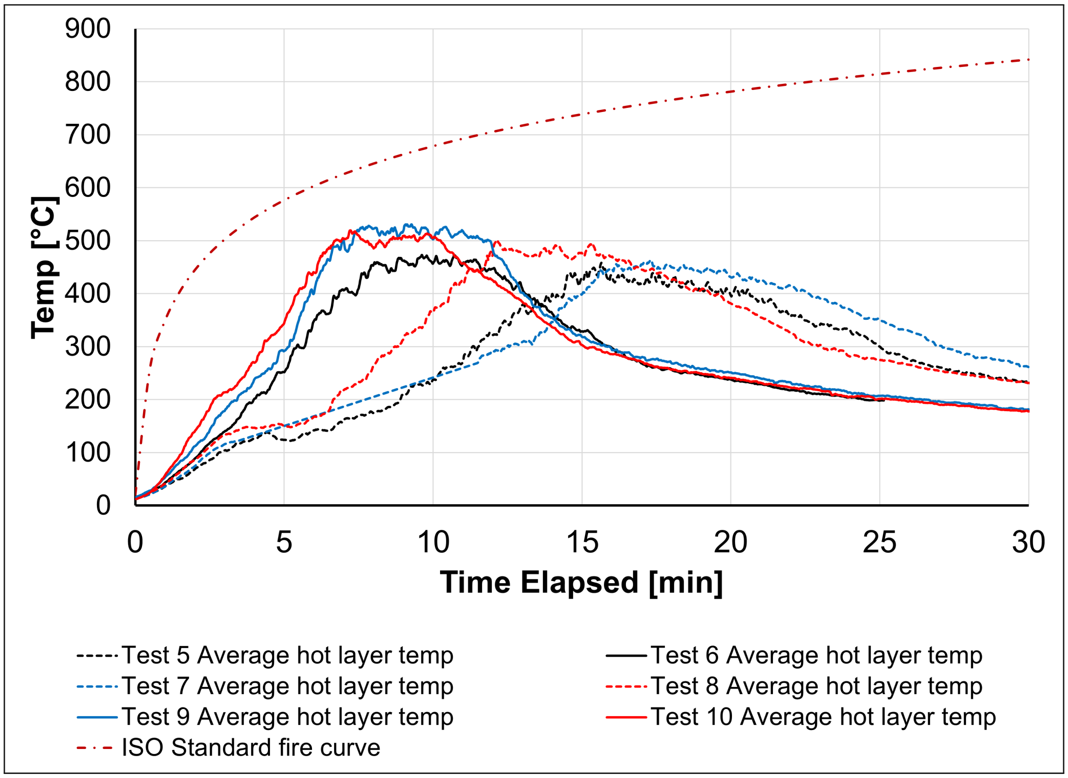


Figure 4.23: Affect on compartment temperature of wood crib conditioning

In Figure 4.23, which shows the average hot gas layer temperature at the wall for both the partially and fully conditioned cases, the compartment temperatures are higher when comparing the insulated test wall against the uninsulated case. This is due to the addition of the insulation changing the boundary condition at the test specimen so the fire compartment retains more heat. The ISO 834.1 fire curve is shown for comparison, but demonstrates how the test criteria is significantly more severe of a scenario than a more realistic fire.

In addition to adapting to the practical limitations available, this approach gave some insight into how the wood conditioning process and wood moisture levels impacts the design fire considerations, so provides a possible alternate approach for future testing if time is not available to fully condition the wood over 8 weeks but still provide repeatable results.

4.5 Insulated test wall results

4.5.1 Industrial mineral wool insulation results

Two tests, Tests 7 and 8, are conducted using industrial mineral wool as outlined above. Results are used to verify the installation method for the insulation, particularly around the piping, stiffeners and other penetrations, and to ensure that deficiencies identified in the previous tests are adequately addressed for the final tests with marine insulation. Before these tests, therefore, the thermocouple wiring is rerouted and the labels on the unexposed side that are visible in the IR images in Figure 4.21b are removed to minimize their impact on the thermal analysis of heat transfer through the insulated wall.

While the Minwool product is not certified for marine use, the thermal properties, in particular the thermal conductivity, of the JM Minwool 1200 insulation are similar to those of the Rockwool SeaRox SL 620. Therefore, the same thickness of Minwool insulation is installed on the steel test wall as for the SeaRox tests so that this experiment set also gives another data set by which to judge surface temperatures on the unexposed side of the insulated wall, but for a fire with a slower growth rate as defined by use of only partially conditioned wood as fuel.

At the same time, a key difference between the two insulation types is that the JM Minwool insulation is more of a batting product, where the Rockwool product is a stiff board. Batting is more difficult to cut precisely, but easier to maneuver into place around the piping and underneath the stiffener. The final installation is shown in Figure 4.24. The insulation for the upper portion of the center panel that included the pipe penetration is cut down the middle, which allows easy installation around the pipe and other penetrations while also allowing the insulation to be pushed flush against the stiffener.

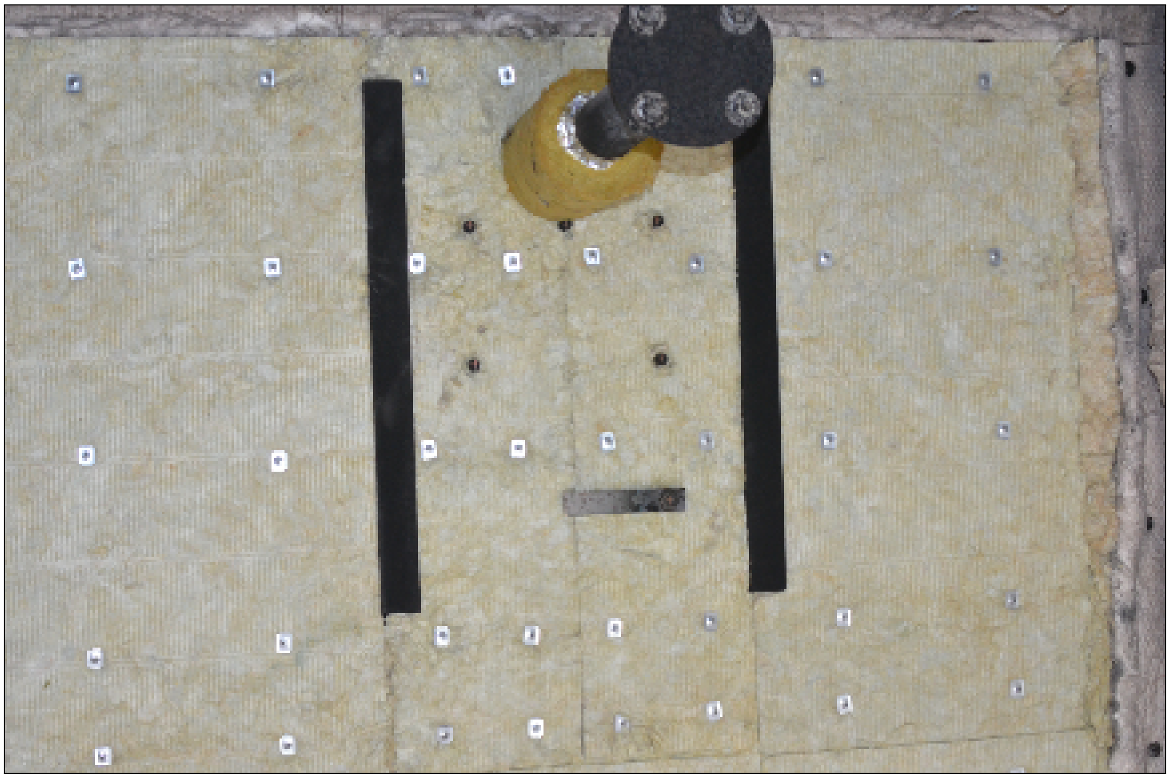


Figure 4.24: Test 7: Navy bulkhead test specimen with 50 mm of JM Minwool®1200 batting and pipe insulation installed

Initially, and as can be seen in Figure 4.24, additional pins and washers are used to mount insulation to the center portion of the wall to ensure the insulation stayed in place after being cut to fit around the obstructions. Results of this test indicated that this is not necessary so the insulation mounting is changed to the same arrangement as the side panels for subsequent experiments. In the final configuration, therefore, the steel pins were also in compliance with the IMO certification arrangements.

Test 7 results

Test 7 is done using the Minwool insulated steel test wall to examine the thermal response of this wall to a fire fueled by partially conditioned wood (m= 29.977 kg) in the two crib side-by side configuration. Results for the thermocouple temperature measurements in the fire compartment and the unexposed side of the wall are plotted in Figure 4.25 and discussed further detail below.

It can be seen in the figure that communication is lost with the data acquisition back plane and the laptop recording data from between t=204 s and t= 689 s while the fire is in the growth stages. Although communication is reestablished after t=689 s which allowed capture of the fire peak, it is not entirely certain whether the time stamps for this test are actually valid. Nonetheless, peak gas temperatures at the wall are likely reached at approximately 15 minutes after ignition, with the average upper layer temperatures varying between 400 - 500 °C and peak temperatures of 550-600 °C. To assess any changes in the fire growth rate and consequent fire compartment and wall exposure temperatures between non-insulated (Test 5) and Minwool insulated walls (Test 7), temperatures from thermocouples located at z= 915 mm and up in Trees 1 and 2 were averaged. Figure 4.28 summarizes the results, but because of the data interruption and uncertainty in elapsed time for Test 7, it is unclear whether this set of results is useful in establishing a trend in fire growth and wall response between uninsulated and insulated wall tests. Therefore, additional data is required to confirm that the partially conditioned fuel load fire scenario changes when the test specimen wall is insulated. The comparison will be discussed further when results for the repeat Test 8 are presented below. Fortunately the main purpose of this test is to verify the insulation installation methodology and the use of the TIC to capture IR data, and this data loss did not affect that goal as discussed below.

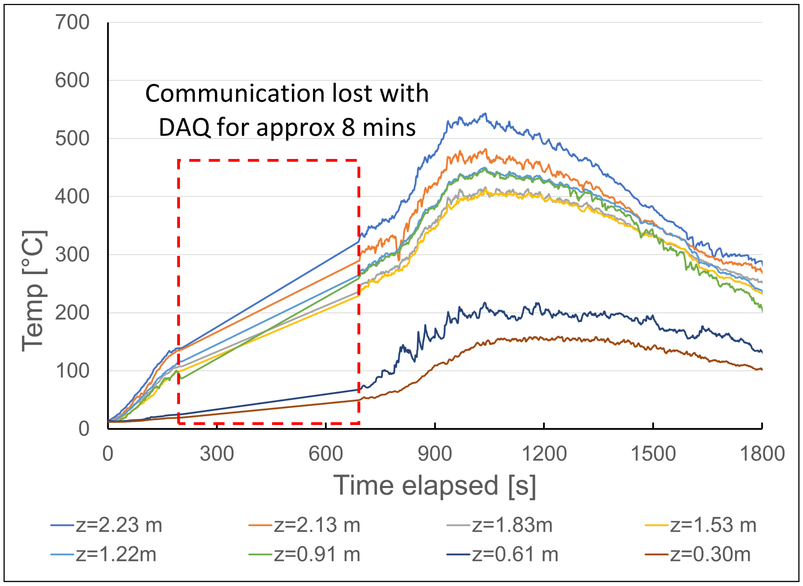


Figure 4.25: Test 7: Fire compartment average gas temperature at the wall test specimen

As previously seen in Test 6, Figure 4.26 shows the temperature on the unexposed side continues to rise after the fire has peaked at the 15 minute mark (900 s), indicating a similar system lag that is observed for the uninsulated cases. Because there was no fire suppression efforts, which would have included cooling the fire compartment and hot surfaces, it is uncertain how this compares to a real scenario. This aspect is part of the recommendations to further investigate how the insulation impacts the existing boundary cooling tactics and will be discussed in further detail below.

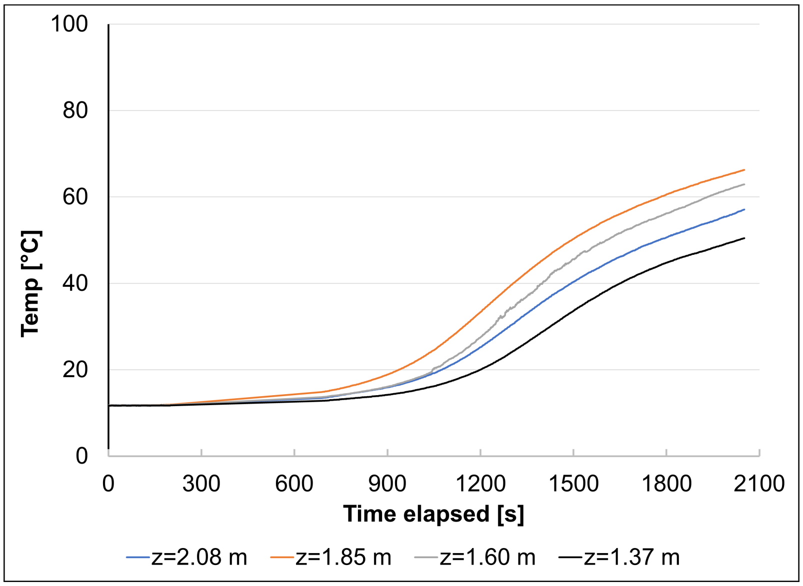
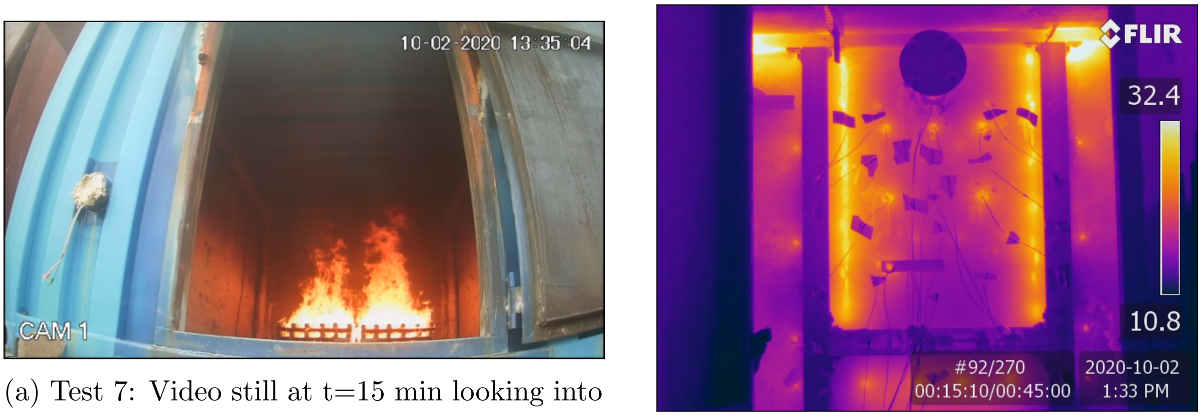


Figure 4.26: Test 7: Unexposed side centerline plate temperature

Comparison of temperatures in Figures 4.25 and 4.26, the thermocouple data on the exposed and unexposed sides of the Minwool insulated wall as well as the IR images from this test showed that, as expected, the insulation is very effective at preventing heat transfer through to the unexposed side of the wall. Along the centerline, the measured temperature remains close to ambient conditions at 15 minutes as compartment temperatures reach their peak values, with some warmer spots along the stiffener weld points and one the bolts.



(a) Test 7: Video still at t=15 min looking into the fire compartment

(b) Test 7: IR at 15 mins

Figure 4.27: Test 7: Video still of fire compartment and IR image at t=15 min

Figure 4.27a shows the fire conditions at the 15 minute mark for Test 7. The IR image on the unexposed side at 15 minutes is shown in Figure 4.27b, some heat leakage from the fire compartment to the unexposed side of the wall can be seen along the top of the wall frame. This is due to a small gap between the wall insulation and the permanent insulation panels on the wall mount frame, but overall still leads to very low increases in temperature. Large cold spots are visible on the panel at various spacings along the thermocouple wires. These are from the highly reflective, high temperature silver ducting tape used to secure the thermocouple wire in place when they are rerouted following previous test results. Due to the undesired impact of these areas on the over map of temperature distribution on the back side of the insulated wall, these pieces of tape are trimmed down further prior to the next test. In general, based on the results of Test 7, it appears that wall insulation installation is generally good in the main area of concern but requires improvement along the perimeter where the wall frame is mounted, and shows that the mineral wool insulation itself is very effective at reducing the heat transfer through the wall in a real fire scenario.

Test 8 results

Test 8 is done using a Minwool insulated steel test wall exposed to a fire fueled by partially conditioned wood (m= 29.968 kg) in the two crib side-by side configuration. Results for the thermocouple temperature measurements in the fire compartment and the unexposed side of the wall are plotted in Figure 4.29 and Figure 4.30. Peak gas temperatures at the wall are reached at approximately 12 minutes after ignition, with the upper hot layer temperatures varying between 400 - 500 °C, and temperatures between 550-600 °C at the ceiling.

Temperature variation with time is compared to that for the repeat Test 7 and Test 5 for the non-insulated wall in Figure 4.28. When comparing the average gas temperature at the wall between repeat tests with the Minwool insulated wall, Test 7 and Test 8, there are noticeable differences in the fire growth rates and peak temperatures, with Test 8 apparently growing faster and reaching higher peak temperatures. The slower growth rate may be a result of time synchronization errors between the initial and restored data for Test 7 resulting in an unknown uncertainty in timeline, so it is difficult to assess the significant differences observed between Tests 7 and 8 results. At the same time, review of the videos for the two tests did suggest that, visually at least, Test 7 did appear to grow at a slower rate then Test 8 and did not reach the same maximum fire height during the peak burning period. In past testing, development of the fire compartment environment in the wall fire test unit has been found to be very repeatable for similar test wall types, wood crib fuel loads and levels of conditioning. Since the test walls were the same in both tests, the fuel loads were approximately the same weight and both measured between 6-8% moisture content using the handheld meter, the reason for these apparent differences is not clear. In any case, due to the continuity of data acquisition in Test 8, the integrity of the measured time-varying data from Test 8 is considered higher, so that data will be used here in further comparisons of fire compartment evolution and wall exposure conditions with non-insulated and insulated wall situations.

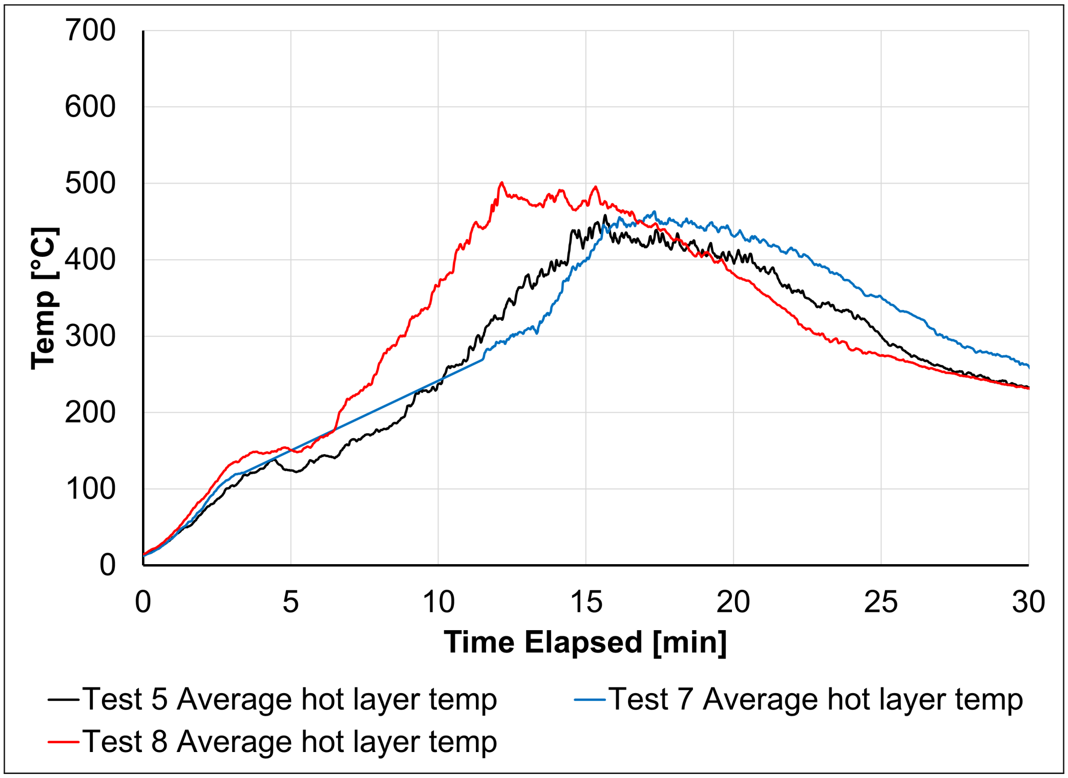


Figure 4.28: Partially conditioned fuel load average gas temperatures at the wall

The fire in Test 8 exhibited a faster growth rate and higher peak temperatures than that in Test 5, which is consistent with the addition of mineral wool insulation on the test wall. The presence of the insulated wall significantly changes the boundary condition on one end of the fire compartment by significantly reducing heat loss from the compartment. In terms of thermal transfer through to the unexposed side of the wall, the insulation proved to be equally effective as in Test 7, with most temperatures on the unexposed side measuring between approximately 20 °C and 26 °C after 15 minutes, with the exception of the upper thermocouple which indicates a considerably higher temperature at 43 °C.

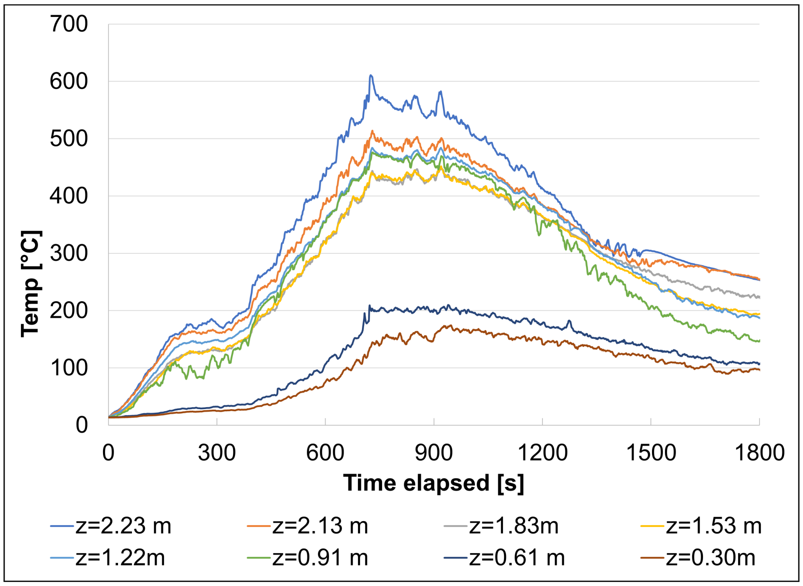


Figure 4.29: Test 8: Fire compartment average gas temperature at the wall test specimen

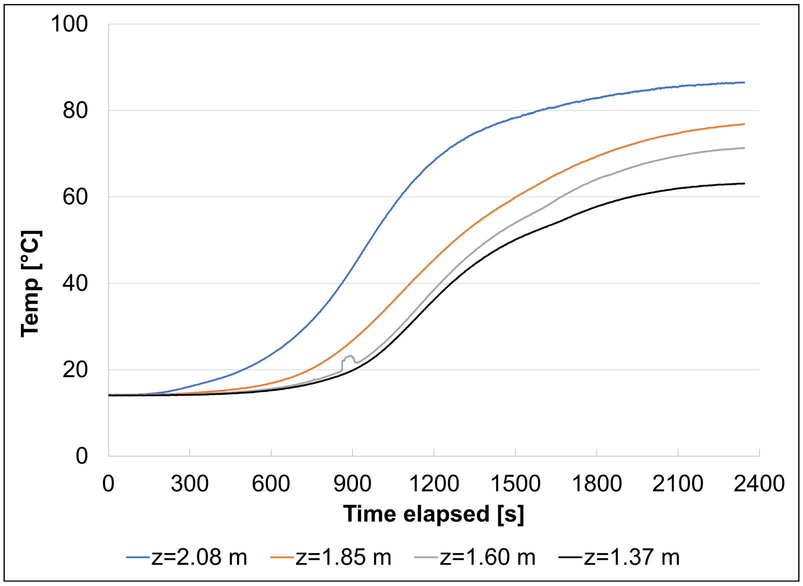
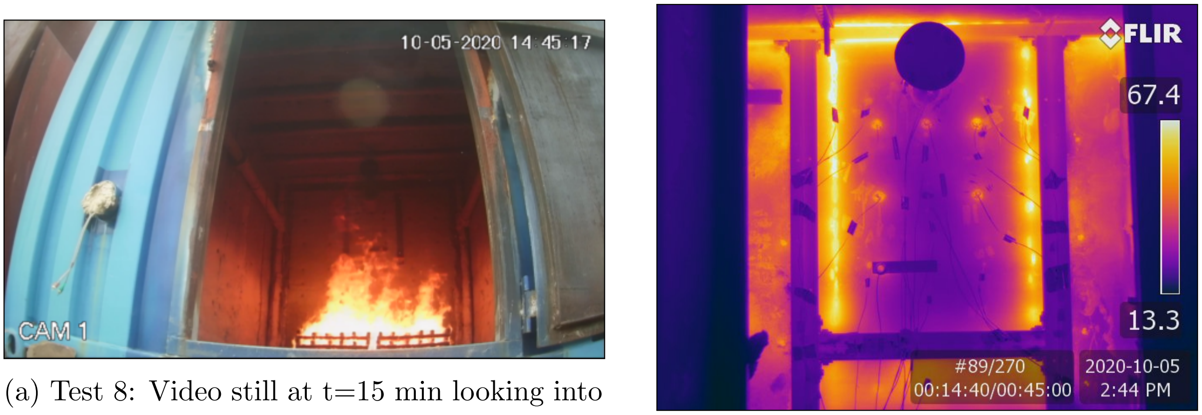


Figure 4.30: Test 8: Unexposed side centerline plate temperature

Figure 4.29 shows the fire conditions at 15 minutes of Test 8. Thermocouple results on the unexposed side are consistent with visual observations from the IR image shown in Figure 4.31b. In the IR image from 15 minutes into the test, a hot area that corresponds approximately with the position of the high temperature reading is visible in behind the upper frame in the centre panel. Overall the measured temperatures remain well within the maximum limit of 180 °C specified in the IMO standard for an A-15 rating. In fact, they did not exceed 90°C after almost 40 minutes. The localized heating due to the small gap in the insulation, on the other hand, does illustrate the importance of tight fitting installation of insulation when seeking proper performance in a fire.



(a) Test 8: Video still at t=15 min looking into the fire compartment

(b) Test 8: IR at 15 mins

Figure 4.31: Test 8: Video still of fire compartment and IR image at t=15 min

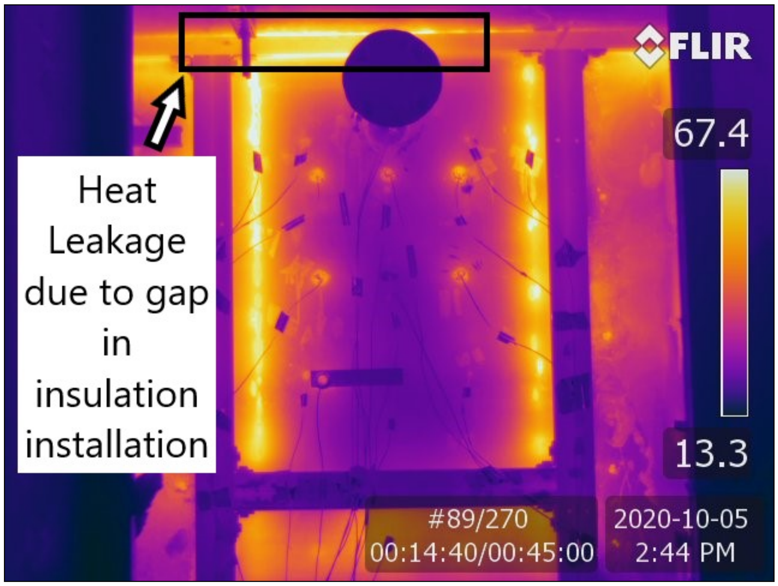


Figure 4.32: Test 8: Heat leakage around the perimeter observed using IR camera at 15 minutes

Heat leakage around the perimeter of the wall mount frame is still evident in the IR images, which is highlighted in Figure 4.32. Following the fire, it is found that there is a small gap (less than 4 mm tall) between the insulation and the permanent insulation on the mounting frame in the vicinity due to improper installation of the piece of insulation around the piping. This results in some additional heating to that portion of the panel and explains the higher reading on the thermocouple, as well as the hot area seen in the IR camera image. This continued to be a challenge throughout the testing, but serves to highlight the benefits in using a TIC and the corresponding IR images in determining thermal penetration even through insulated steel bulkheads. The gaps were sufficiently small that although there is clearly heat penetration, no other visual signs of the fire in the test compartment, such as visible smoke visible, were evident on the unexposed side of the wall. Thus, in addition to providing useful IR images for training and potential decision making in the presence of similar ’gaps’ on board an actual vessel, the TIC did prove to be a useful diagnostic tool for improving the experimental setup during this research as well.

4.5.2 IMO A-15 compliant insulation testing results

On completion of Test 7 and 8, sufficient experience had been gained with installation and testing of the steel wall insulated with industrial mineral wool to be confident in successfully completing the final two tests using the limited amount of IMO certified Searox 620 SL insulation that had been generously donated by Rockwool for the experiments.

This 50 mm thick insulation is a stiff board that comes in standard 600 mm by 1200 mm sheets and is easy to cut to size without the use of any special tools. Prior to installation of the insulation, the 3mm steel pins on the center panel were removed and repositioned to the 300 mm that matches the IMO guidelines for installation and testing of marine insulation as shown in Figure 4.33. This more closely mimicked the anticipated as-installed system and also allowed enough room to maneuver the stiffer board under the face of the stiffener which was necessary to ensure good insulation fit across the test wall. Once the new insulation was installed, Test 9 commenced.

Figure 4.33: Test 9: Navy bulkhead test specimen with 50 mm of Rockwool Searox ®620 SL board insulation and JM 1200 pipe insulation installed

Test 9 results

Test 9 uses fully conditioned wood (m= 22.569 kg) in the two crib side-by side configuration, with 50 mm of Rockwool Searox ®620 SL board insulation mounted on the test wall and 50 mm of JM Minwool 1200 insulation fitted on the piping section. The mounting arrangement is based on the IMO FTP rules and installation follows the Rockwool technical guide instructions, using 3mm steel pins welded to the bulkhead and 38mm locking washers to hold it in place. Temperature traces from the fire compartment and unexposed sides of the test wall are shown in Figure 4.34 and Figure 4.35.

The fire grows quickly and peak gas temperatures at the wall are reached at approximately 8 minutes after ignition, with the upper hot layer temperatures varying between 400 - 550 °C, and the ceiling layer reaching temperatures above 600 °C.

Temperature traces on the unexposed side shown in Figure 4.35 indicate that there is a temperature gradient from top to bottom of the wall but that insulation is effective at preventing heat transfer from the fire compartment through the wall, with surface temperatures varying between 20-50°C over the height of the upper portion of the center panel at 15 minutes into the test.

These tests show the same temperature lag as the previous testing, with the unexposed surface temperature continuing to increase as the fire is decaying. At the 40 minute mark (2400 s), the fire compartment temperature was between 100-200 °C, while the unexposed surface temperature was between 50- 80 °C. It is unknown if this system lag would similarly be observed if there was some fire suppression efforts, which would have included cooling of the hot surfaces, or how the normal boundary cooling tactics would affect this, and is part of the recommendation to include this aspect in future work. Some preliminary conclusions are discussed in the in section below on the potential impacts to the RCN boundary cooling tactics.

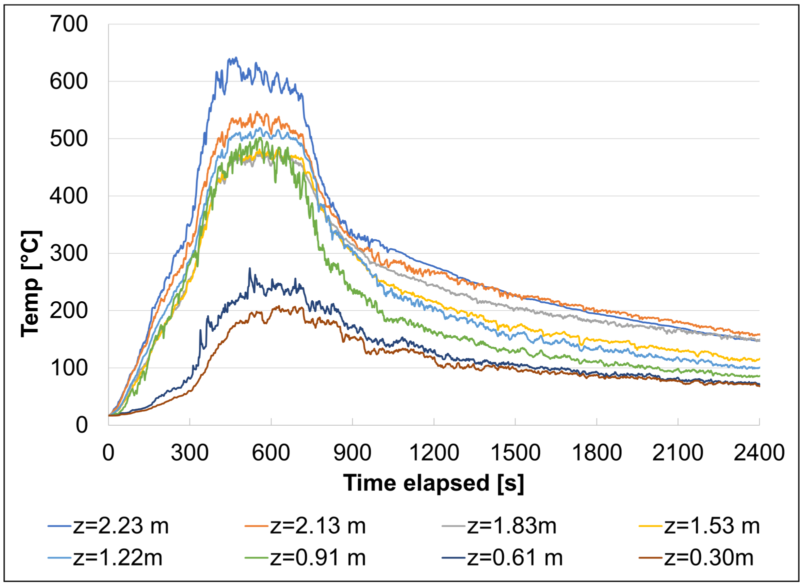


Figure 4.34: Test 9: Fire compartment average gas temperature at the wall test specimen

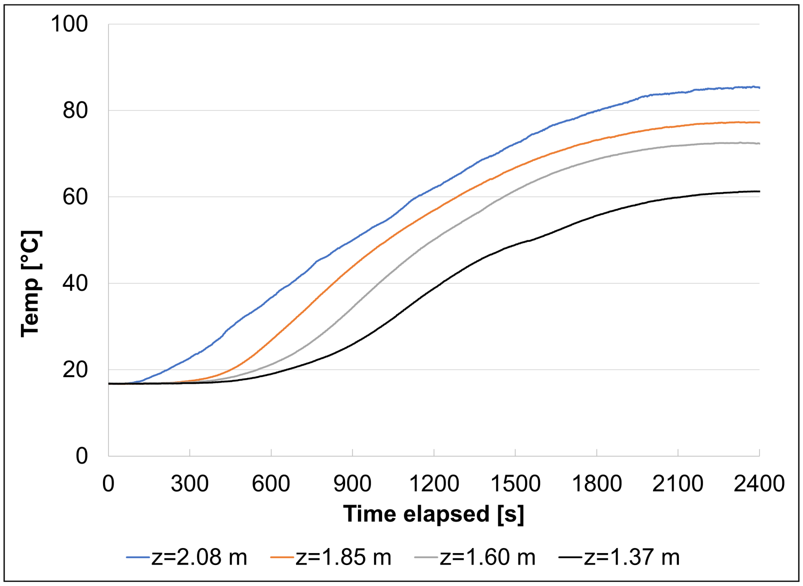
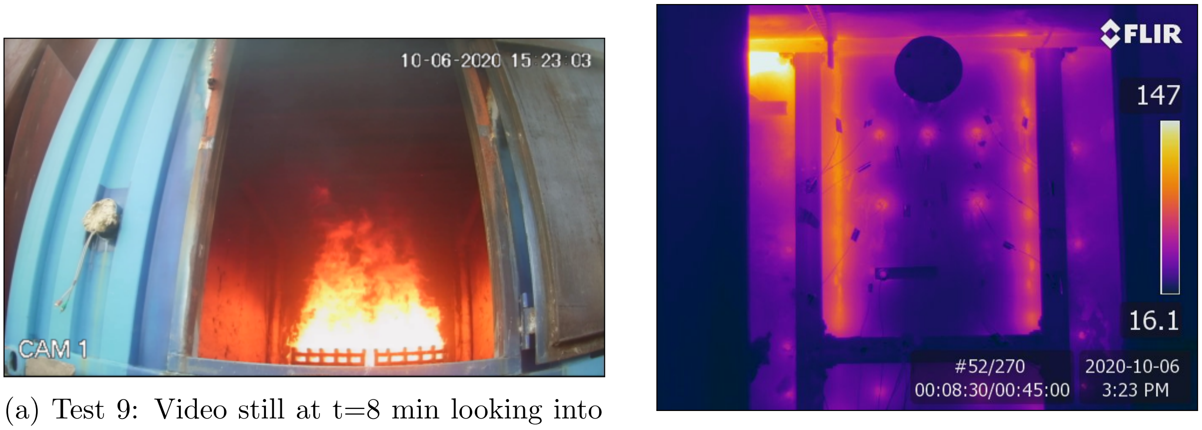


Figure 4.35: Test 9: Unexposed side centerline plate temperature

For this test, the fire burned preferentially hotter on the right side of the fire compartment. Although there is some heat leakage observed in the corner the overall test specimen temperatures are largely unaffected. This is illustrated in the IR image in Figure 4.36b taken at 8 minutes after ignition when the ceiling gas temperatures in the fire compartment exceed 620 °C, values higher than in any of the previous tests. Even though a peak temperature of 147 °C is observed on the metal frame on the far left hand side of the IR image (suggesting heat leakage in this area of the test unit), there is relatively little evidence of preferential thermal transfer into the insulated wall panel in the center of the frame.



(a) Test 9: Video still at t=8 min looking into the fire compartment

(b) Test 9: IR at 8 mins, with visible heat leakage in the upper left corner of the test specimen

Figure 4.36: Test 9: Video still of fire compartment and IR image at t=8 min

Although the temperature scale is different from previous IR images due to the higher compartment temperatures and resultant hot spot due to heat leakage to the wall frame in the left hand corner of the image, the thermal gradient measured by the thermocouples mounted to the unexposed side of the wall, as well as increased thermal transfer through parts of the insulated wall, are clearly visible in the IR image. In these respects, the use of a TIC can distinguish thermal transfer even through the insulation and in the present context also greatly assists in data analysis and experimental design. For the data analysis, these IR images are similar to what would be seen by the Attack Teams using a hand held TIC, so is directly relevant to understanding how the use of fire insulation on new designs will change the on site feedback from RCN personnel responding to the fire. On the latter point, it is recommended for use in similar wall fire tests performed in the future, as this gives an overall view of the surface, providing additional context that may not be possible with the limited number of point measurements on the test specimen.

Here, due to the continuing evidence of heat leakage through the wall unit test frame, faster fire growth and higher temperatures measured in this test, additional measures were undertaken to insulate the gaps between the insulated test wall and the mounting frame for the subsequent test with the Searox 620 SL insulation on the wall. Previous efforts to reroute the thermocouple cable and minimize the highly reflective, high temperature tape was successful so no further changes were required to that aspect.

Test 10 results

Test 10 is conducted as a repeat test to confirm and extend the results described above for Test 9. Therefore, it is again done using fully conditioned wood (m= 22.993 kg) in the two crib side-by side configuration, with 50 mm of Rockwool Searox®620 SL board insulation mounted on the wall and 50 mm of JM Minwool 1200 insulation fitted on the piping. The mounting arrangement is the same as Test 9, so is compliant with the IMO FTP guidelines.

Peak gas temperatures again occurred approximately 8 minutes after ignition, with the upper hot layer temperatures measuring between 400 - 550 °C, and the ceiling reaching temperatures above 600 °C, as shown in Figure 4.37.

On the unexposed side, the insulation is effective at preventing heat transfer, with the surface temperatures measured by the wall thermocouples varying between 20-40°C over the height of the upper portion of the center panel at 15 minutes as shown in Figure 4.38. There is again evidence of a gradient in wall temperature during fire growth, though the wall temperature measured by the thermocouple located at a height of 1.85 m above the floor surpassed that measured by the higher wall thermocouple just before 15 minutes into the test. Both sensors are located in the vicinity of the pipe penetration, with the higher reading occurring below the pipe, and may be due some intermittent flame impingement and/or higher gas temperatures on the underside of the pipe. It is not definitively known, so further study and possibly some computer modeling may assist in determining how the geometry of the test specimen and the resulting air flow may have interacted with specific thermocouple measurements.

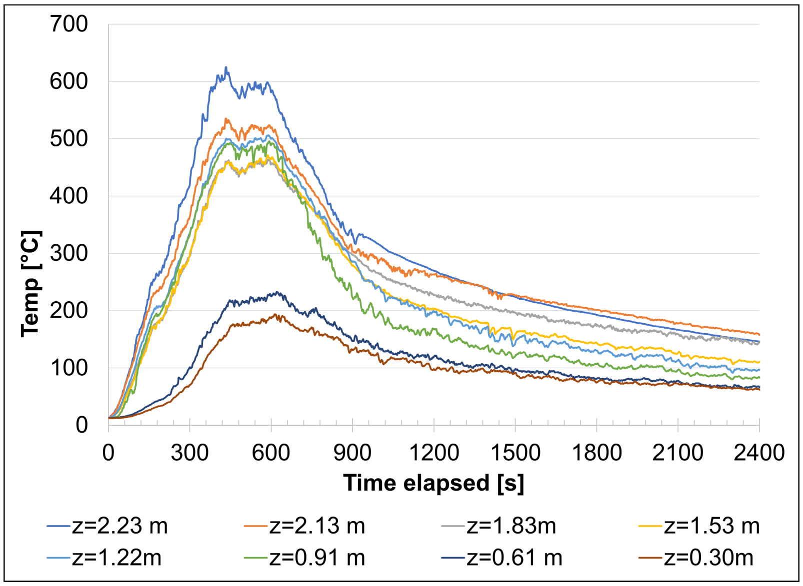


Figure 4.37: Test 10: Fire compartment average gas temperature at the wall test specimen

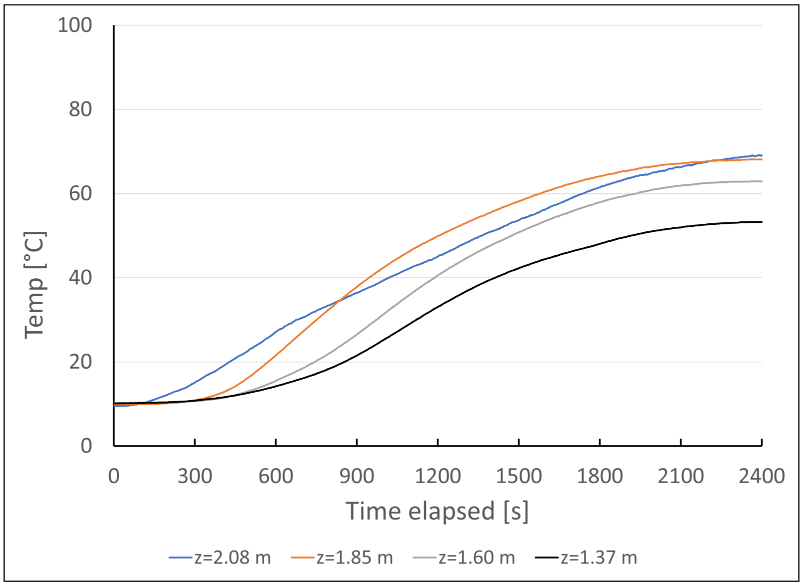
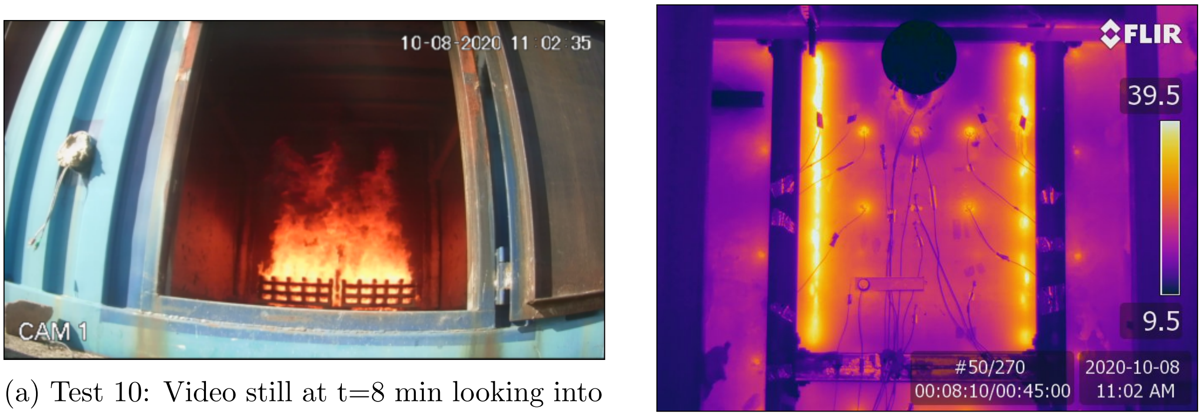


Figure 4.38: Test 10: Unexposed side centerline plate temperature

In this test, no preferential leakage of heat is observed around the upper edges of the wall mount frame (Figure 4.39b), so overall, Test 10 gave the cleanest and most internally consistent results of the entire series of experiments. An image of the fire at 8 minutes after ignition is shown in Figure 4.39a. In the corresponding IR image taken at that time, no heating of the wall frame or around the perimeter of the test wall is observable, showing that the use of earlier IR images and additional methods used to insulate the gaps between the insulated test wall and the mounting frame were successful.



(a) Test 10: Video still at t=8 min looking into the fire compartment

(b) Test 10: IR at 8 mins

Figure 4.39: Test 10: Video still of fire compartment and IR image at t=8 min

Since results from these tests are not affected by any observable asymmetries or unanticipated thermal variations due to unintended heating of the metal wall frame, they are used for analysing the accuracy of the IR images at the lower temperature range. Using the method outlined in 3.3.5, the IR images were within 1-2°C of the point measurements from the thermocouples for the low temperature range on the unexposed side, and provide a good representation of the overall thermal condition, enabling them to be used with confidence as part of the assessment of implications for RCN fire fighting tactics, and potentially also to incorporate into existing training.

Average temperatures measured in the hot layer at the wall (thermocouples located at z= 915 mm and up in Tree 1 and 2) for both Test 9 and Test 10 are compared to those from Test 6 and presented in Figure 4.40. The fires in Test 9 and Test 10 exhibit similar behaviour to one another. As expected, both grew faster and reached higher peak temperatures than the fire in Test 6 for the steel wall without insulation. These results are consistent with expectations since the insulation added to the wall test specimen for Tests 9 and 10 should reduce heat loss from the compartment.

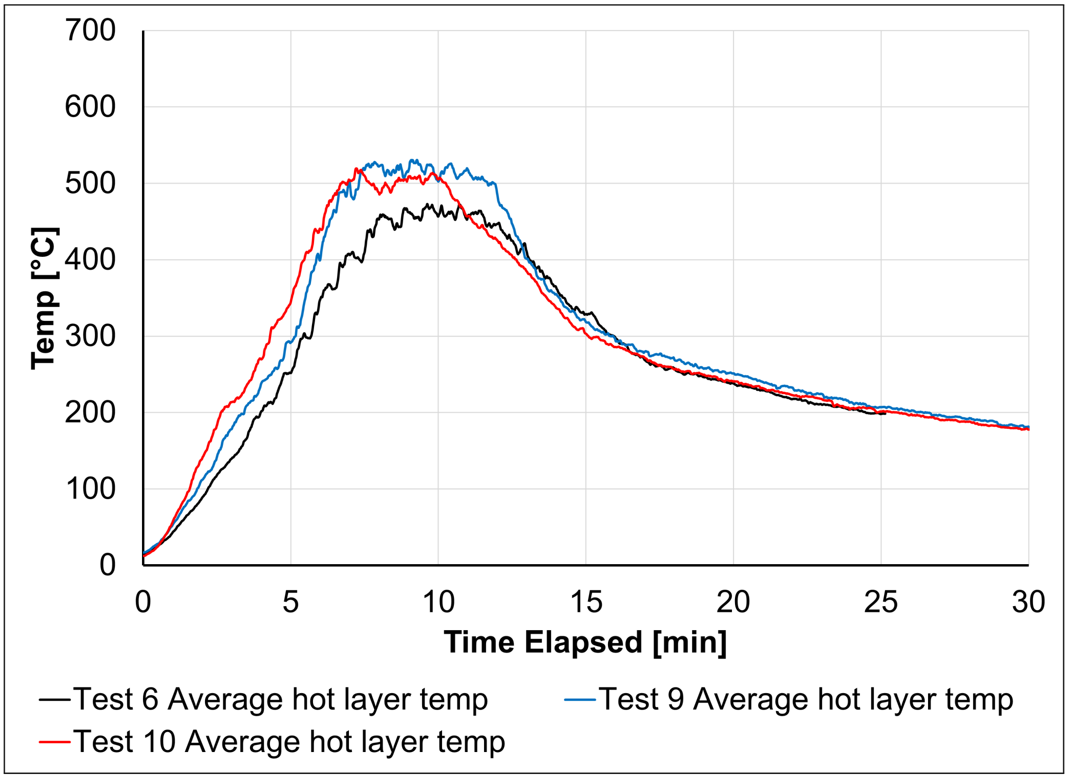


Figure 4.40: Fully conditioned fuel load average gas temperatures at the wall

Some heat leakage to the wall frame is still visible in Test 9 on the right hand side wall panel but this is successfully addressed and corrected with additional insulation for Test 10. Overall, the A-15 SeaROX 620 SL insulation performed very well leading to low wall temperatures throughout the unexposed side, even despite the increased intensity of the fire scenario compared to tests 6, 7 and 8.

Because the objective was to look at how a more realistic wall assembly performs in fire conditions, in the following sections the results from tests 9 and 10 are broken down further to specifically examine the results on the key monitoring points. This includes the standard monitoring points on the steel plate and stiffeners required under the IMO testing protocols, as well as the pipe penetrations and the additional monitoring points added on the features meant to simulate naval watertight door components that may act as heat shorts, and may potentially be used as a 'tell-tale' during the fire fighting response.

4.6 Impact of using mineral wool insulation - IMO test points

It is clear from the discussion above that the addition of the mineral wool insulation as a fire barrier greatly reduced the heat transmission from the fire compartment to the adjacent compartment, which is consistent with the certification testing requirements that require the unexposed surface temperature to remain below a threshold temperature during the test period. Figure 4.41 shows an overview of the temperature reduction on the unexposed side, using several different representative measuring points from the IMO testing standard. The plate, which is fully insulated is reduced from a peak temperature of 346 °C when uninsulated, down to 40 °C. Both the stiffener and the bolts (used to represent the door closing mechanisms) are partially exposed in the fire compartment, but their temperatures are below the overall maximum allowed point temperature of 180 °C. The left stiffener has a maximum point temperature of 123°C measured when insulated, compared to 330 °C with no insulation, with the bolt having a maximum temperature of 60 °C when insulated, compared to 250 °C for the uninsulated test.

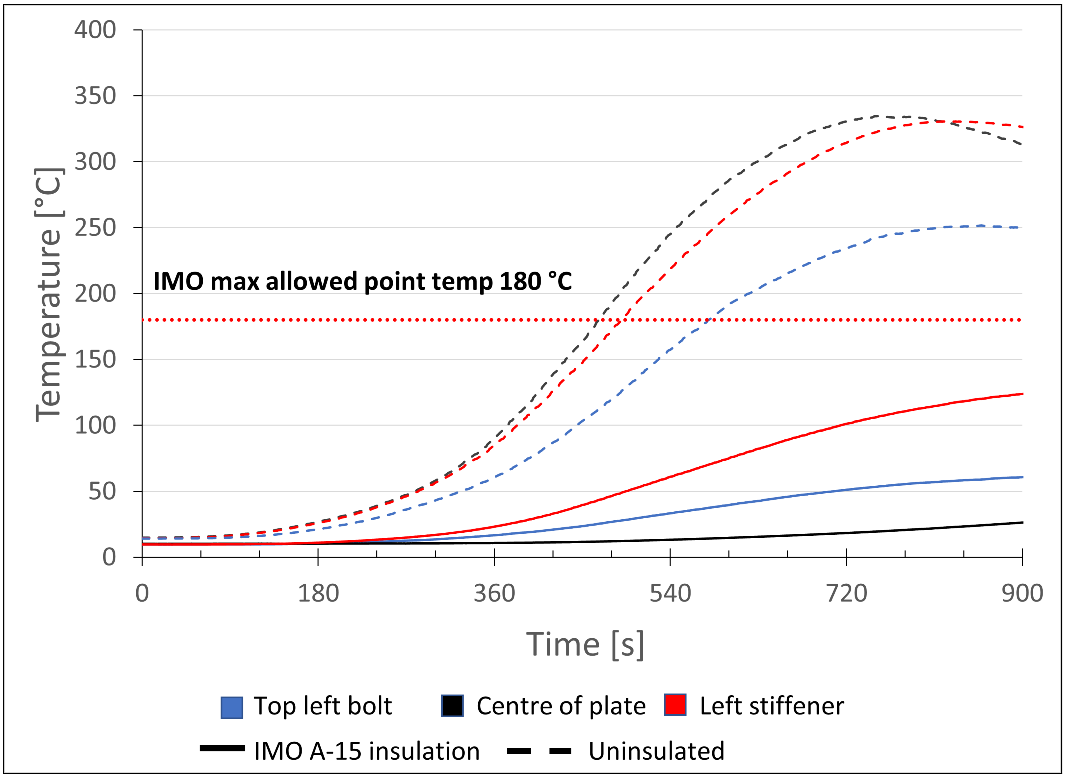


Figure 4.41: Impact of using IMO A-15 insulation on reducing the unexposed side temperatures using representative measuring points

Similarly, when insulated, the maximum average temperature allowed is 140 °C, and, from the IR images, after 15 minutes the average temperature on the area of interest is estimated to be only 45°C. This is shown in 4.42, which shows that the overall thermal gradients across the test area, with the hottest locations at the stiffener, with some warmer areas in the vicinity of the bolts, but otherwise cool areas on the majority of the plate which is fully protected by the insulation.

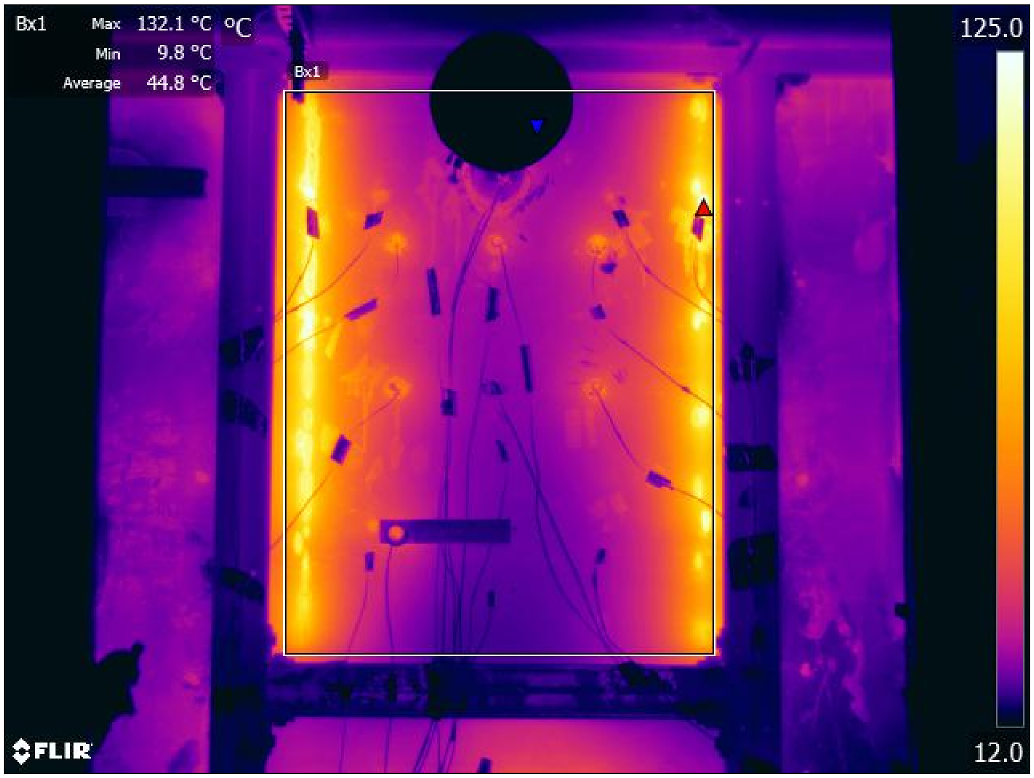


Figure 4.42: IR image at 15 minutes of Test 10 with IMO A-15 insulation fitted, showing an average surface temp of 45 °C in the test area of interest

Therefore, instead of providing only the IMO pass/fail result at the end of set testing time interval, these test results provide a quantifiable set of time dependent results on a composite insulated steel wall assembly that includes a number of penetrations representative of those encountered in a real situation . This is critical information in terms of looking at the context of fire fighting tactics, as it means that the test data can be used to look at unexposed temperatures at specific time intervals (such as during the initial response) to get a better idea of what surface temperatures may be seen in adjacent compartments, which would include any closed doors/hatches. Prior to this testing, the assumption is that the insulation would reduce the surface temperature in adjacent compartments, but there was no basis upon which to quantify the amount of the reduction. While the test data is only valid for this specific scenario, and different fuel loads, growth rates and configurations would change the output, it does give some concrete results to base decisions on. Additional testing with different fuel loads and configurations would give a wider variety of data to base any tactical decisions on, but this work is a reasonable starting point to build on.

In addition to the vertically spaced center line measurements presented, the IMO FTP looks at the temperatures recorded at several key points on the plate, along the stiffeners, and on the pipe penetration. These measurement points are highlighted in blue in Figure 3.17. Additional measuring points are located on the threaded bolts in these tests. These are meant to duplicate the steel rods that penetrate the door and form part of the door securing arrangement on the watertight doors on naval vessels.

For the discussion below, the results are limited to the measurements taken during tests 6, 9 and 10 fueled by fully conditioned wood cribs, with no insulation (Test 6) and with IMO A-15 insulation (Tests 9,10) installed on the test wall. The left and right hand sides referenced in the discussion are relative to the image views, taken of the unexposed side of the navy test wall from the back of the shipping container and looking at the wall from the instrumentation compartment.

IMO plate monitoring points

The first group of five temperature monitoring points are on the plate, and positioned at the center of the plate, and at the center of each quadrant. Measured surface temperatures are shown as functions of time in Figure 4.43, which includes results from all three tests, with the IMO "A Class" temperature limit included for reference.

For Test 6 with the uninsulated wall (solid lines in the figure), the peak plate temperature of approximately 330 °C is reached at approximately 12 minutes after ignition. Temperatures measured by the thermocouple at the monitor point in the bottom left quadrant center are clearly outliers, as it registers lower temperatures relative to any other measured temperatures on the test wall. This monitoring point is located within 50mm of the through bolt with the handle attached and in general, the IR images show localized cooler zones in the vicinity of each bolt. Unfortunately in the IR image taken at t=12 minutes for this test and included as Figure 4.44, the test wall surface at the bottom left quadrant and plate center monitoring points, marked as Sp1 and Sp5 in the IR image, are obscured by the thermocouple wire routing in this early Test. These were rerouted for further tests, as part of the adjustments discussed above for Test 7 onward.

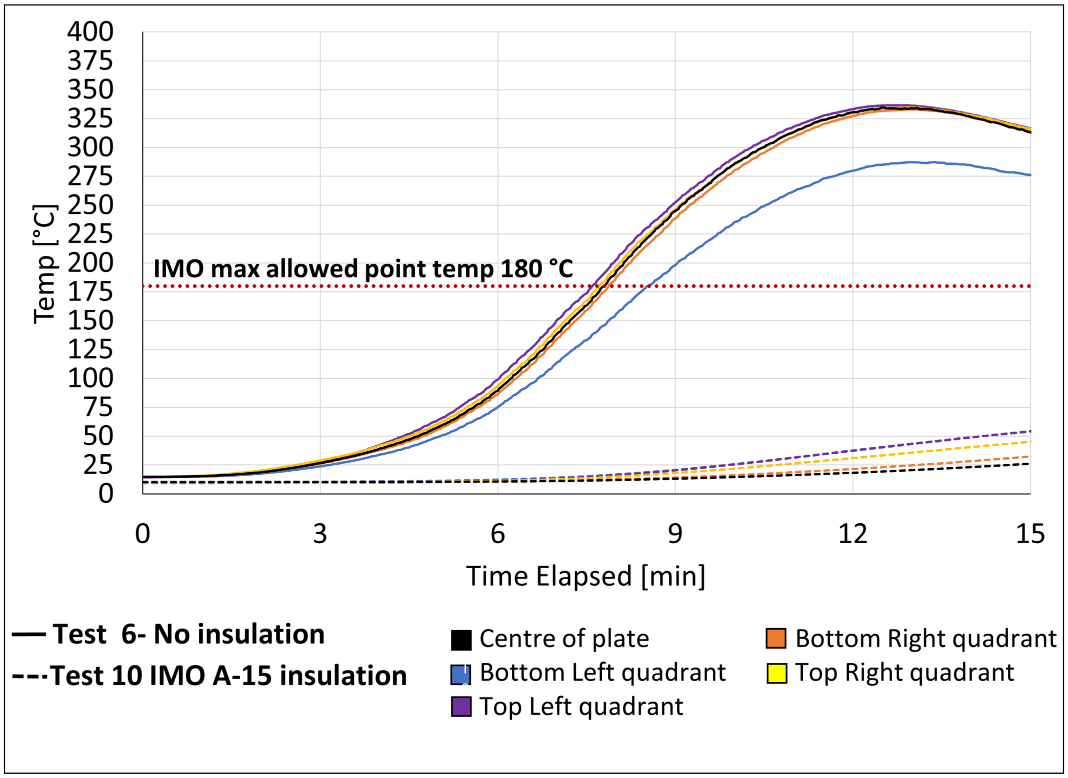


Figure 4.43: IMO FTP plate temperature monitoring point results

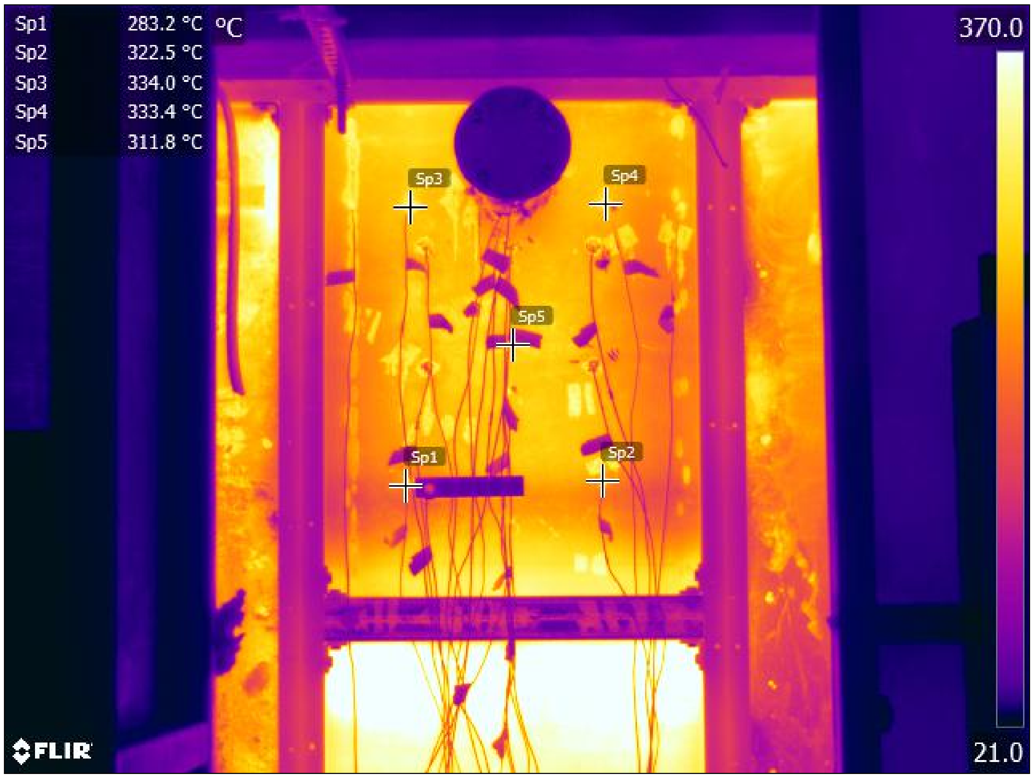


Figure 4.44: Test 6: IR image at 12 minutes, $\epsilon = 0.85$, 5 IMO monitoring points shown (Note center quadrant point obscured)

For the insulated test cases, plate temperatures vary from quadrant to quadrant due to local conditions around the monitoring points but in general at 15 minutes after ignition they are between 25-60 °C, and are between 52-103 °C at 30 minutes. Overall the 50mm thick IMO A-15 insulation is very effective at preventing heat transfer to these points in the steel plate.

IMO stiffener monitoring points

For the vertical stiffeners, in the A-15 configuration, insulation was installed flush to either side of the web, leaving the flange and a portion of the web exposed (which will vary depending on the height of the web used for the stiffener and the thickness of insulation for the particular insulation product chosen). This creates a direct path for heat from the exposed side to conduct to the unexposed side through the web of the stiffener into the steel plate along the mating face and welded joints. In A-30 and A-60 configurations the stiffener is also insulated to eliminate this heat transfer path to the unexposed side, but is still a mandatory monitoring point in the IMO FTP protocol to ensure that it does not exceed the temperature limits.

For the IMO test points, the vertical stiffener temperatures are measured at 0.75 of the height of the test wall. As seen in Figure 4.45, installation of insulation decreased the peak temperature at 15 minutes after ignition from approximately 325°C in Test 6 with no insulation on the steel test wall to between 125-145°C for Tests 9 and 10 on the insulated wall. While these temperatures are still well within the IMO temperature limit of 180 °C, they are significantly hotter than other areas on the unexposed side of the insulated wall, so will appear as hotter regions in IR images of the unexposed side for the case of A-15 insulated wall. Unfortunately, for for A-30 and A-60 class wall configurations this is likely not the case since the stiffener is completely enclosed with the facing covered in insulation, protecting this heat conduction path to the unexposed side.

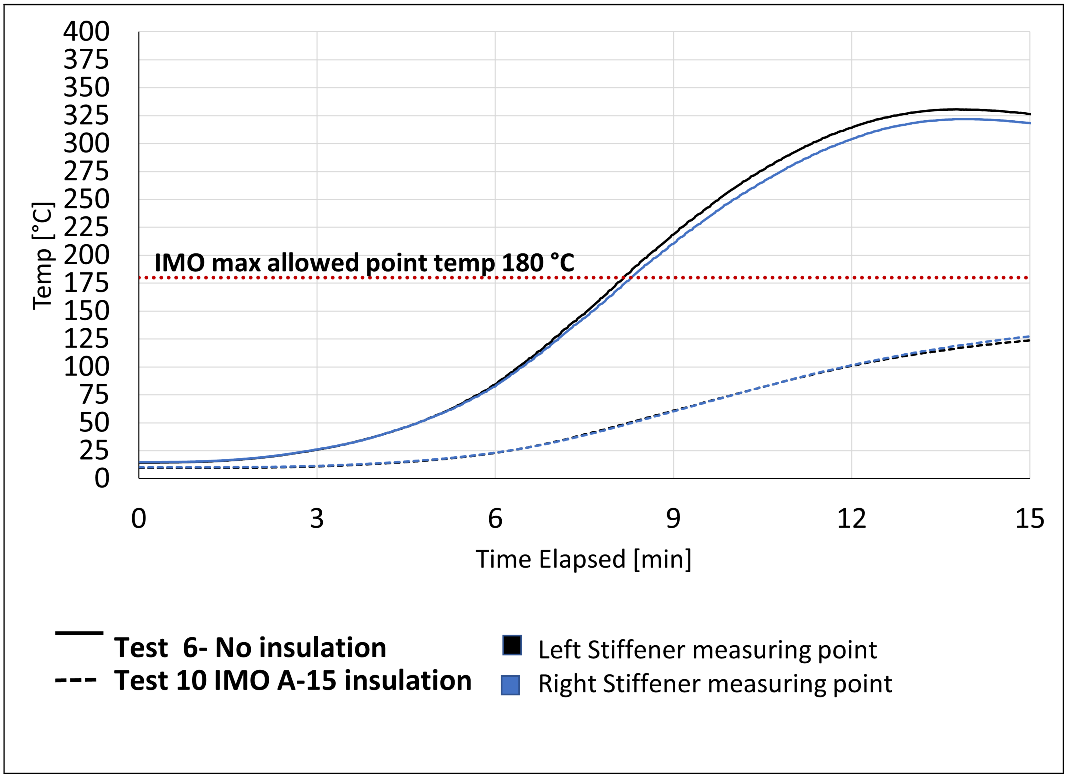


Figure 4.45: IMO FTP vertical stiffener temperature monitoring point results

The stiffener measurement point is consistently the hottest point on the insulated test wall, with the IR image in Figure 4.46 showing the overall temperature profile at t=15 minutes.

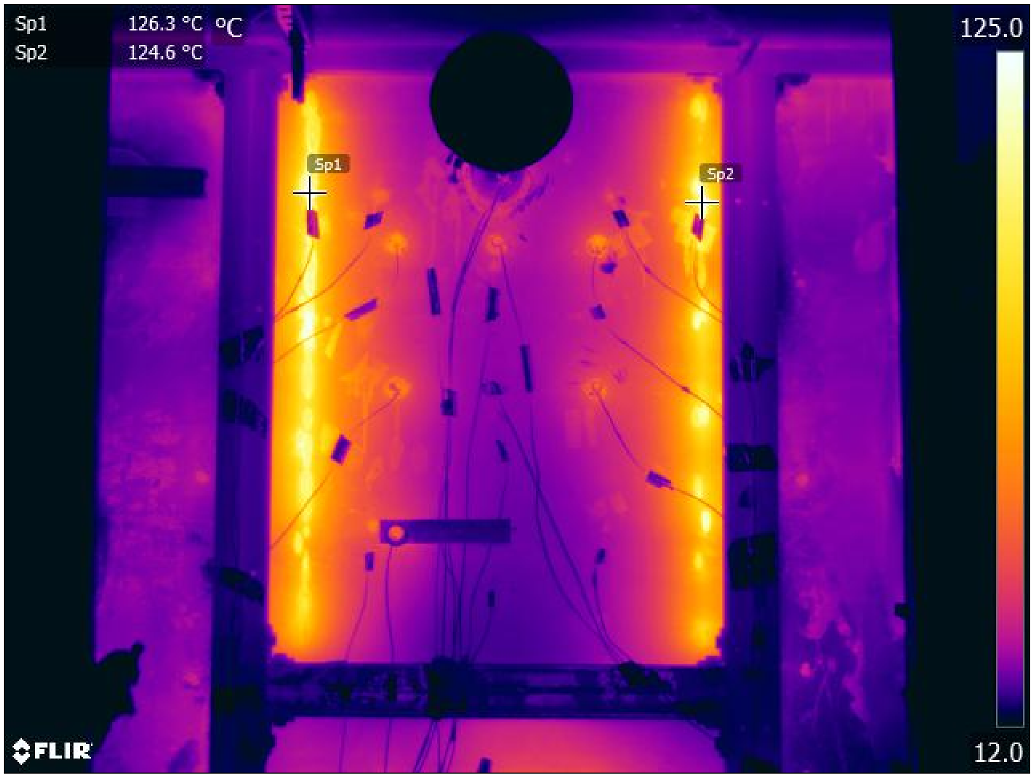


Figure 4.46: Test 10: IR image at 15 minutes, $\epsilon = 0.85$, 5 IMO wall stiffener monitoring points

Pipe penetration monitoring points

In the IMO FTP pipe testing protocol, the only IMO specified temperature monitoring point is located 25 mm (1 inch) from the wall on the outer surface of the pipe on the unexposed side of the wall [12]. For the experiments, a thermocouple was located at this location to verify the IMO testing results, along with two additional temperature measurement points on the pipe; one at 102 mm (4 inches) from the wall on the outer surface of the pipe, and the other at 254 mm (10 inches) from the wall. All three pipe thermocouples were located along the bottom of the pipe These are intended to monitor any temperature gradient along the pipe on the unexposed side of the steel test wall.

Both ends of the pipe are fitted with blank flanges bolted in place to prevent hot smoke from flowing through the pipe during testing. No signs of smoke infiltration are observed from the unexposed side of the pipe in any of the tests. Therefore the heat transfer mechanism along the pipe section is due to the exposed section of the pipe in the fire compartment being heated via convection/radiation, with that heat conducting along the length of the pipe into the section of pipe that extends through the steel test wall to the unexposed side in the transition compartment.

For Tests 9 and 10 with the insulated steel test wall, in accordance with the IMO FTP requirements, in addition to the 50mm of the insulation fitted to the wall and thus around the pipe, an additional 330 mm of pipe insulation is fitted onto the pipe on the exposed side (giving a total of 380 mm of protected piping in the exposed side). As shown in Figure 4.47, this is effective in reducing the temperature on the exterior of the pipe, at a location 25 mm along the pipe from the test wall, from 235°C at 15 minutes after ignition in Test 6 with no insulation on the wall, to approximately 35°C (a rise of only 20 °C above ambient conditions) in Tests 9 and 10 for the A-15 insulated wall-insulated pipe configuration.

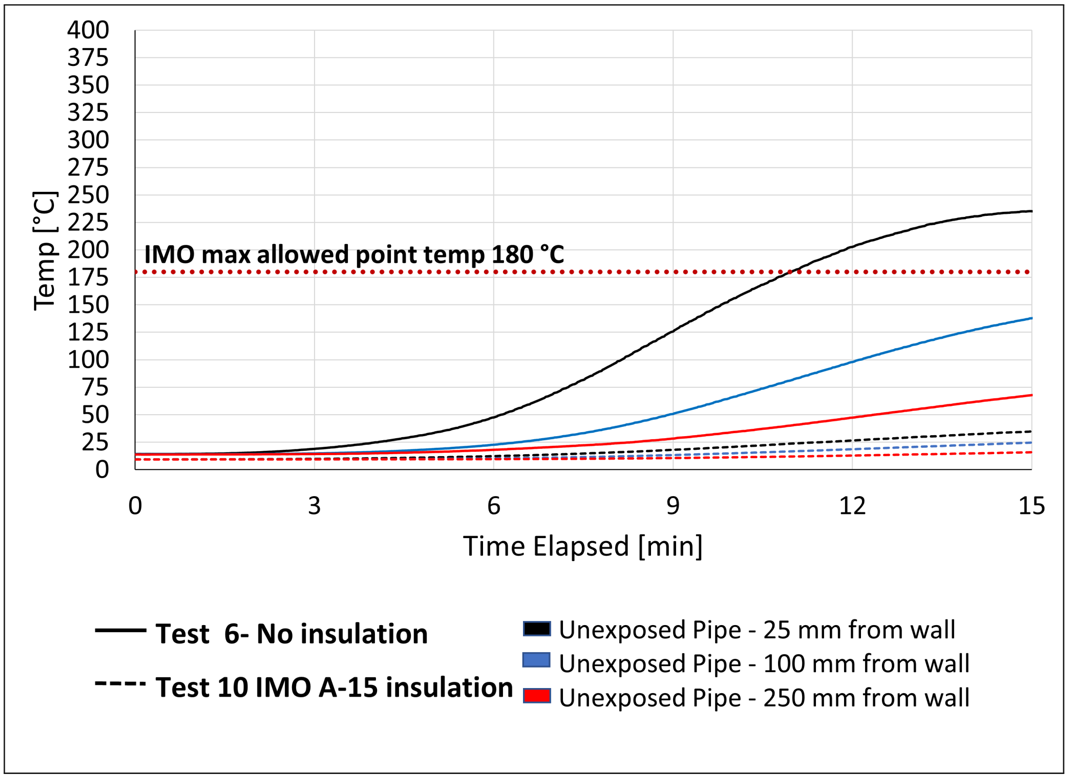


Figure 4.47: IMO FTP pipe temperature monitoring point results

It is evident from these results that although the exposed section of pipe in the fire compartment is directly exposed to the fire plume and experienced intermittent flame impingement, the IMO specified insulation configuration is highly effective in preventing heat transfer along the pipe into the adjacent compartment. While this is excellent in terms of protection of piping penetrations from damage under exposure to fire, as well as from the point of view of minimizing the potential for heat transfer paths along piping to adjacent compartments, it is unlikely that observation of the thermal state of piping through wall penetrations from the unexposed side will provide useful information to crews in terms of fire response decision making. While these results are consistent with the expectations from the certification testing, this is a useful result to provide more granular data and eliminate questions about the effectiveness of the individual component testing being valid when looking at more complicated arrangements commonly found on a warship. For training purposes, being able to conclusively demonstrate the effectiveness using a combination of video, temperature and infrared image data can be critical for the personnel to have confidence in the introduction of new equipment, and understanding what we can and cannot use it for is a key factor when developing and refining tactics.

It should be recognized that the present result is based on using a schedule 40 carbon steel pipe, which has a thermal conductivity of approximately 43 W\m K [1] with a wall thickness of 5.486 mm. These parameters, and thus the anticipated heat transfer along the pipe, would vary with thinner/thicker walled piped, and would also be dependent on the material. For example, naval bronze (C83600 alloy) is a commonly used pipe on naval ships, and has a notably higher heat conductivity, approximately 72 W\m K, than the carbon steel used here. Thus, when looking at these results and applying them to a real ship design, the pipe material and specifications must be taken into consideration as well.

Additional monitoring points

In addition to the standard IMO monitoring points on the unexposed side of the wall and the monitoring points on the pipe penetration, 6 sections of 19 mm (3/4 inch) threaded rod were used to use simulate portions of the door securing mechanisms (the door 'dogs') that penetrate through watertight doors on a naval vessel and rotate inside a sleeve to open/close the door. It is anticipated that these steel cylinders could allow some limited direct heat conduction from the fire compartment through to the unexposed side of the door. They were included in the test wall, and fitted with thermocouples, to see if the temperatures measured at these locations were feasible to use as indicators of the possible thermal/fire conditions on the opposite side of the door. Time varying temperatures measured at each location for the non-insulated (Test 6) and insulated (Tests 9 and 10) steel test wall are plotted in Figure 4.48. In the figure, each rod is labeled as a 'bolt' and designated with a location specified when looking at the unexposed side of the test wall from the rear of the container to match the point of view in the IR images.

During the test with an uninsulated test wall, the threaded rods reach maximum temperatures of between 250-280 °C at 12-15 minutes after ig nition. The rod fitted with a steel handle has a much larger thermal mass and thus reads a consistently lower temperature and takes longer to reach a peak temperature of 225°C at approximately 18 minutes after ignition. When insulated, the temperatures on the unexposed side of these rods reach only between 50-75 °C at 15 minutes after ignition. Given that the only exposed portion of the bolt in the fire compartment after the insulation is mounted is approximately 25 mm (1 inch) of length extending out past the insulation, these results are consistent with expectation.

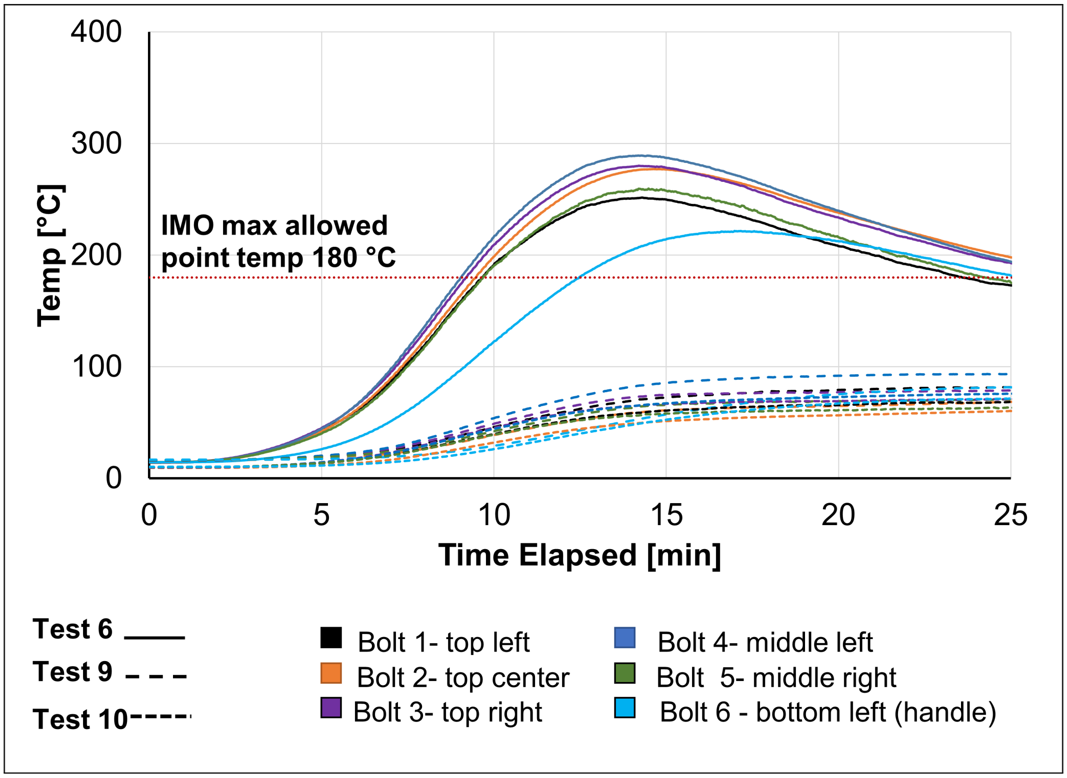


Figure 4.48: Door securing bolts temperature monitoring point results

For the A-15 wall insulation configuration, the steel rods were at a distinctly higher temperature, 50-75 °C, than the surrounding surface of the unexposed side of the insulated steel wall plate at 15 minutes after ignition. Therefore, they show up as hotter spots than other surfaces on the IR images taken by the TIC and shown in Figure 4.49, which includes the measured values from the IR images for reference, which correspond to within 1-2 °C of the temperatures measured by the thermocouples at that location. The measured temperatures are still well below the stiffener temperatures of 125-150°C and as such do not provide as marked an indication of fire conditions on the other side of walls insulated to A-15 specification. For A-30 and higher insulation configurations, however, where the stiffeners would be insulated, these may be more relevant locations to check, but additional test data (either experimental or calculated) would be required to verify impacts of the higher insulation on heat transfer through the rods and thus, how feasible that may be.

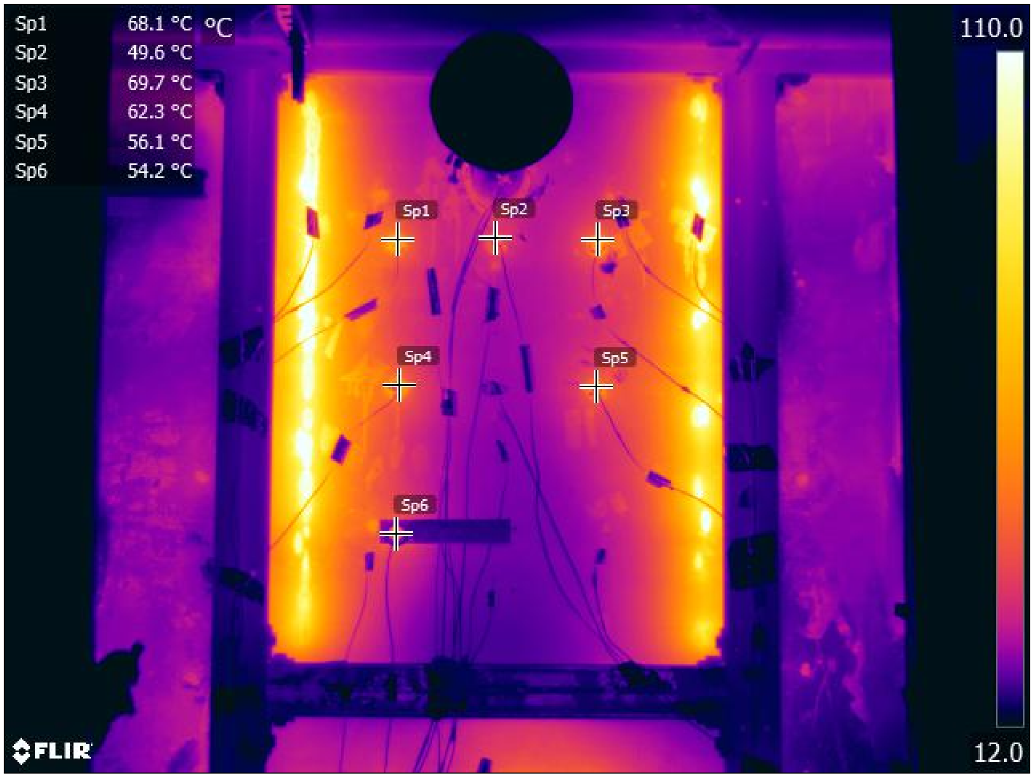


Figure 4.49: Test 10: IR image at 15 minutes, $\epsilon = 0.85$, 6 additional monitoring points

Further, heat shorts of the types considered above are highly dependent on how the door is constructed. For example, some hatches may have a single hand wheel with a central cylinder which may perform a similar function as the rods used in the present investigation. In general, heat transfer through door penetrations will depend on whether there is a continuous piece of steel (or other metal) that fully penetrates the insulation on the exposed side and also passes fully through the door to the unexposed side. Thus, details of hatch and wall construction will govern whether there will be useful points to check for heat shorts during the door entry procedures for insulated bulkheads.

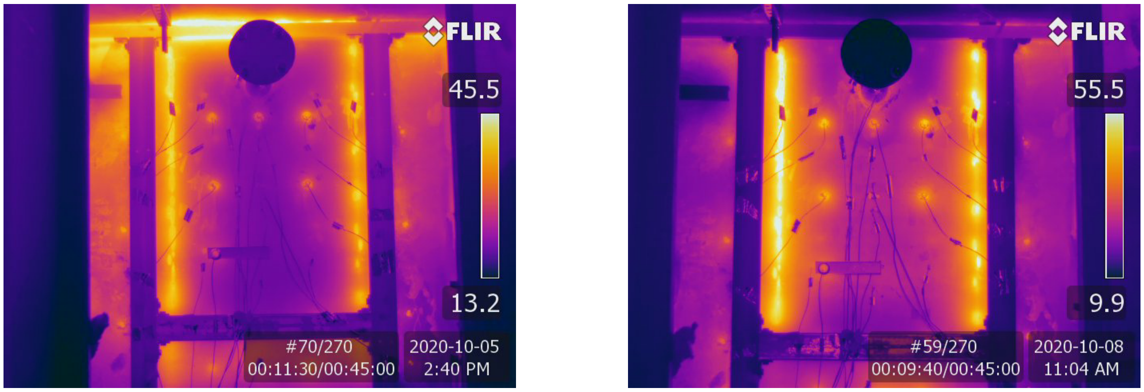
As demonstrated, there are various points that, while not providing a direct indication of the fire temperatures on the exposed side of a steel bulkhead may, in the case of fire rated division, give some indication that there is a nearby fire. Thus, these points will still be useful as 'tell tales' to use as warning signs to exercise additional caution when opening the door.

4.7 Comparison of the experimental results to a real ship fire

While this work is intended to take an insulation material that has passed the standard IMO certification method, install it onto a wall assembly that is more representative of a real bulkhead and perform fire testing to assess thermal response of that assembly, it is certainly important to note several differences between the test wall configuration used in the present research and a standard installation procedure that might be found on board a naval vessel.

One key difference is that the insulation used in the present research had no facing material. Typically, an aluminium or fibreglass facing would be installed on board a vessel. While this would not be expected to change the overall thermal performance of the insulation or the general heat conduction paths via uncovered metal attachments on the fire side, this would significantly change the fire scenario itself. Thus, the more common situation of insulation under false ceilings or wall panels also requires analysis and possibly specifically designed fire test scenarios to determine how these would affect heat transfer and smoke movement. Over the longer term this is necessary to allow interpretation of results via comparison of different installation contexts in tests versus those on the ship in question.

On a typical ship construction, the vertical stiffeners would run the full length of the wall, and would connect to the structure at both the floor and ceiling. In the test wall assembly used in the present research, the stiffeners only extended along the plate section, and further, ended short of the edges to avoid interference with the test wall mounting arrangement. Because insulation is installed flush to a stiffener, this resulted in a gap above and below the stiffener in the test configuration that would not be there onboard a vessel. Although the gap is insulated as well as practicable, it may have resulted in additional heat exposure and thus heat conduction along portions of the metal stiffener that normally would not be exposed. Therefore the temperature measured at the stiffeners may be higher than would be seen in a real construction.



(a) Test 8 Thermal image at 10 min showing heat leakage around top of test specimen frame

(b) Test 10 Thermal image at 10 min with heat leakage addressed

Figure 4.50: Thermal images showing some minor heat leakage in Test 8 compared to Test 10

Additionally, it is noted from the IR images that in many of the tests heat leakage is observed around the top of the insulated portion of the test wall, specifically from locations between the installed mineral wool insulation and the existing front face of the ceramic insulation and cement board panel that is fitted onto the wall mount that holds the test specimen. This is corrected for the final test, via minor adjustments during the installation process in which the insulation is cut to approximately 3mm over the height measurement to ensure a tight fit. The contrast in the IR images before and after this adjustment is made is shown in Figure 4.50. While it is thought that these minor gaps in the insulation were a sufficient distance away from the main test wall that they did not affect the key points of interest excessively, they do show up as high temperature areas in the IR images that would not exist with a fully welded, continuous steel bulkhead. These details are generally not visible in IR images of thermal transfer through non-insulated wall sections, for example Tests 5 and 6, due to the significantly higher surface temperatures throughout the unexposed side of the wall, but do appear as the hottest points once the wall is insulated. While these kind of gaps would not exist in certification testing, as time and effort would be taken to ensure optimal installation of the insulation for testing, gaps such as this may occur on a ship, and thus aid in identification of fire events, where installation is over a more complicated structure and series of penetrations and would frequently involve mounting in areas with poor access around a number of interference items.

Of note in Figure 4.50b, on the side panels made out of 10 gauge steel (3.416 mm thick) the connection points where the 3mm steel pins are welded show up in the IR images as warm spots, which are not visible on the thicker 4.5mm plate in the navy bulkhead test specimen. This may be due to a number of factors, which may include some porosity in the weld in the thicker plate, as the plate thickness is at the limit of the rating for the flux core wire feed welder used. In general, however, very little of the 3mm mounting pin is exposed, so these are not expected to result in significant heat shorts, and in any case, the relative degree of local heating at the attachment point will also decrease as the plate thickness and, thus, thermal mass of the entire bulkhead increases.

Finally, in a real ship fire, the steel surfaces would all be coated using an enamel paint system to minimize corrosion of the steel during operation. The paint coating itself is required to pass a series of IMO FTP requirements, which include limits on flame spread rates, smoke production and toxicity, but the paint is still subject to thermal degradation and will also be combustible when heated to a sufficiently high temperature. The impact of this on fire evolution, particularly when applied in combination with insulation on the steel walls, is currently not known. Therefore, results of some initial bench testing conducted in attempts to better understand this are described in more detail below. A more realistic experimental setup might include the paint coating on the test wall to determine how that affects the fire scenario, as well as the generation of smoke and toxic byproducts on the unexposed side. While not possible here due to the many unknowns associated with possible hazards of such testing, it may be a valuable line of inquiry for future work that builds on the present research.

Based on the combined results presented above, it is clear that prior to making any significant changes to fire response tactics due to the new requirements for installation of insulation on the bulkheads, several considerations are important. In terms of the insulation acting as the anticipated fire barrier, it would be prudent to ensure that proper quality control inspections are in place during the installation of the insulation fire barriers and also to understand what kind of tolerances are appropriate for gaps in insulation and other issues that might affect coverage. Installation integrity and gaps may also be important in terms of use of IR images of insulated bulkheads for fire response decisions, although in this case, it is critical to understand the installation, heat shorts and potential gapping of insulation in order to interpret information from IR images of the unexposed side of an insulated bulkhead in terms of the potential fire development in a compartment on the other side. Additionally, if any tactics are adapted, it should be understood that the changes are only valid when a fire barrier is installed and maintained, so for example, during maintenance periods where insulation may be removed, the removal would have to be tracked and tactical response adjusted accordingly for that period.

The large scale testing conducted above involves fire exposure on a steel test wall that is not coated with IMO certified paint as would be the case on an in-service naval vessel. To further study the impact of the paint on overall fire indicators on board, a final small-scale experimental portion of the thesis is conducted and key results are outlined and discussed in the section below.

4.8 Small scale test results

In this section, results of the series of instrumented smoke density and cone calorimeter test results are presented and discussed. These were conducted to gain additional insight into how installed fire barrier insulation might interact with painted steel surfaces. In particular, it was of interest to conduct some preliminary experiments to determine temperatures at which the paint will exhibit visual cues of heat exposure and begin to generate smoke and compare these to measured temperatures on the unexposed surfaces as determined in the large scale testing. Also of interest, was to begin to understand how accumulation of paint over the life of the ship might change the fire properties of the coating and thereby contribute to, and potentially exacerbate, a fire situation. As well as the increased understanding of fire risk on board naval vessels, these results may also be used in future modeling of shipboard fires and to modify the experimental design in this work to safely include paint in the insulated test wall experiments.

4.8.1 Smoke density chamber testing

Smoke density chamber testing was conducted on standard steel specimens coated to varying degrees with marine paint to study how the buildup of multiple layers of paint over the life of the ship will affect the generation of smoke by the paint coating. When combined with the heat release rate data obtained from cone calorimeter testing and discussed below, this will give some experimental data to determine if the presence of the paint coating on a steel bulkhead will significantly affect the fire scenario, as the walls, ceiling and other steel surfaces will all be coated in service.

RCN paint coating experts were consulted and provided a target thickness of approximately 18 mils (457 microns) as a representative dry film coating thickness on the interior a 30 year old ship, based on their extensive experience as to what is frequently seen when measurements of coating thickness are taken. This represents the initial coating of primer and top coat, plus additional re-coats every 5 years, with some variability based on the method of application, skill of the painter and level of associated quality control checks. In accordance with the manufacturer's instructions included in table 3.5, the initial coat of primer and paint should measure between 3.1 and 5.6 mils (78-142 microns) , with an additional 1.6-2 mils (40-50 microns) for each additional coat. So the target thickness of 18 microns corresponds to the initial coat with an additional 5-6 coats, which is consistent with the re-application frequency expected on and RCN ship over 30 years of service life.

For the smoke density chamber testing, a sample is prepared on one of the standard 12 gauge (2.5mm thick) 100 mm x 100 mm coupons made for this purpose, with the weight and dry film thickness recorded as per table 4.4. The coupon is weighed at each stage of the coating process, so the mass of the primer and paint on the substrate is known. These values can be used in combination to account for normal variations in paint application when analysing the results and the contribution of each against test parameters. The table also includes the paint coating thickness measurements taken at each of the 4 corners (designated C1 through C4 respectively) as well as the measurement at the center of the test coupon after application of the primer, as well as after the multi-layers of topcoat are applied. Although the average coating thickness is approximately 12 mils, the thickest reading, measured at corner 3, is near the target thickness, so the coupon is used for the preliminary test.

Table 4.4: Smoke Density Test Painted Coupon Dry Film Thickness Measurements [mils] with multiple coats of the Top coat to simulate 30 years of paint accumulation

Description	Mass [g]	C1	C2	C3	C4	Ctr	Avg	SD
Steel Coupon	230.27	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Primer	232.72	3.232	6.890	2.900	2.784	2.385	3.638	1.843
topcoat (multi layer)	236.22	8.220	8.517	17.637	10.537	12.890	11.560	3.878
After testing	233.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Under the IMO FTP, three smoke density chamber tests with a duration of 20 minutes each are normally performed as part of the certification:

- irradiance of 25 kW\m^2 in the presence of a pilot flame
- irradiance of 25 kW\m^2 with no a pilot flame
- irradiance of 50 kW\m^2 with no pilot flame

It is further specified that the maximum measured optical density (Ds_{max}) shall not exceed 200 for any of the three tests, with additional testing required for the toxicity of the gas products and the surface flammability required for the certification.

Only the smoke density chamber was available for this preliminary testing, so it was run in a mode compliant with the ISO 5659-2 test protocol for testing of smoke density of plastics as required under the IMO FTP. The irradiance set to 50 kW\m^2 and no pilot flame used to mimic the most severe exposure specified amongst the three tests above.

A plot of the variations of measured optical smoke density versus time are shown in Figure 4.51. The smoke density initially increases and reaches a peak smoke density reading of 319 at t= 289 seconds after initial exposure to the radiant flux. This level is well above the limit of 200 specified in the certification standard. It is also an expected result since the certification testing is done using only a single application of coating, and this sample had the equivalent of 25-30 years of paint accumulation with multiple layers of the top coat applied. Thus, in a real fire situation it is of import that the smoke density from multiple years of paint accumulation could results in smoke generation that is likely to surpass the original IMO specified safety limit.

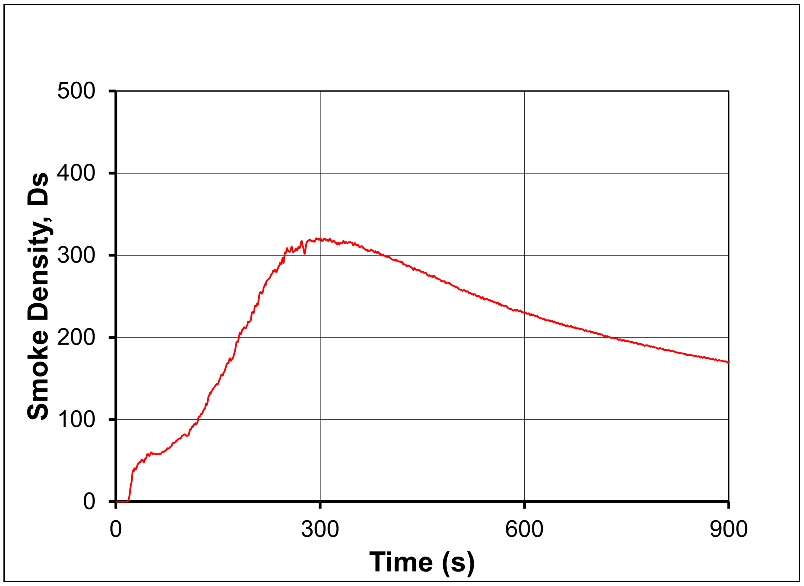


Figure 4.51: Smoke Density chamber test results for the sample with 25 - 30 years of simulated paint accumulation

Unfortunately, timing and COVID delays precluded further smoke density testing under this research. Based on this preliminary result, further experiments are recommended to compare the impact of paint coating thickness on Ds_{max}. The testing should include repeat testing to generate baseline results for the initial paint coating application along with additional testing on intermediate target thicknesses to build a data set from which to perform potential trend analysis.

Successful results would allow correction for the impact of the build up of paint to be included in analysis of the compartment fire risks over the life of a vessel. In the context of this thesis, that would also apply to the potential for smoke generation in adjacent watertight compartments, which would affect both the visibility and the tenability in those areas. In more general terms, results would also be relevant for estimation and verification of models related to smoke generation inside fire compartments on board naval vessels.

4.8.2 Cone Calorimeter testing results

Two separate preliminary experiments using painted steel coupons are run on the cone calorimeter to begin to determine the decomposition temperatures, ignition and potential heat release characteristics of marine coatings. For these, one test is conducted with the paint coating directly exposed to the incident heat flux from the cone calorimeter heating element. The second set involves testing of samples under two insulation scenarios: one with insulation on the unexposed side of the test coupon and the other with insulation exposed to the incident heat flux, as shown in Figure 3.26 and Figure 3.28.

In the first test with the paint coating directly exposed, key pieces of information are collected including estimates of the amount of heat released, the effective heat of combustion, and the carbon monoxide and smoke production rates. This data is primarily for assessing the potential contributions of paint coatings to the overall fire scenario in a compartment if all the paint is to be involved. These would include indicators of the additional energy anticipated from burning paint, as well as potential impact of the paint on visibility and tenability in the fire compartment, and spread to adjacent connecting compartments, during both thermal decomposition and burning phases.

The second set of experiments that include the insulation are designed to assess the impact of the paint coating in an adjacent compartment when the steel separating bulkhead is fire protected with insulation. When the insulation is installed on the fire compartment side, the steel structure will not be directly exposed to the fire, so this scenario duplicates the large scale experiment in terms of what would be anticipated if the experiment was run with the back steel test wall coated with paint. The other configuration has the insulation on the unexposed side, so the painted steel structure will be fully exposed to heat from the fire and the insulation will prevent direct heat transfer from the fire room into the adjacent compartment. This scenario with an uncoated steel test wall is not examined in the large scale experiments in this thesis due to time limitations. It would have resulted in the insulation installed on the transition compartment side, with the steel exposed in the fire compartment. Since it might be of interest to run additional tests to study this configuration in future, from experimental design and safety standpoints it is important to anticipate the contribution of any paint coating to the test fire situation - information which can begin to be obtained from the small scale testing conducted here.

So while the fire division itself is effective in either scenario in preventing the transfer of heat into adjacent compartments, it may mean that the paint on the structure underneath the fire insulation in the adjacent compartment may still generate smoke, and possibly ignite if the temperatures between the steel and insulation are sufficient.

The combination of these two bench tests is intended to provide some insight into what conditions may be seen during a fire in a ship in real world conditions, and how that may impact the fire fighting tactics. Because this also includes smoke management, understanding the contribution of paint, and how that changes over the life of the vessel as additional layers are added gives additional insight into the significance, and thus need, for inclusion of paint coatings in future fire risk analysis may be, or at least, a better understanding whether excluding the accumulation of paint introduces a significant source of error into the decision making process.

Sample with RCN paint coating

The first cone calorimeter test involves investigation of the response of a painted steel coupon to an external incident heat flux. The coated paint coupon is prepared as per the previously described procedure, with the mass at each stage of coating and the dry film thicknesses recorded in table 4.5. For consistency with testing undertaken in the smoke density chamber, the same average dry film thickness is used as the target, with this test sample having an average DFT of 11.491 mils (368 microns). Based on the manufacturer's instructions and the frequency of RCN paint routines, this average thickness corresponds to approximately 15-20 years of accumulated paint thickness.

Table 4.5: Cone calorimeter exposed coating; test coupon mass and DFT measurements

Description	Mass [g]	C1	C2	C3	C4	Ctr	Avg	SD
Steel Coupon	249	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Primer	251	2.912	3.864	2.562	1.953	2.802	2.819	0.692
topcoat (multi layer)	256	9.870	11.970	8.163	12.873	14.580	11.491	2.519
After testing	252	N/A	N/A	N/A	N/A	N/A	N/A	N/A

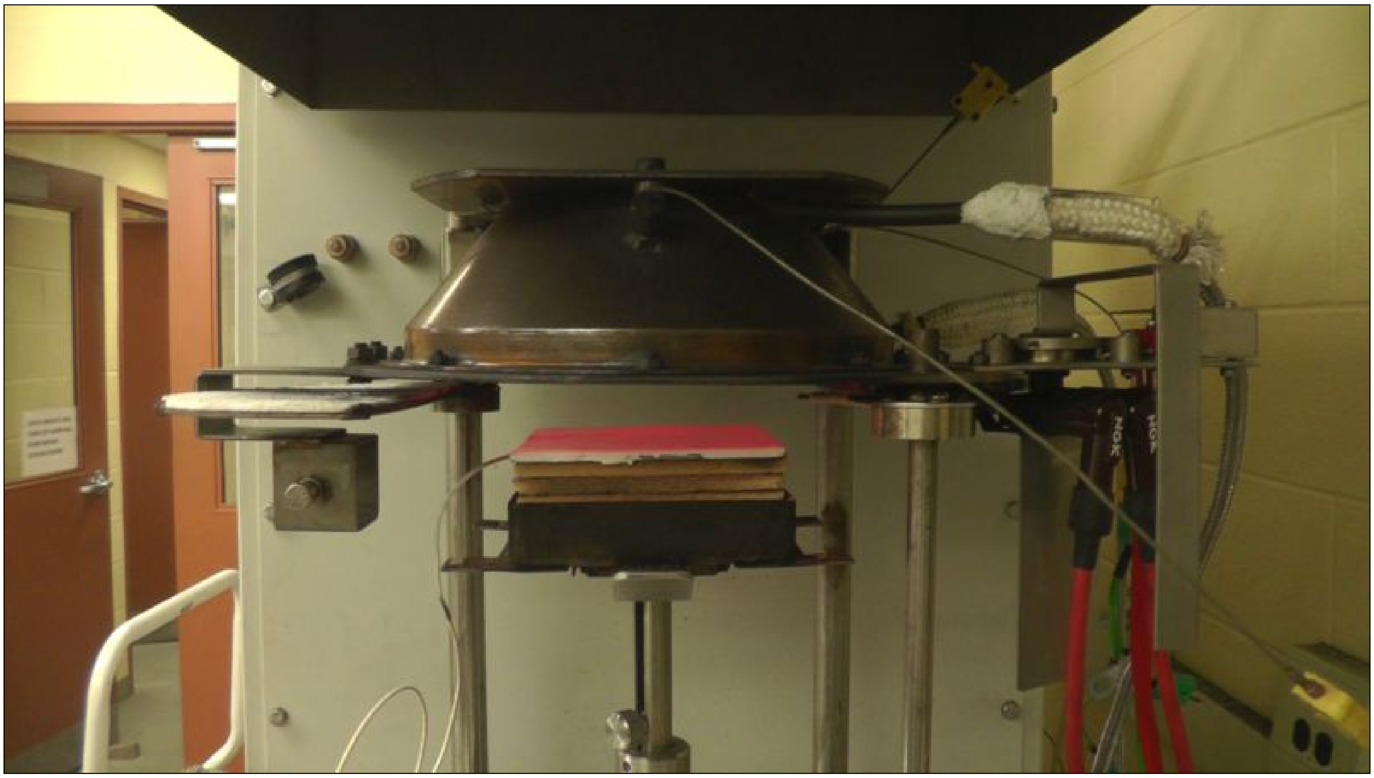


Figure 4.52: Cone calorimeter exposed coating; average DFT of 11.5 mils, 50 kW\m^2 exposure

In addition to the standard data set that is collected during cone calorimeter testing, this experimental setup includes a thermocouple installed on the coupon surface at the center of the unexposed side to monitor the sample temperature and allow an approximation for the surface temperature at key points in the heating process. The experiment runs for a duration of 340 s, with the HRR results shown in Figure 4.53 and the CO and smoke production rates in Figure 4.54.

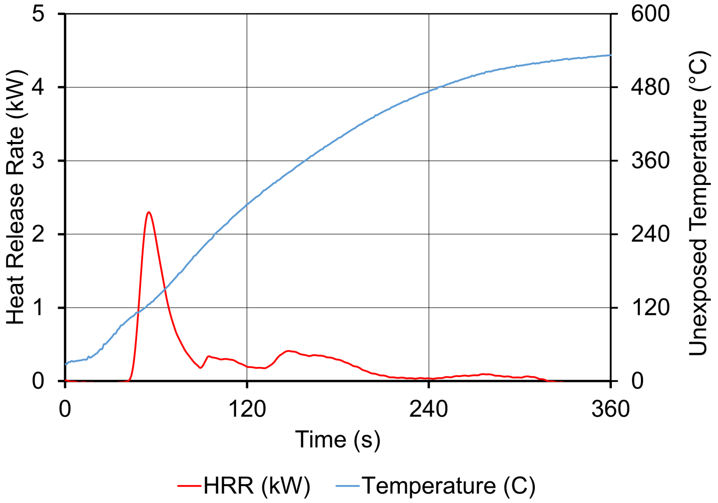


Figure 4.53: Cone calorimeter exposed coating; HRR and unexposed surface temp

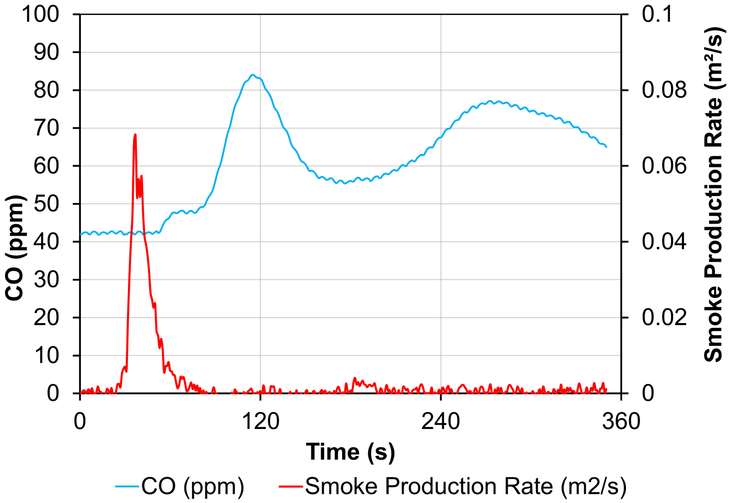
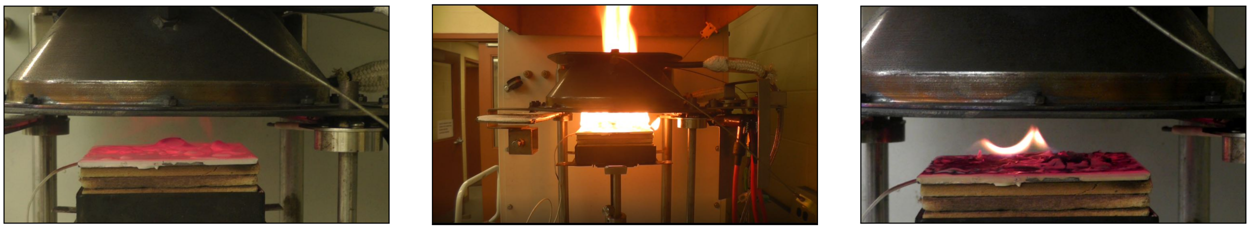


Figure 4.54: Cone calorimeter exposed coating; CO concentration and smoke production rates

After exposure to the incident heat flux, the paint coating begins to off-gas and blister, with Figure 4.55a showing the condition of the sample surface immediately prior to ignition at the t=30 s after exposure. The flame quickly grows to involve the entire surface (shown in Figure 4.55b reaching a significant flame height for approximately 30 seconds after ignition. The flame then continues to decrease in height until flame out occurs at t=184 s. The overall progression is demonstrated in Figure 4.55, and follows a timeline that is consistent with the measured heat release rate data. The peak smoke production rate occurs during the period of peak heat release rate when the full sample surface is involved, with CO production rates peaking as the flame begins to burn out and smolder on the edges, then increases again for a period after flame-out.



(a) Cone calorimeter exposed coating; paint coating blistering at t=29 s

(b) Cone calorimeter exposed coating; complete involvement at= 35 s

(c) Cone calorimeter exposed coating; reduced flame at t=90 s

Figure 4.55: Cone calorimeter exposed coating; ignition and burning over 90 s

No mass loss from the sample is seen until the unexposed surface temperature reaches 70 °C, which is also consistent with the time evolution of the measured smoke production rates in this test and in the previous smoke density chamber testing.

The peak heat release rate for this preliminary test involving a 10 - 15 year accumulation of paint is measured at 2.3 kW from a painted sample area of 0.01 m^2, with a short growth and decay period (due to the small amount of available fuel) . If this result is consistent over a larger area, this translates to a peak heat release rate of 230 kW/m^2. For context, a compartment that measured 3m in length, 3 m in width and a 2.5 m ceiling (approximately 10 feet x 10 feet x 8 feet) with painted walls and ceiling would have a total coated surface area of approximately 39 m^2 (with additional coated surface area on structural elements), which would give a peak heat release rate of 8970 kW from the ceiling, if the result scales up linearly with the surface area involved. If accurate, this could potentially result in an extremely intense (but brief) fire if all the paint were to be involved at the same time, so by this could potentially be a significant issue that is not typically considered during fire risk assessments of compartments.

With a total measured heat release of 84.4 kJ and a measured mass loss of 2.18 g (out of approximately 6 g of primer and multiple topcoat layers), this particular experiment gives an effective heat of combustion of 38.72 MJ/kg. Further experimentation is recommended to validate the results, compare against samples tested with the baseline coating thickness typical of the initial coating application, and investigate other variables, but this is a useful preliminary result that appears to justify some additional work.

Specifically, these preliminary results suggest that the contribution from paint coatings in a real ship fire may be non-trivial, so the inclusion of these coatings is important to understanding both how they affect fire conditions, as well as their possible impacts on conditions in adjacent compartments. As this coating thickness represents a build up of paint over time, and the heat release rate, flame spread rate and other factors may also vary depending on the sample orientation, coating thickness and other variables, further testing is recommended. This should include testing at the baseline initial coat thickness, as well as sufficient samples representing different amounts of coating accumulation over time for trend analysis.

In scaling results up to a full compartment situation, it is understood that the actual fire temperature, heat flux and surface temperature would vary greatly, but as the full scale experiments reached ceiling temperature in the fire compartment above 600 °C, with the hot gas layer varying between 400-500 °C the potential for the paint coating to contribute to the fire scenario are significant, and may also be an important factor when looking at variables such as visibility and tenability in the fire compartment, as well as various aspects of tactical response and smoke management practices.

Painted coupon with 50 mm of IMO A-15 insulation

This test is intended to assess how the location of the insulation relative to the fire impacts the thermal response of a paint coated surface. In the full scale testing, the Navy test wall specimen is designed to be reversible to facilitate testing of wall configurations with insulation on either side, but due to time limitations, only scenario 2, where the insulation is directly exposed to the fire is completed. Scenario 2 was chosen as the large scale test configuration since it is a more challenging test for the insulation which experiences direct flame impingement and higher incident heat fluxes in this situation. But it means that the insulation is between the fire and the steel structure, so the steel structure itself is not exposed to the fire temperatures.

To conduct some preliminary investigations on the configuration outlined for scenario 1, where the insulation would be on the unexposed side of the coated steel wall, a small scale test method is developed. The cone calorimeter, set to the same 50 kW\m^2 incident heat flux, is used to heat a steel coupon painted with the same process described above, and with the coupon placed onto a layer of insulation in the final configuration shown schematically in Figure 4.56. The key difference between this test and the previous one is that the paint is on the unexposed surface between the steel coupon and the insulation below. Thermocouples are again positioned to measure the heat propagation over time through the composite sample via temperatures at the painted, unexposed surface steel as well as a point midway through the 50 mm thickness of the Rockwoll SeaROX 620 SL insulation.

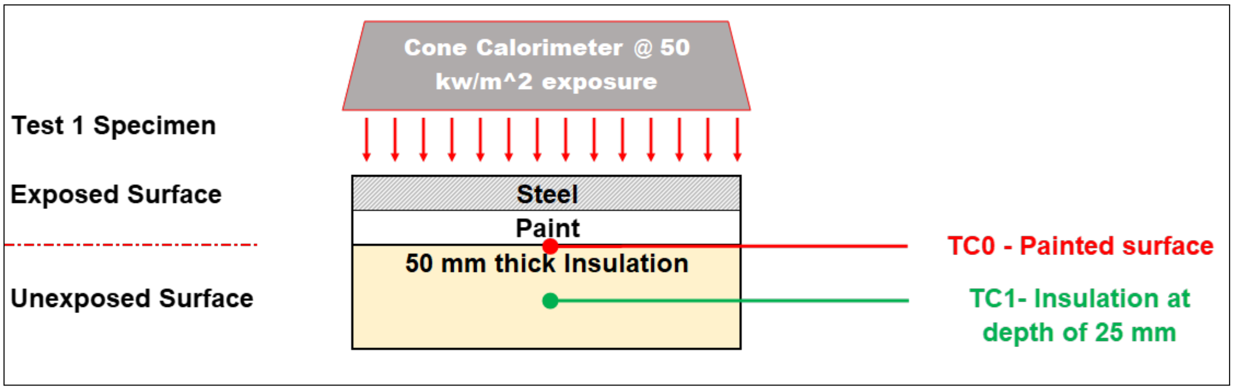


Figure 4.56: Insulated cone test - scenario 1 schematic

The paint coating for this test was thinner than for the previous tests, and is meant to represent the initial application (vice a build up of paint over 20 years of recoats). It consisted of 3.65 mils (92 microns) of primer and 4.07 mils (103 microns) of top coat, so direct comparison to the previous preliminary tests that used thicker average coatings is not possible. Nonetheless, all of the small-scale tests are still useful to quantify the general behaviour and impact of including paint coatings in insulated fire barrier testing.

The time-varying temperature profile through the composite test specimen is shown in Figure 4.58 which includes annotations for time estimates obtained through video review for the onset of blisters in the paint, the ignition point and flame-out. Compared to previous results, the surface temperature, approximately 220 °C, where blistering is seen is significantly higher than the previous temperature of 70°C where off gassing is observed, but since the painted surface of the sample is under the exposed surface of the specimen, this could be an overestimate since is determined as the temperature corresponding to the time when smoke is visible at the perimeter of the sample. Ignition in this case was delayed as well, as it did not occur until 183 seconds after exposure of the sample to the incident flux, with flame-out at 257 seconds. Further experimentation is recommended to investigate possible interactions and variables contributing to these delayed times, but as the paint would not experience the same exposure conditions and also is not in a path of free air flow, it is logically consistent that it would be more difficult to ignite paint that is applied on the unexposed side and thus located under the steel specimen on the insulation.

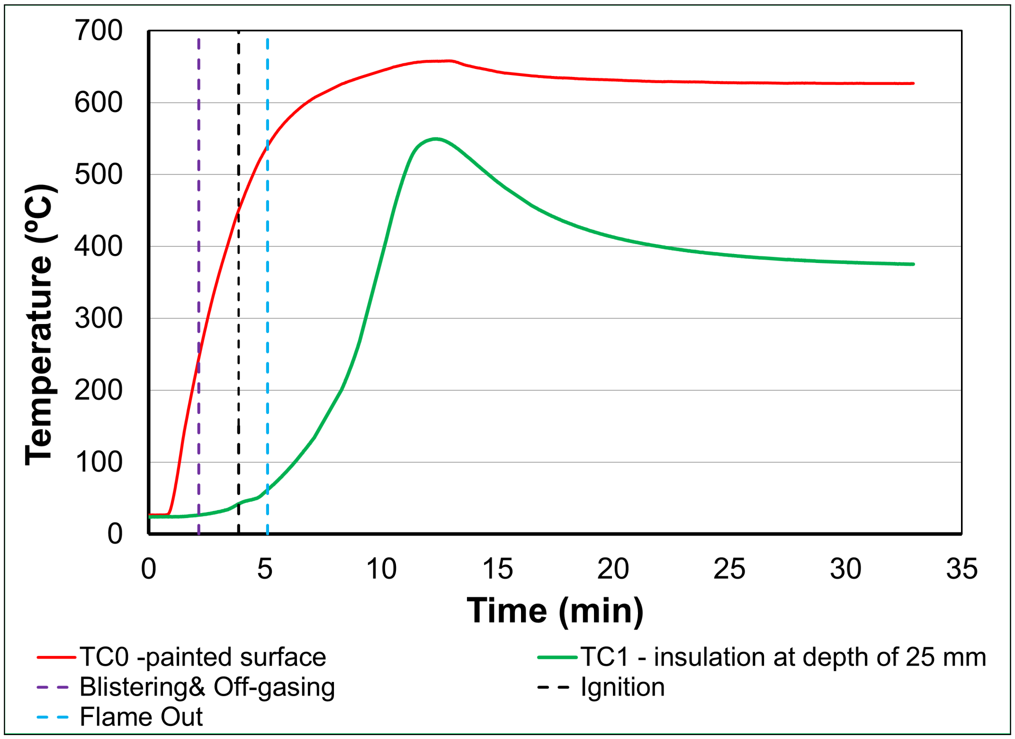


Figure 4.57: Cone calorimeter scenario 1: temperature profile

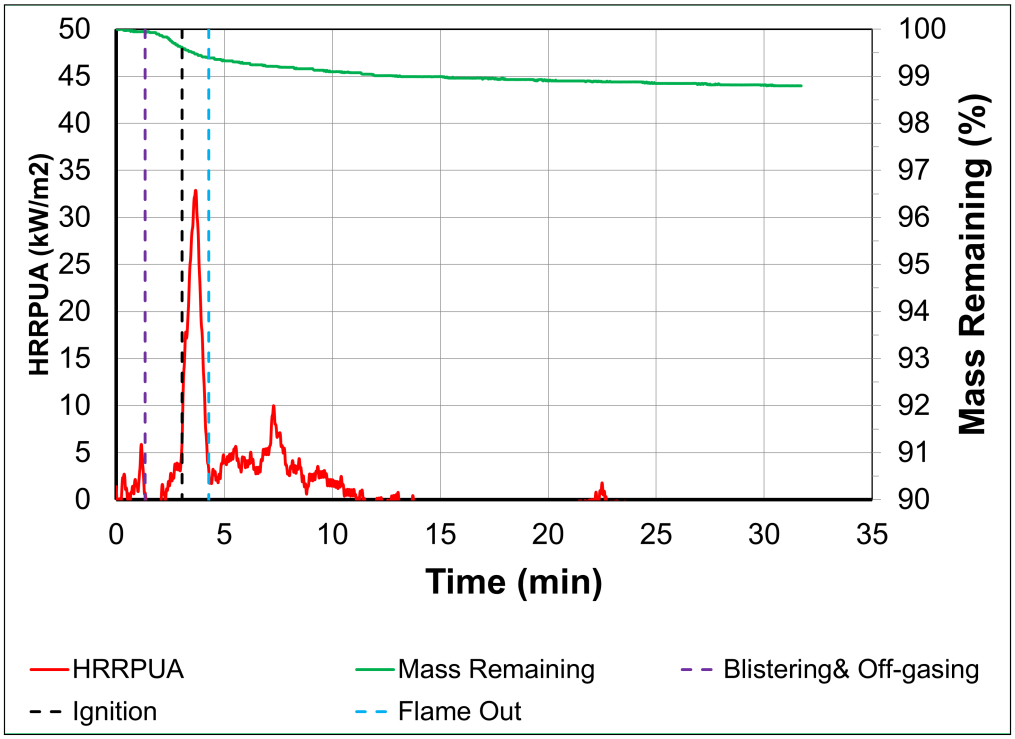


Figure 4.58: Cone calorimeter scenario 1: HRR and mass loss rate

The ignition point for the paint is difficult to determine in this experiment because the sides of the sample holder are open and the sample is located under the cone heater. As the paint heats and smoke is produced, unburned pyrolysis products naturally flow up into the cone heater. Because the cone heater can exceed 800 °C, it can act as an ignition source and because of the smoke density (see Figure 4.59a it is difficult to determine what causes ignition. Once ignited, sustained burning occurs until the paint is consumed. Localized burning is also observed at the point where the thermocouple wiring is routed between the steel coupon and the insulation to reach the center of the sample; this is most likely the result of the creation of an air channel along the thermocouple wire pathway, and therefore may also change the ignition/burning behaviour.

Investigation into methods to improve these aspect of the experimental setup are recommended before future testing is undertaken in order to meet the overall intent to assist in scaling these results to full scale, where the pyrolysis products in the smoke will be isolated from the fire compartment by the steel structure, so the most likely ignition source will be the exposed, hot surface of the steel wall.

(a) Cone calorimeter scenario 1: Smoke production prior to ignition

(b) Cone calorimeter scenario 1: sustained burning following ignition

Figure 4.59: Cone calorimeter exposed coating; result overview

For comparison, a test using the scenario 2 configuration (depicted in Figure 3.28) is also conducted. This setup is the same configuration as used in the full scale testing. Because the unexposed surface temperatures at the measuring points on the insulated plate in the full scale testing did not exceed 70 °C, the threshold temperature at which the preliminary cone tests indicated off gassing/smoke production from the paint would occur, it is not expected that there will be any observable effects of heating on the paint during this test. This is the case, with the results shown in Figure 4.60 for the temperature at the middle of the 50 mm thick insulation layer and the steel surface temperature across the duration of heating. Although the surface temperature of the steel eventually exceeds 70 °C and reaches a maximum temperature of 107 °C at t= 2000 s, there are no obvious signs of smoke emanating from the paint along the perimeter during the test. There was no obvious damage to the paint surface, and further study would be required to better quantify the temperature range at which the paint coating shows observable signs of surface damage, such as discolouration or bubbling.

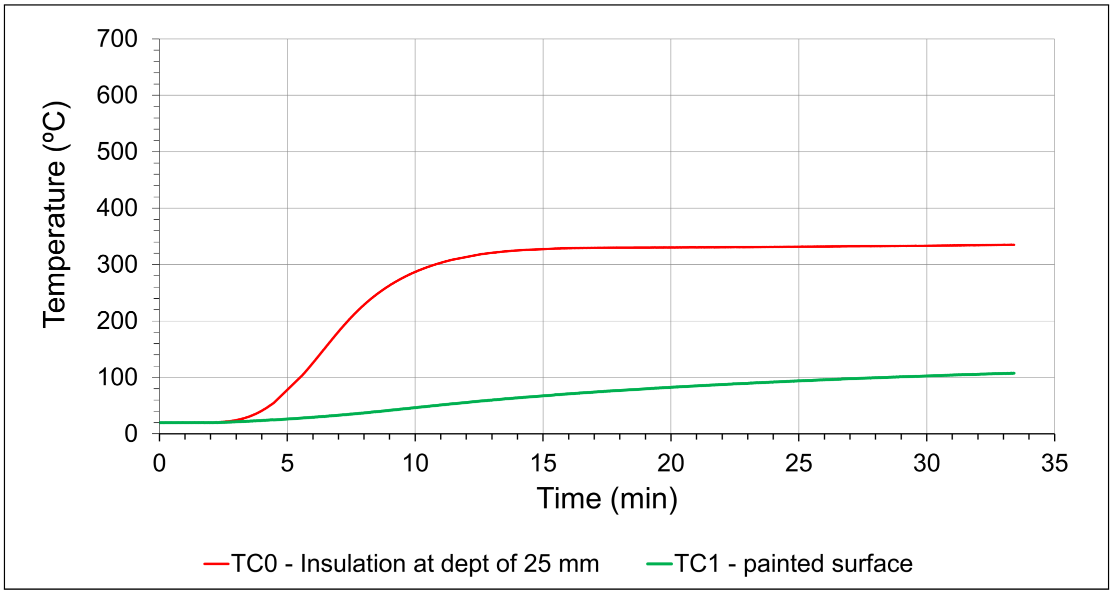


Figure 4.60: Cone calorimeter scenario 2: temperature profile

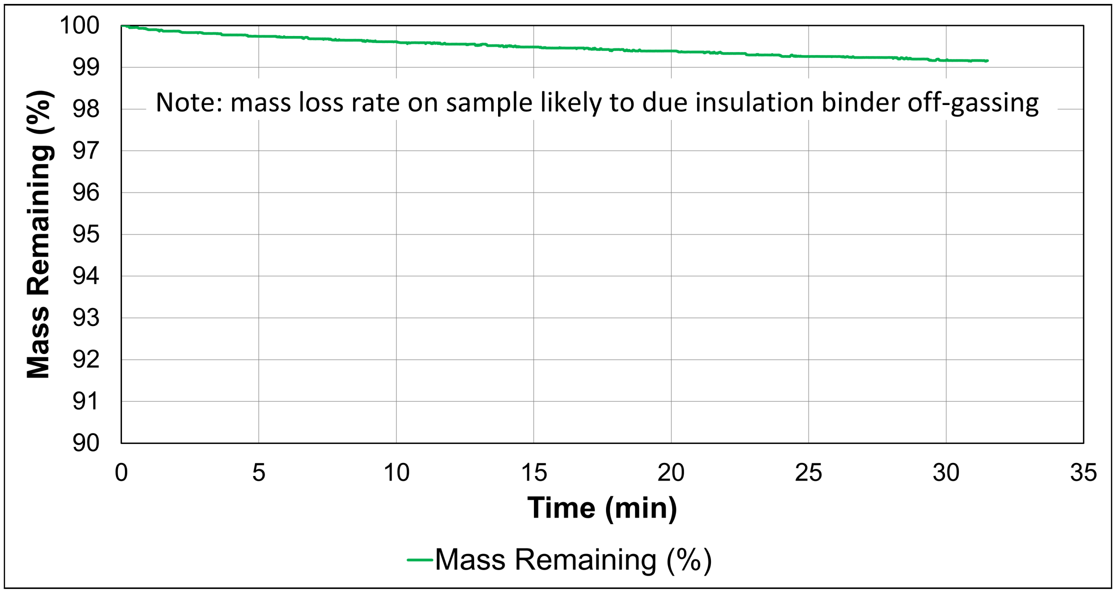


Figure 4.61: Cone calorimeter scenario 2: mass loss rate

Of note, mass loss is recorded for all samples during the cone calorimeter tests. However, care must be taken in interpretation of the results since it is previously shown in [21] that when exposed to higher temperatures, some mass loss is recorded even in mineral wool insulation as the binder begins to break down. This is likely what drives most of the mass loss observed in the scenario 2 test, since there are no visually observable signs of changes in the paint. In scenario 1, where the paint coating burned away, the mass loss is due to the combustion of the paint, although decomposition of the binder in the insulation likely contributed as well. Because both the paint and the binder compositions and formulations are proprietary, the specific contributions cannot be estimated, but could potentially could be measured through additional tests on the paint and for the specific mineral wool insulation following techniques in [21].

Further research on the interaction between the coated steel structure and the insulation mounted in configurations similar to scenario 1 is recommended, as this has direct implications for several facets of shipboard fire response and fire fighting tactics. During the response by both the attack team as well as the rapid response team, there may be indications from the adjacent compartment of smoke underneath the insulation, with possible leakage around any seams in the installation or similar pathways.

From the perspective of determining a fire boundary, the current training includes investigating sources of smoke, in order to cool any smoldering material and remove combustibles from the area to prevent further spread of the fire. It is unknown to what extent smoke may be generated in a scenario where the insulation is installed on the unexposed side of the compartment with the fire, but could potentially lead to the fire boundary attempting to remove the fire insulation while investigating the source of the smoke, or wetting the insulation in an attempt to provide cooling. The risks/benefits to either approach are at present unknown.

Because of the challenges of properly simulating the various insulation, paint and steel configurations with the cone calorimeter, investigations into the impact of paint underneath the insulation in a scenario 1 fire configuration, along with determination of the signs and potential effectiveness of boundary cooling would be good candidates to scale up to larger scale testing in future. Because of the interrelated aspects, both issues could likely also be addressed using the same experimental setup.

Overall the bench scale tests provided useful preliminary data that can be incorporated into reviewing how the fire insulation may impact current RCN fire fighting and decision making processes. Further work would be required to better quantify how painted surfaces on an insulated steel structure will behave when during different fire scenarios, but does provide some key temperature ranges where visual indications such as blistering paint and smoke generation may occur. Combined with the surface temperature measurements taken on the bare steel used in the large scale testing, this data can assist in understanding what visual cues may be available to personnel during different time intervals to assist in decision making. Additionally, because smoke management and containment is an important consideration when fighting fires on a ship, understanding how smoke generation rates may change depending on which side of the fire division the insulation is installed on relative to the fire, particularly when looking at prioritization of assignments when personnel resources are limited.

4.9 Implications for RCN firefighting tactics

This section further investigates temperatures observed in the fire compartment, as well as on the unexposed sides of both uninsulated and insulated walls during the large scale testing. In particular, results are re-examined to define conditions that might be encountered during 4 stages of fire response activities. Conditions encountered during the Rapid Response period (3-6 minutes from ignition) are discussed first, followed by those in the Attack Team Response period (7-14 minutes from ignition), the Fire Boundary Establishment period (approximately 10 minutes and onwards) and finally the Overhaul of the Fire. Tests conducted with the uninsulated wall installed (Test 6) effectively defines the status quo for the temperatures seen on the unexposed side during a compartment fire on which the current response tactics are based on for existing ships. Experimental results for the insulated test walls (Tests 9 and 10) are replotted in this section as they are relevant for response considerations for the new ships currently under construction and soon to be delivered to the RCN since these new ships are fully compliant with IMO requirements for fire insulation.

4.9.1 Rapid Response period (3-6 minutes from ignition)

Temperatures on the unexposed side of the uninsulated wall in Test 6 set reference values for what would be expected during a response for a similar fire scenario onboard current naval ships. A representative sampling of the temperature data on several of the key IMO test points during the RRT time interval is shown in Figure 4.62, which compares both the temperature measured at the upper left bolt, center of the plate and upper left stiffener for both the uninsulated case in test 6 to the IMO A-15 insulated case in test 10. These results clearly demonstrate the effectiveness of insulation in preventing heat transfer to the unexposed side, while also showing that, in an A-15 configuration where the stiffeners are partly exposed, the upper region of where the stiffener connects to the plate structure may be a possible location to use during the checks. The resulting temperatures stay well below the 180 °C temperature threshold allowed in the IMO certification testing [12], and this data provides insight into the actual temperature range that may be expected to be seen during the RRT time interval under similar fire scenario. This kind of data is not provided by the certification testing which simply gives a PASS/FAIL result, so these results provide the context that wasn't previously available, while using a more realistic class A fire growth profile vice the more sever ISO 834 fire curve used in the certification testing.

However, as the stiffeners are insulated in both the A-30 and A-60 configuration this may not apply universally, so further testing would be useful in quantifying this. The bolts, which are intended to represent the door securing arrangements, will likely remain exposed in the A-30 and A-60 configurations, as there are allowances around the door perimeter due to the strength requirements of the components to meet the over pressure requirements for flooding and blast wave situations, so may be a more reliable point to check in all scenarios. Because this will depend on the door hold back construction details, this should be verified against actual design arrangements, which may vary between the warships and non-combatants in the RCN fleet.

As can be seen in Figure 4.62, the insulation results in almost no detectable change in the surface temperature of the plate on the unexposed side, while greatly reducing the increase in the bolts and stiffener connection points. The details are further discussed below using IR imaging to better understand the overall context, but from this representative data set, it is clear that using existing tactics that rely on visual and tactile indications as part of the decision making process to decide if it's safe to open the door to the compartment with a potential fire, the surface temperature can no longer be used as a reliable indicator by the RRT, and the temperatures may not reach the threshold where they are warm or hot to the touch, and, as the surface temperature doesn't exceed the normal maximum operating range of the coatings of 50 °C [4], there will not be any visual indications of damage or off gassing/smoke generation.

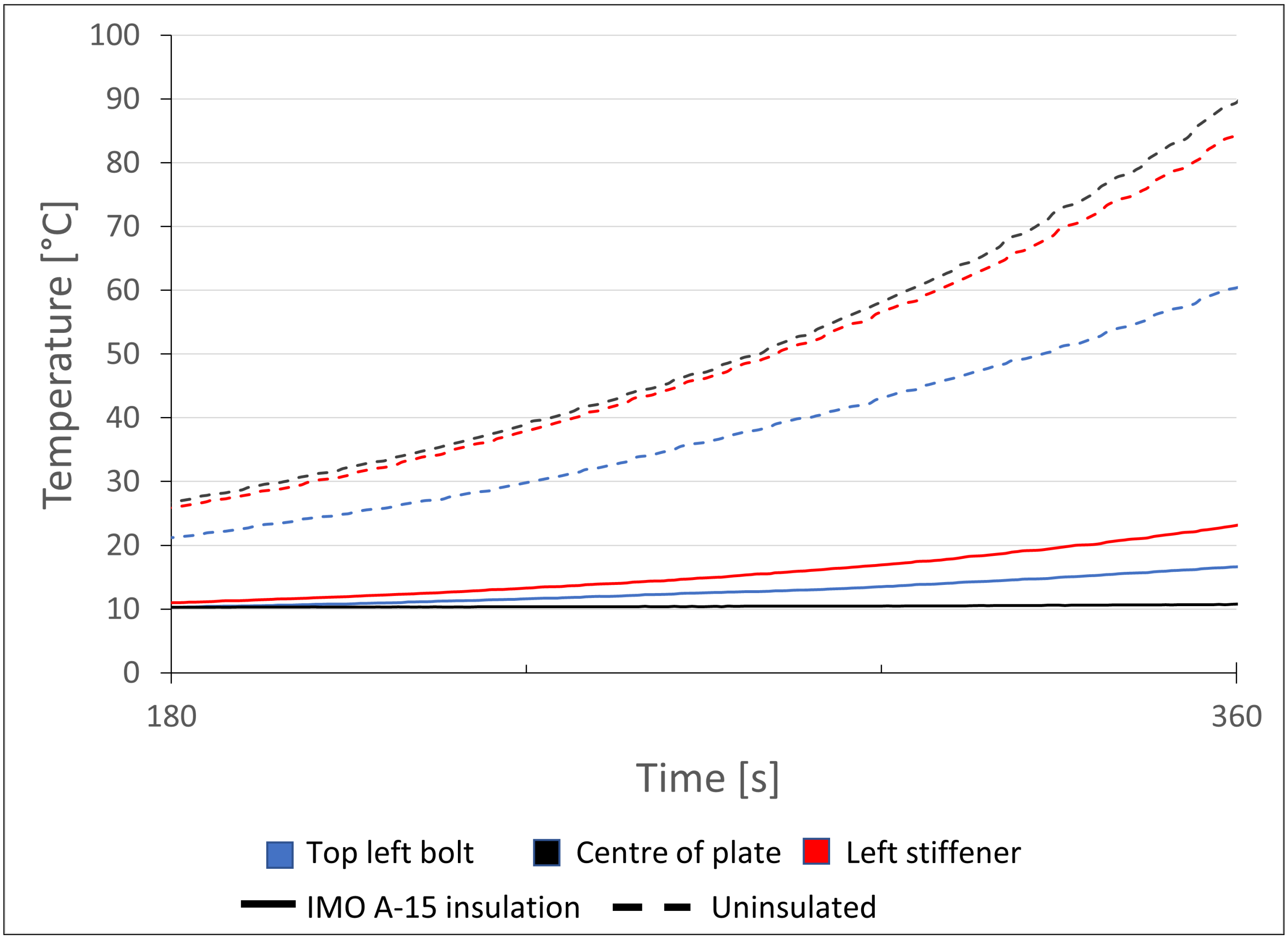
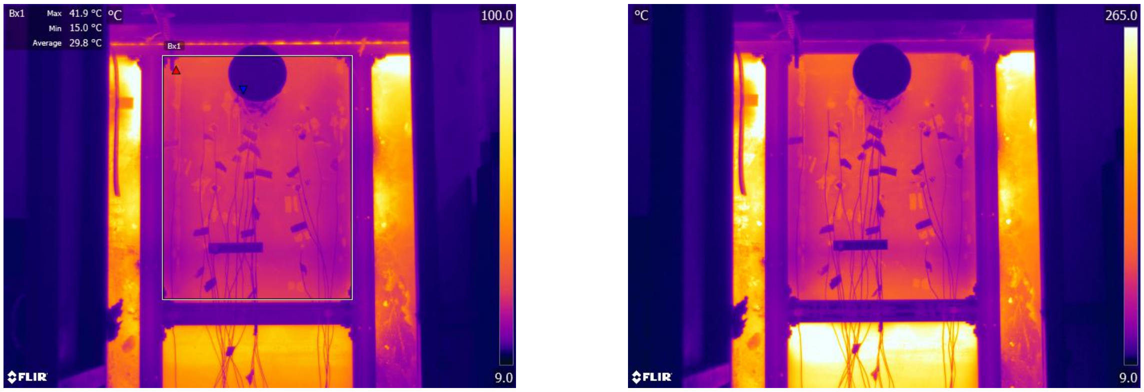


Figure 4.62: Comparison of a representative selection of key measuring points from the uninsulated versus the IMO A-15 insulated tests

When the initial response window opens at 3 minutes, the IR image in Figure 4.63a shows several locations area of interest where the maximum temperature is 42 °C, with an average temperature of approximately 30 °C on the majority of the surface. Therefore, depending on where the personnel performed the checks by feeling the surface temperature, the door would be assessed as either 'warm' or 'hot' using the ASTM C1055 criteria. At this time, the fire is still sufficiently small that it may been safe to attempt first aid with a fire extinguisher. At the six minute mark, which is the latest time interval at which the RRT is expected to respond and begin conducting the door checks, Figure 4.64b shows an average surface temperature on the unexposed side of 98 °C, with a peak temperature of

148 °C in the area of interest. At this point, the surface would be dangerously hot to the touch, and, based on the preliminary results of the small scale testing, personnel would likely also have visual indications on the painted such as off gassing/smoke generation, discolouration and the formation of bubbles on the coating, and provide confirmation that there is a fire in the adjacent compartment. Under current RCN tactics, this would indicate that it is possibly not safe to enter from this location to attempt first aid on the fire with an extinguisher, and also authorize personnel to activate a fitted system for the compartment (if available). Depending on the context, the RRT personnel may decide to attempt entry from an alternate route to attempt first aid, or may decide to confine the compartment (to prevent further spread of the smoke and fire) and allow the fully equipped attack team to attempt to extinguish the fire during the second phase of the response. Whatever the decision, the surface temperature conditions on the unexposed side do provide enough information in terms of visual and tactile feedback to ensure that the RRT can safely make an informed decision and exercise suitable caution, prior to opening the door to the compartment and exposing themselves to potentially unsafe conditions.

These results, which represent the situation on the legacy RCN ships in the current fleet that do not have IMO fire insulation fitted, validate that the current tactics provide a reasonable method of approximating fire conditions in the adjacent compartment using the surface temperatures on the unexposed side. These surface temperatures will give appropriate visual and tactile clues that can be used by the RRT to make appropriate tactical decisions with the available information.

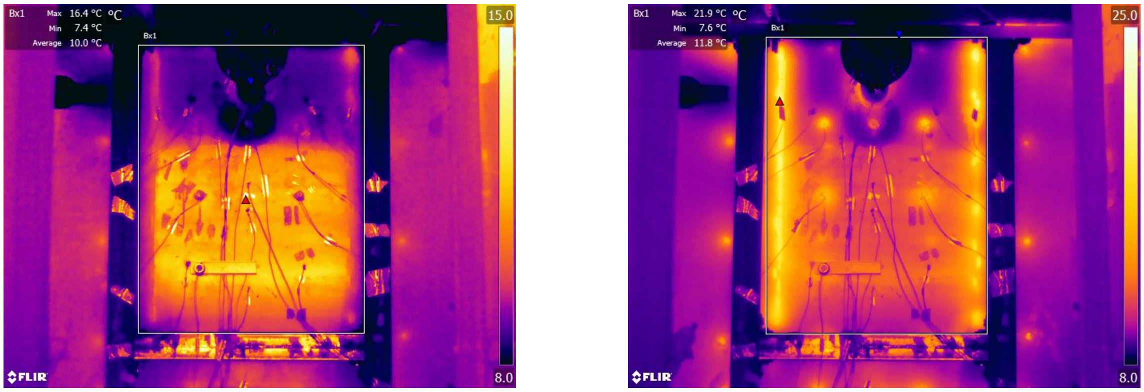


(a) IR image of the unexposed side at 3 minutes of test 6 with no insulation. Max temperature 42 °C in area of interest, with an average temperature of 30 °C

(b) IR image of the unexposed side at 6 minutes of test 6 with no insulation. Max temperature 148 °C in area of interest, with an average temperature of 98 °C

Figure 4.63: IR images of the unexposed side of the test wall during the RRT window with no insulation installed

Figure 4.64 shows the IR images of the unexposed side at the opening and closing of the RRT window for context, with a maximum temperature of approximately 10 °C at three minutes, and 21 °C at six minutes. There is almost no discernible temperature difference on the unexposed side over ambient conditions at the earliest time where the RRT would be responding, and only small temperature changes in the latest time interval where the RRT would be responding. Using the ASTM C1055 guidelines, the door would be assessed as 'cool' to the touch by the RRT, with some areas such as the upper bolts and along the stiffener possibly discernible as slightly warmer to the touch compared to the plate, but still overall 'cool'.

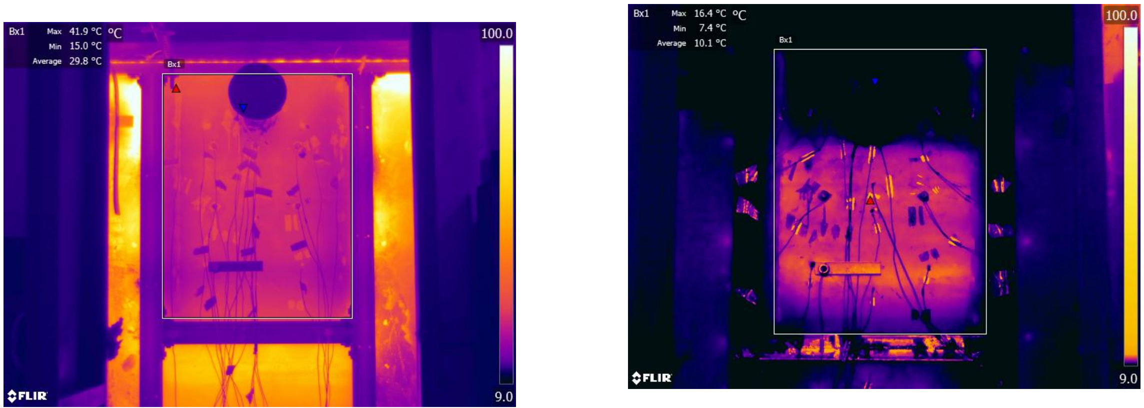


(a) IR image of the unexposed side at 3 minutes of test 10 with IMO A-15 insulation. Max temp 10 °C in area of interest

(b) IR image of the unexposed side at 6 minutes of test 10 with IMO A-15 insulation. Max temp 21 °C in area of interest

Figure 4.64: IR images of the unexposed side of the test wall during the RRT window with IMO A-15 insulation installed

In order to allow a direct comparison of the temperatures on the unexposed side, the IR images from the test 10 had their temperature scales adjusted so that both images have the same colour palette. Figure 4.65 shows the significant difference made by the insulation at the 3 minutes after ignition, with the surface temperatures being effectively ambient temperature.

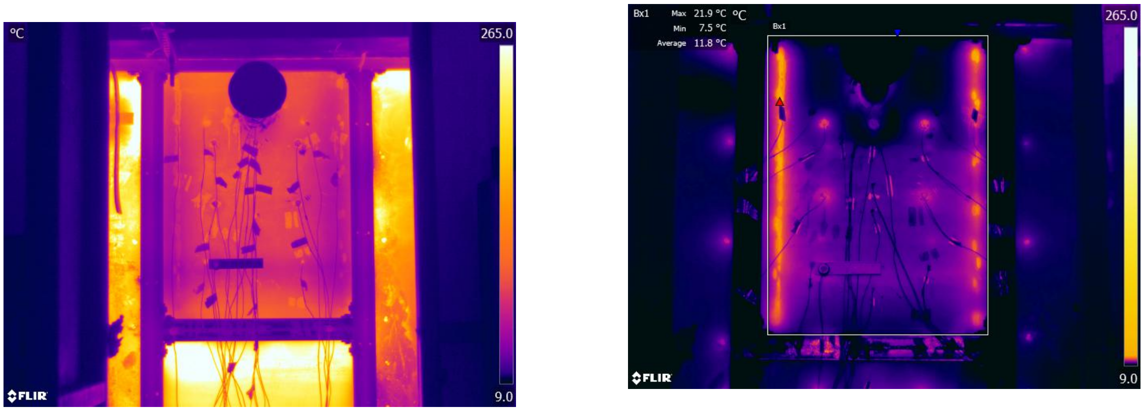


(a) IR image of the unexposed side at 3 minutes of test 6 with no insulation. Average temperature 30 °C

(b) IR image of the unexposed side at 3 minutes of test 10 with IMO A-15 insulation, scale matched to uninsulated test image. Average temperature 10 °C

Figure 4.65: IR images taken at 3 minutes to compare the uninsulated and insulated surface temperatures on the unexposed side at the start of the RRT window

The surface temperatures at the end of the RRT response interval is shown in Figure 4.66a and provides an even more stark difference when compared to the start of the RRT window. The average surface temperature for the uninsulated case from test 6 has risen from 30 °C to 98 °C, with peak temperatures in the 130 - 148 °C seen, where as the IMO A-15 insulated case from test 6 has experienced very little change, with the average temperature rising from 10 °C to 12 °C and a peak temperature of only 21 °C seen, which may be indistinguishable to the touch and will have no visual indications.



(a) IR image of the unexposed side at 6 minutes of test 6 with no insulation. Average temperature 98 °C

(b) IR image of the unexposed side at 6 minutes of test 10 with IMO A-15 insulation, scale matched to uninsulated test image. Average temperature 12 °C

Figure 4.66: IR images taken at 6 minutes to compare the uninsulated and insulated surface temperatures on the unexposed side at the end of the RRT window

Based on the temperatures measured during large-scale testing, in combination with results from the preliminary paint testing, there would also be no off gassing evident or visible signs of heating on the painted surfaces. Thus, based on these test results for steel surfaces insulated to A-15 specifications, it is likely that current door check procedure for rapid response, which includes touching the door surface with the back of the hand to check for warm or hot spots, may not be effective during rapid response to fires on the new vessels.

Based on the current training doctrine, these surface temperatures indicate that it is safe to enter the compartment throughout the entire window of the initial response by the RRT personnel. This may result in personnel not using appropriate caution when opening a door or hatch, and may result in injuries from the heat and smoke. Therefore, the following is recommended;

Recommendation: Personnel involved in rapid response on RCN vessels fitted with IMO compliant fire insulation be made aware that 'cold' doors may not mean that the compartment is safe to enter, and to proceed with caution when opening the door.

As explained in section 2.5, with higher insulation ratings a door check that indicates only a 'cold' door is even more likely, as the conduction path on the stiffener is insulated for A-30 and higher insulation ratings. Figure 4.67 shows a simplified diagram of the thermal conduction path through the stiffener in the A-15 installation, which is protected by insulation when the time rating is increased.

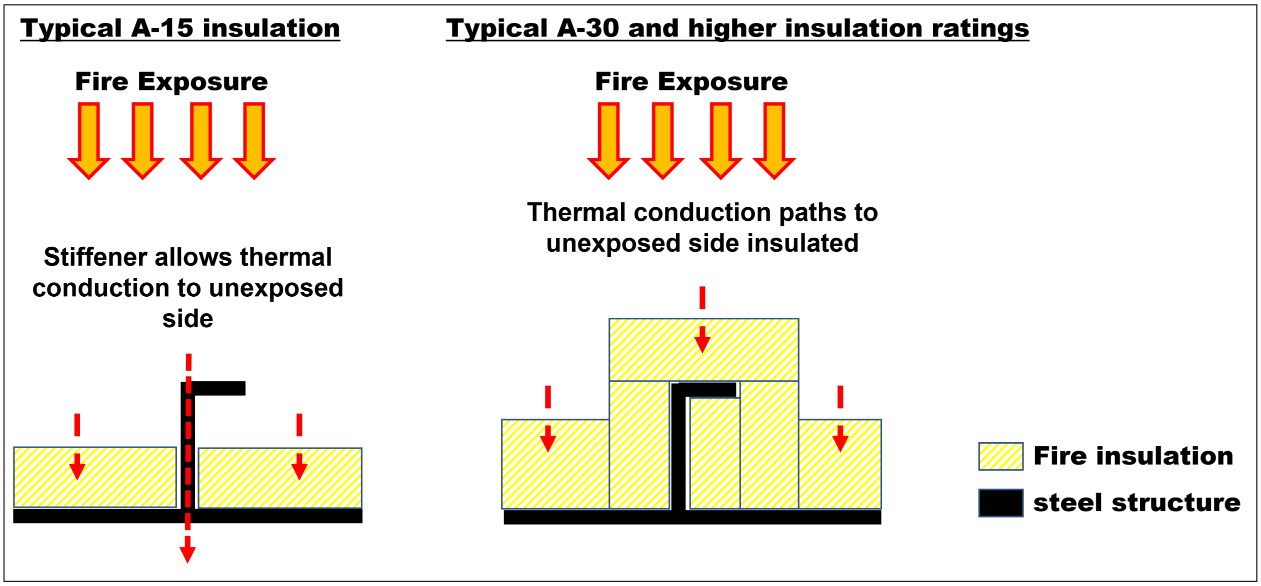


Figure 4.67: Simplified diagram showing the thermal conduction path along the stiffener for A-15 installations vs A-30 and higher rated installations

This is relevant for both the initial response by the RRT as well as the follow on response by both the attack team and boundary personnel. For A-15 fire divisions, the stiffener connection points may be useful locations to check as part of the door entry procedure by RRT personnel. Based on the experimental results, which showed the stiffener connection points to be the hottest location on the unexposed side during the insulated bulkhead testing, this is likely to be the point where personnel would first see visual indications, such as discolouration of the paint and smoke generation. That assumption would no longer be relevant if the fire division has an A-30 rating or higher, so it would also be important for personnel to understand what the different ratings mean, and how that changes the available information when making tactical decisions. To assist personnel, it may be useful to note what fire divisions and rating is involved for the specific scenario, as well as include local markings as a reminder.

Therefore, in addition to incorporating the impacts of the fire insulation into the training it is also recommended that;

Recommendation: Training is updated to explain how the different time ratings for an IMO fire division impacts the insulation, and that an A-30 or A-60 fire division may present different indications for making tactical decisions compared to an A-15 or an uninsulated division. The installation instructions for specific products used should be verified in case there are differences between products.

Recommendation: The RCN should include local markings on both sides of doors and hatches fitted at fire divisions to denote the fire rating to assist personnel responding to fires.

Although it was not measured during the experiments, it is noted by the author that the fire was clearly audible in the transition compartment for all six experiments where no insulation was fitted, and was subjectively quite loud during the period when the fire reached the peak HRR. During the four tests conducted with both the industrial mineral wool and the IMO A-15 compliant mineral wool insulation installed, it was subjectively significantly quieter on the adjacent compartment side, which is consistent with the technical data for the product, which gives a measured sound reduction of 45 dB for the IMO A-15 product [16]. Based on the author's experience on RCN ships, in addition to the fire insulation largely eliminating any visual or tactile indications on the unexposed side, the residual sound transmitted through the insulated bulkhead may be difficult to distinguish above the normal ambient noise levels. Improving the experimental design to include noise level measurements would allow an objective analysis, but when fire insulation is fitted, the sound transmitted to the adjacent compartments may be a more critical indicator compared to the surface temperature, as there would not be expected to be any visual or tactile indications on the unexposed side, but personnel may still be able to hear the fire from the adjacent compartment. If this is the case, then it may be appropriate to emphasize this point when adapting current training, which currently focuses largely on what indications personnel can see and touch during the initial response by the RRT.

Additionally, because the fire rating at each division will vary based on the fire risk in the compartments and the level of fire rating provided by the installed insulation may not be apparent, consideration may be given to marking the fire rating (if any) on the door or hatch for reference.

4.9.2 Attack Team period (7-14 minutes from ignition)

For the attack team, the relevant time interval is estimated to be within 7-14 minutes from ignition. This allows for approximately 1-2 minutes of delay from ignition until detection and between 5-12 minutes for the attack team to arrive on the location, set up the fire hose and be prepared to enter the compartment. The variation in the attack team arrival time is due to the differences between a fully crewed ship in at sea compared to a ship alongside in home port after hours (when most of the crew is disembarked), as well as the time taken to get to different areas of the ship. In addition to the attack team all wearing the full ensemble of bunker gear and having a personal self contained breathing apparatus, it is assumed that the attack team leader would have an NFPA 1801 compliant TIC capable of showing IR images in real time to survey the door prior to entry. As seen in Figure 4.68, similarly to the RRT time interval, there continues to be very little detectable change in the surface temperature at the centre of the plate on the unexposed side, and while the temperature continues to increase on the bolts and stiffener, it is much less than the uninsulated test results, and is still well below the 180 °C maximum point measurement temperature allowed by the IMO certification.

Because the AT will have a TIC to be able to monitor the outputted temperature gradients of the IR image on the display, the tactile indicators from touching a hot surface are not relevant for this time interval. Therefore the temperature curves and IR images will largely be used to discuss the overall context, along with other visual indications that may be present. Based on the preliminary small scale results with the painted surfaces, it is expected that the AT would also begin to see indications of off gassing/smoke indication as the surface temperature on the unexposed side exceeded the 70 °C threshold, with the stiffener measuring point reaching this benchmark at approximately 9.5 minutes (570 s) after ignition.

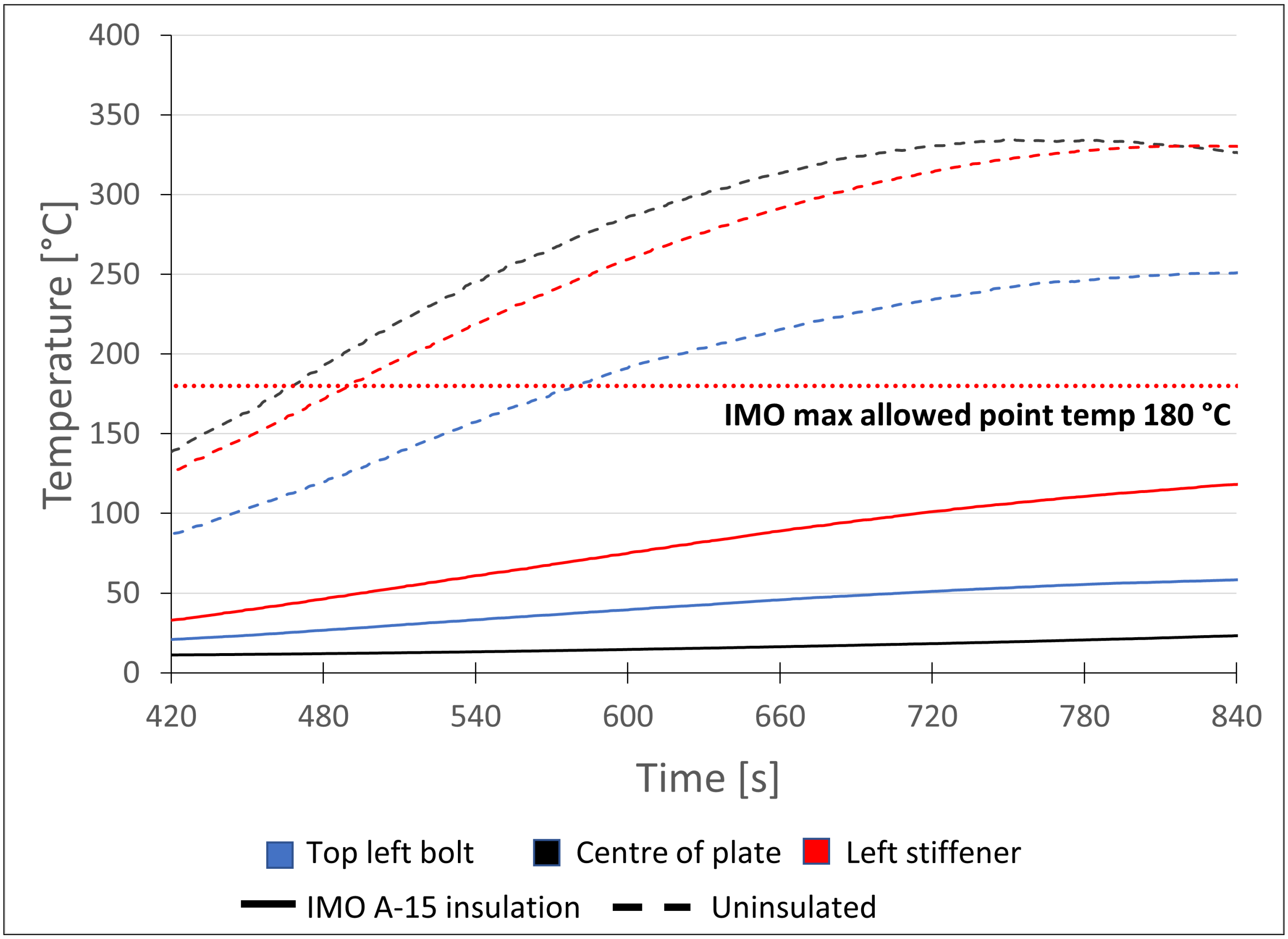
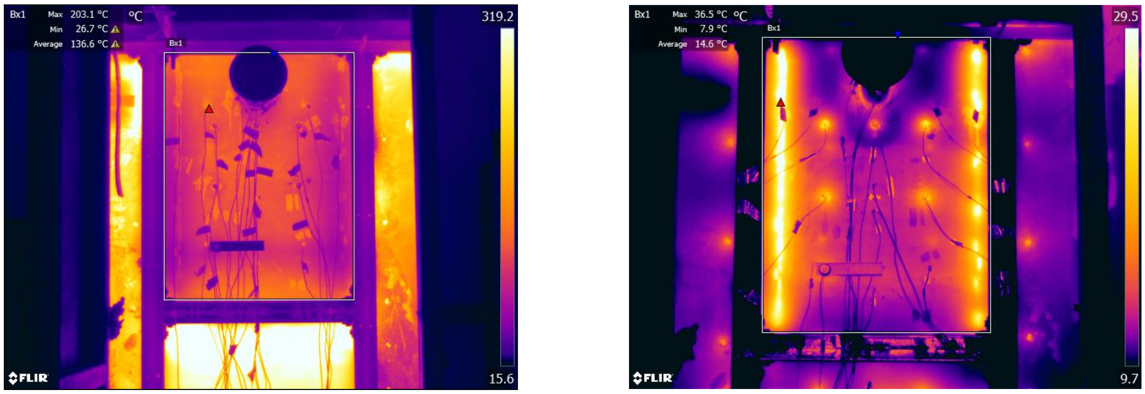


Figure 4.68: Comparison of a representative selection of key measuring points from the uninsulated versus the IMO A-15 insulated tests during the AT time interval

From the results in Figure 4.68, it is clear that temperature variations would be detectable on an A-15 wall using the TIC, and based on the combined measured temperatures in this particular fire scenario with cone calorimeter results, there would also be off-gassing and smoke generation along the stiffener weld point. Although the measured temperatures on the unexposed side were significantly lower in the insulated case compared to the uninsulated case, there was still enough of a temperature variation to be detectable with a TIC. The RCN uses TICs that are compliant with [24], which automatically adjust the temperature scale for the display to account for the measured temperature range, this is similar to what the personnel on the AT would see on the display screen. So despite the temperature on the unexposed side being significantly lower for the insulated test, Figure 4.69 demonstrates that at the 7 minute mark the increased temperature would be detectable with insulation fitted with an average temperature of 15 °C and a peak of 36 °C, (compared to an average of 136 °C and peak of 203 °C for the uninsulated test case). In this case there would be no other indications on a painted surface for the insulated case, where as for the uninsulated case, there would be off gassing, smoke generation and likely some other indications such as bubbling and discolouration.

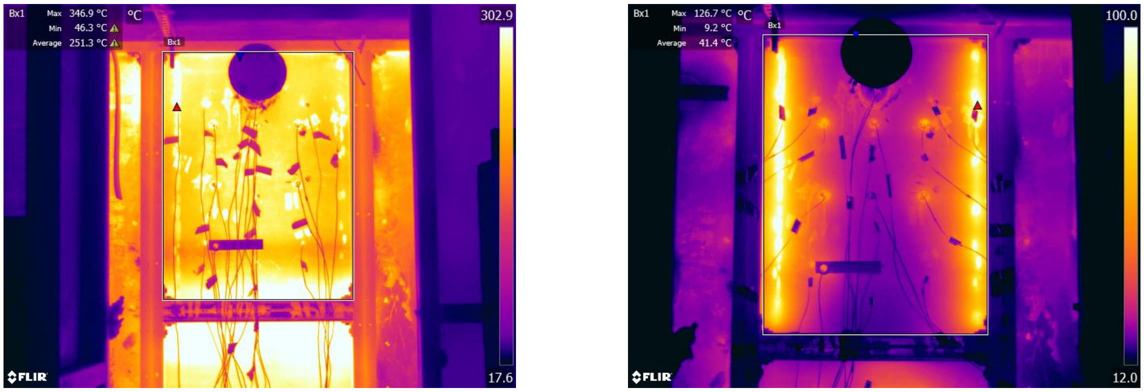


(a) IR image of the unexposed side at 7 minutes of test 6 with no insulation. Average temperature 136 °C

(b) IR image of the unexposed side at 7 minutes of test 10 with IMO A-15 insulation. Average temperature 15 °C

Figure 4.69: IR images taken at 7 minutes to compare the uninsulated and insulated surface temperatures on the unexposed side at the start of the AT window

Similarly, Figure 4.70a, which shows the IR images at the 14 minutes mark, the average temperature has increased to 41 °C and a peak of 126 °C, (compared to an average of 251 °C and peak of 349 °C for the uninsulated test case). For the insulated test, there would likely be some additional visual indications, such as discolouration and some off gassing and smoke generation, whereas the uninsulated case would likely have significant evidence of bubbling, discolouration and smoke generation. Further study is required to better document what happens in the higher temperature ranges, but with no insulation, the unexposed side may be in the temperature range approaching ignition of the paint.



(a) IR image of the unexposed side at 14 minutes of test 6 with no insulation. Average temperature 251 °C

(b) IR image of the unexposed side at 14 minutes of test 10 with IMO A-15 insulation. Average temperature 41 °C

Figure 4.70: IR images taken at 14 minutes to compare the uninsulated and insulated surface temperatures on the unexposed side at the end of the AT window

So throughout the relevant time interval for the AT response, with the insulated wall there would likely be detectable hot areas that provide indication of the presence of a fire, they do not give any direct reading on the conditions in the fire compartment though. For comparison, the IR image at the 14 minute mark for the insulated test (Figure 4.70b) shows lower average and peak temperatures compared to the uninsulated case at the 7 minute mark (Figure 4.69a), which is a concrete demonstration of the 'masking' effect that the fire insulation will have on the current tactical decisions by the attack team, if training is not adjusted to take this into account where it's fitted.

For A-30 rated fire divisions and higher, additional analysis or testing would be required to estimate the impact of the additional insulation on any indicators of a fire within the adjacent compartment, since as the stiffeners are fully encapsulated, they may show little temperature difference from the surrounding plate. Some door fastenings and other components that penetrate the insulation may be visibly warmer on the TIC, but again would not give a direct reading of the fire compartment conditions.

As noted above by the author, the sound levels in the transition compartment were significantly reduced but still audible, particularly as the fire was reaching peak HRR during the growth. This corresponds to the AT response time, so in addition to some measurements with the TIC showing reduced surface temperatures on the unexposed side, the AT may also be able to hear the fire burning, but it is expected to be significantly dampened due to the sound reduction impacts of the IMO compliant fire insulation. No objective evidence is available to understand how the residual noise levels compare to normal ambient noise levels on ships and make a determination, but if incorporated into future experiments, this would provide objective data to understand how this should be incorporated in the existing training and tactics.

In general then, during their period of operation, an attack team may have some indications that there is a fire in the adjacent compartment, but they will be unable to accurately determine the fire severity or current compartment conditions on the other side of the fire division.

Recommendation: Personnel trained to respond as part of the attack team on RCN vessels fitted with IMO compliant fire insulation be made aware that the compartment conditions may be significantly different than what is displayed on the thermal imaging cameras (TIC) and to proceed with caution when opening the doors/hatch.

Although it is not possible to accurately judge current fire compartment conditions from the opposite side of a fire division, knowing that the division is rated to A-15, A-30 or A-60 would be useful in understanding the context of the IR images. For example, high temperatures on an A-60 division may be indicative of a higher severity fire, or that the seat of the fire is in closer proximity to the door. Similarly, if only limited hot spots are evident, different assumptions would potentially be made by the attack team depending on whether the fire division is rated for A-15, for example, instead of A-30 or A-60.

Additional investigations using different levels of insulation and different severity fire scenarios would help quantify some of these factors, but because there are a wide variety of different scenarios that could lead to the same surface temperatures on an adjacent compartment bulkhead or door, it will likely be difficult to provide any overarching guidelines for direct assessment of the fire situation. The best approach may be to incorporate fire insulation into crew fire response training so that personnel can gain experience with the lower temperatures on the unexposed surfaces of fire protected doors and thus may also be more likely to proceed with caution when they encounter similar scenarios in a real life situation.

4.9.3 Fire boundaries (10 minutes and onward)

The traditional role of the fire boundary is to prevent the spread of the fire through application of cooling water at the watertight divisions to and thus prevention of the heat conduction along the divisions leading to secondary fires. In general, investigation of this aspect of overall RCN fire response was not envisioned as part of the present research, so no specific recommendations to change current fire boundary tactics will be made. Instead several implications and avenues for further research arising from the current results will be outlined here.

If the watertight division is fire rated, with the insulation properly installed and no significant gaps, the boundary role for that adjacent compartment may no longer be necessary to prevent spread of fire from thermal conduction through the steel structure. It should be noted however that, based on the preliminary bench testing with the coated steel coupons, regardless of the effectiveness of the insulation, it is possible that the paint will still reach sufficiently hot temperatures to off gas and possibly generate smoke. In particular, when the insulation is located on the unexposed side of the bulkhead relative to the fire, it is possible that the paint on the unexposed side may heat up significantly to generate smoke and possibly ignite (depending on the fire compartment conditions) underneath the insulation. Thus, for safety, any personnel acting as a boundary should at a minimum always wear self contained breathing apparatus (SCBA).

Additionally, with fire insulation fitted, it is unknown how effective the boundary cooling tactics of spraying water onto the bulkhead/deck will be. On an uninsulated bulkhead, spraying the steel structure with water will reduce the surface temperature on the unexposed side, and also provide indirect cooling to the fire compartment. Using this principal, boundary cooling has been shown to be effective at preventing fires from spreading beyond the compartment of origin. However, because it involves the use of water inside a ship, the accumulation of water can eventually become a stability concern, with several examples of ships capsizing due to fire fighting water.

When the bulkhead is a fire division with insulation installed, this changes the heat transfer path significantly. Because the insulation is typically only installed on one side of the structure to form the fire division, the context if the insulation is on the exposed side (with the boundary on the steel side, shown in Figure 4.71) or on the unexposed side (with the insulation between the boundary and the steel structure, shown in Figure 4.72) is also relevant.

In the first case, shown in Figure 4.71, the cooling water makes direct contact with the steel structure, so is able to provide effective cooling on the unexposed side. While the insulation on the exposed side may limit the amount of indirect cooling in the fire compartment, this tactic allows any hot spots where the paint is beginning to off gas or smoke to be cooled. This case is the same as the experimental design setup, and based on the results, it is expected that the overall unexposed surface temperatures would be significantly decreased, with some minor hot spots where limited amounts of boundary cooling water may be useful. There may still be some areas where paint is off gassing or generating smoke. With further research, this could be better understood, but may result in the focus in this particular case changing to smoke management.

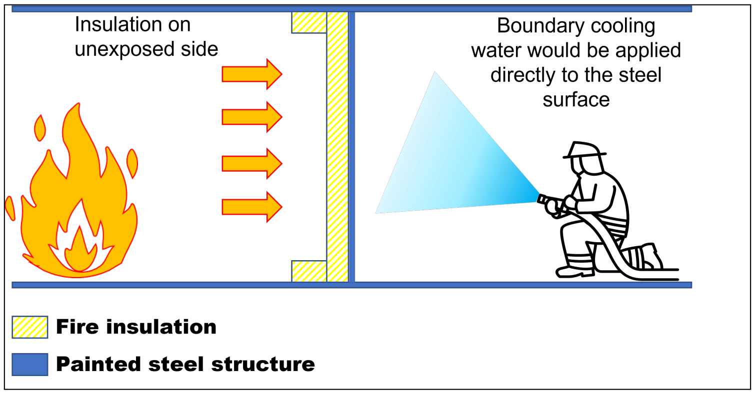


Figure 4.71: Boundary cooling scenario for experimental setup, with insulation installed on the exposed side of the bulkhead. Firefighter Icon from [29].

For the second case where the insulation is installed on the unexposed side, shown in Figure 4.72), the preliminary bench test results indicate that the paint on the structure is likely to generate smoke, and may exceed ignition temperatures. While the insulation will continue to prevent secondary fires by limiting the heat conduction into the adjacent compartment, the amount of smoke generation and the risk of smoldering paint underneath is an area where additional study is recommended. In this scenario, any cooling water applied at the bulkhead will contact the insulation instead of the steel, so is unlikely to provide any cooling to the structure itself, or be able to extinguish any smoldering fires on the painted structure beneath (unless the insulation is removed or fails).

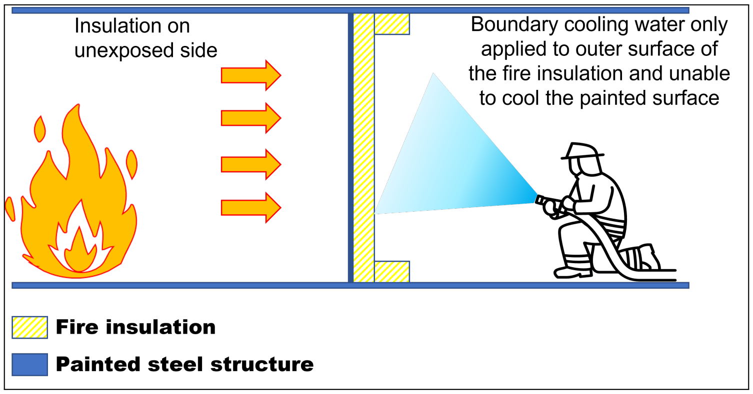


Figure 4.72: Boundary cooling scenario for the alternate insulation installation location on the unexposed side of the bulkhead (not tested). Firefighter Icon from [29].

The mineral wool insulation does not readily absorb water, and any facing product (such as aluminum foil or fiberglass) will also repel water, but it is likely that the insulating properties of the mineral wool will also decrease when wet. With the variety of different configurations, possible facing materials, fire nozzle settings and other variables this is a potentially complex issue.

The data from the testing does indicate a potential system lag effect, in that the unexposed surface temperature may continue to increase while the fire is in the decay period, but was for a scenario that did not include any fire suppression efforts. These fire suppression efforts would include cooling the fire compartment and any hot surfaces, but it is unknown if this would be effective in cooling the fire insulation, which may continue to dissipate heat. Based on the results, the fully insulated areas stayed between 50-80 °C, with the hot spots observed on the partially exposed stiffeners and bolts. So if the insulation was to retain heat it is unlikely to be a significant issue, but may still result in some paint continuing to off gas in adjacent compartment after the fire is extinguished until the heat is dissipated.

Therefore, for both considerations noted above, additional research is recommended. Through further study, it may be possible to evaluate the risk of significantly altering the current approach to fire boundaries, and may indicate an alternative approach such as placing a greater focus on smoke management. Knowing the performance of the fire insulation may also assist in managing the priority of boundary locations, but this should only be considered by personnel with a good understanding of the context and limitations of the insulated fire barrier designs.

If any decisions are made to change the fire fighting tactics to take advantage of the insulated fire barriers, these should be well understood and clearly noted in any pre-plans, so that when the fire division may be compromised (such as part of normal maintenance) the plans can be changed to take the current status of the fire barriers into account. Although the temperatures in the unexposed compartments are likely significantly reduced, it is still likely that there will be some off gassing and smoke generation, so efforts to prevent further spread of smoke from adjacent compartments to the rest of the ship should continue.

Finally, similar to what is noted in 4.9.2, the boundary personnel may be able to hear some indications of the fire. If sound levels in adjacent compartments is incorporated into future experiments, that information could also be incorporated in the RCN's boundary personnel training.

4.9.4 Overhaul of the fire

Following the successful extinguishment of the fire, the final stage of response is to overhaul the area affected by the fire. This includes exposing and cooling any pockets of fuel still smoldering to prevent re-ignition, general cooling of the compartment, and ventilating the atmosphere to restore tenable conditions. Like boundary cooling, overhaul of the fire is not investigated directly in this research, but some inferences can be made from the full scale experiments and the bench scale testing, and again may point to areas for further investigation.

Firstly, the bench test results indicate that it is possible that, depending on the orientation of the insulation and the fire severity, the paint underneath the fire insulation may still reach sufficient temperatures to smolder and possibly ignite. Personnel should be aware that overhaul may need to involve removal of some of the fire insulation or spot cooling operations from the adjacent compartment to address these types of hot spots. This may be an area that can be combined into further general investigations into how the painted steel structure interacts with the fire insulation in terms of heating, smoke generation and potential ignition in a real fire setting.

Secondly, the results clearly indicate that installation of fire insulation changes the boundary conditions and holds heat in the fire compartment leading to higher overall temperatures. In terms of overhaul, this means that it will take longer to cool the compartment because there is less heat being naturally dissipated from the compartment, so the only cooling may be from an open ventilation path such as an open door, via active cooling through use of fire fighting water or by introduction of cooler air used to ventilate the space. Overall, this is potentially a significant concern and is far outweighed by the inherent benefits of the fire insulation to limit fire spread, but for planning purposes it is a useful item to understand as it may require additional rotations of personnel or careful management of expectations in terms of how long it may take to restore a compartment to normal temperature ranges following a fire.

Further study is recommended to understand how the fire insulation may impact compartment temperatures and post-fire cool-down. This is likely an area where computer modeling of the different boundary conditions and fire scenarios would be an effective tool, and could be done using the actual compartment layout and configuration of the new RCN vessels as part of the evaluation of the fire response.

4.9.5 RCN training demonstration video

Over the long term, the inclusion of fire insulation will be standard on any new vessels, so it is recommended that the existing RCN Damage Control Training Facilities, which include the fire fighting trainers, be updated to include fire insulation so that the training reflects shipboard design. Because the trainers include compartments that are meant to represent specific risks (kitchens, machinery spaces, office spaces etc) a level of fire insulation can be selected that is consistent with the actual compartment fire risk guidelines found in SOLAS and other standards. In the interim, the method below is an example of a simple way to introduce the concept without any significant infrastructure changes.

Since the overall objectives of this research are focused on the impacts of insulated fire barriers on fire response in the RCN, as a final step in the work a short training video is produced to demonstrate the effectiveness of the mineral wool insulation in a fire using some additional insulating material that is available on completion of the full scale experiments. This is intended to be a simple demonstration that can easily be done at a training establishment with readily available materials, as well as a high impact way to explain how the installation of insulation on bulkheads and hatches may affect fire fighting tactics in the RCN.

The video is taken using a sample of the Rockwool SeaROX 620 SL mineral wool insulation mounted vertically and heated from one side using the flame from a mixed gas torch. The TIC is used to monitor temperatures of the insulation sample on the opposite side. The video is time lapsed to cover a period of approximately 10 minutes as the insulation heated very gradually to a maximum temperature of 67 °C. A still from the video in Figure 4.73 shows a sample of the output at the 8 minute mark.

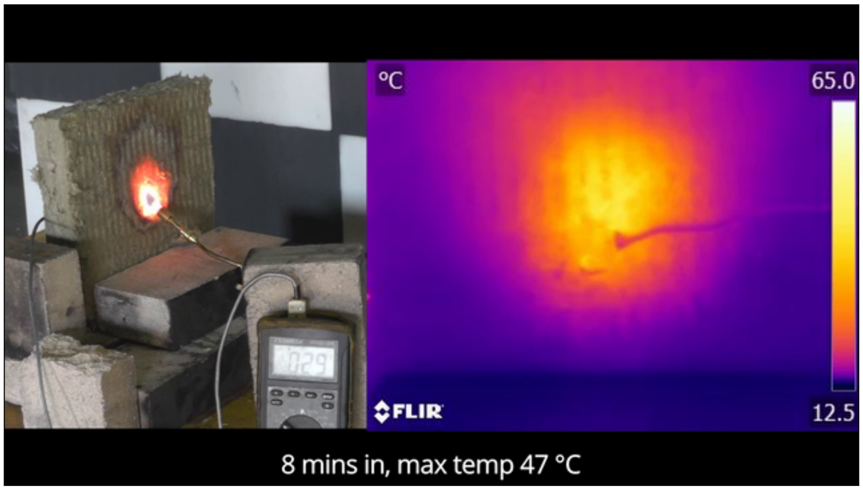


Figure 4.73: Demonstration video sample

For this demonstration in a training setting, an industrial mineral wool or residential mineral wool product can form a suitable replacement to the SeaROX insulation in presenting the concept. As discussed in [21], the lower temperature rated mineral wool insulation will contain more binder materials and may experience some charring and discolouration, but will still be able to convey the general point.

4.9.6 Implications for land based firefighters responding to marine fires

For land based fire fighters, the subject of fire insulation is very briefly alluded to in [10] and [23] but not necessarily explained. Because fire insulation has been incorporated into commercial vessels for a longer time, the impact of installed insulation on the unexposed bulkhead and doorway surface temperatures may already be incorporated into the tactics and training of some land based fire departments, but would depend on their familiarity with changes to vessel construction. Additionally, because land based fire fighters have additional training and experience in residential, industrial and other types of fires, they may not place such an emphasis on using the unexposed surface temperature for deciding whether, and how, to enter a compartment fire. At the same time, if these temperatures are used in response decision making and if they have not been already considered, similar considerations that are included above for the RCN tactics may apply, and should be reviewed by someone suitably experienced to see how they should be incorporated into their approach to fire response on vessels in harbour.

Chapter 5

Recommendations and Conclusion

Overall, as expected, this research confirms that the use of IMO compliant fire insulation to form fire divisions will be extremely effective at preventing heat transfer, but provides data over the entire time span of the testing period to supplement the pass/fail certificates currently available. The test setup also combined multiple structural features into a single test specimen which are typically tested separately for certification purposes, while using a more realistic, and less severe class A fire compared to the IMO test, which gives a better sense of what may happen in a real world fire scenario.

A consolidated list of the recommendations made throughout this work is included below, and includes some items that could be investigated based on the results of these experiments. Additionally, there are some recommendations for some of the tactics where there is not sufficient data to make a change, but may be room for improvements with further study.

The results obtained in the form of video, temperature and IR images used for the analysis can also be used in training to introduce the concept to personnel. A suggestion on how to demonstrate the effectiveness of the mineral wool insulation in a fire scenario using readily available materials was piloted and included for reference, but is an example of how this can be explained in an easy to understand way so that personnel can be confident that the material will work as designed, but also understand what that will mean when responding to an emergency. This is useful for both the RCN and other naval personnel for incorporating into existing training, and may also be of value for land based fire fighters that may respond to a fire in a ship in port that includes fire insulation.

Further research is recommended in a variety of other areas to build on these results, and also investigate some areas that were not part of this work, such as how effective the manual boundary cooling procedure using fire fighting water will be at an insulated division. These results do provide a basis to build upon which was previously not available, and developed some procedures for small scale bench testing to understand how common features such as paint, which is typically not included in large scale testing of structure, may significantly change the real world fire scenarios, so should be considered in the development of tactics as well as fire risk management during the life of a vessel.

5.1 Summary of recommendations

The list below represents a summary of the recommendations made throughout this work for consideration for adapting the current RCN fire fighting tactics to the inclusion of fire divisions in the new vessels being delivered under Canada's National Shipbuilding Strategy. The considerations may also be relevant for land based fire fighters that may be responding to fires on commercial vessels that do not already incorporate this into their fire fighting tactics.

Recommendation # 1: Personnel involved in rapid response on RCN vessels fitted with IMO compliant fire insulation be made aware that 'cold' doors may not mean that the compartment is safe to enter, and to proceed with caution when opening the door.

Recommendation # 2: Personnel trained to respond as part of the attack team on RCN vessels fitted with IMO compliant fire insulation be made aware that the compartment conditions may be significantly different than what is displayed on the thermal imaging cameras (TIC) and to proceed with caution when opening the doors/hatch.

Recommendation # 3: Training is updated to explain how the different time ratings for an IMO fire division impacts the insulation, and that an A-30 or A-60 fire division may present different indications for making tactical decisions compared to an A-15 or an uninsulated division. The installation instructions for specific products used should be verified in case there are differences between products.

Recommendation # 4: The RCN should include local markings on both sides of doors and hatches fitted at fire divisions to denote the fire rating to assist personnel responding to fires.

Recommendation # 5: No changes to current boundary tactics or the fire overhaul process are recommended at this time, as this aspect was not directly studied in this research. Both areas are recommended for further investigation in future work so that this can be taken into account.

Recommendation # 6: In the long term, the RCN Damage Control Training Facilities be updated to incorporate the fire insulation requirements so that the trainers are consistent with the new design standards, and temperatures on the unexposed side of doors and hatches are comparable to what would be found on the new ships being delivered under the National Shipbuilding Strategy.

Recommendation # 7: For future large scale testing of on IMO fire insulation (particularly on more complex geometries), how IR imaging is used should be considered during the experimental design stage. In addition to providing useful experimental data and, the IR images are invaluable in troubleshooting and finding small areas where there were gaps in the installed insulation. This allowed that context to be included in the results analysis as well as to improve the experimental setup.

Recommendation # 8: The experimental design for similar experiments to further investigate how fire insulation may impact RCN firefighting tactics should consider measuring noise levels, as audible indicators of a fire burning are useful data point for personnel to take into consideration. It was subjectively observed that, with mineral wool insulation fitted, the noise levels in the adjacent compartment was significantly reduced. Objective measurements would enable understanding of how this would compare to ambient noise levels on a ship, and understand if this may still be an available data point that should be more strongly emphasized in training.

5.2 Areas for future investigation

The following is a summary of areas for future investigation, based on the findings of this work, and the knowledge gaps that were found during the analysis. That includes expanding on some of the preliminary work done, and to expand on the existing experimental design.

- Investigation into how the fire insulation impacts current boundary cooling tactics, including the effectiveness of using cooling water on insulated bulkheads and/or decks;
- Investigation into how the fire insulation impacts the fire overhaul process, which may include smoldering paint underneath the insulation, and how the change to the boundary conditions may result in longer periods of time required to cool the compartment following a fire;
- More in depth investigation into the interaction with the painted structure and the fire insulation, and how that may result in smoke generation in adjacent compartments;
- Quantifying the impact of paint accumulation on the compartment fire load, smoke generation and toxicity considerations to understand the impact during the 40+ year service life of RCN vessels;
- Repeat the experiments using higher rated insulated walls (A-30 or A-60) with longer fire duration to evaluate how that changes the indicators on the unexposed side; and

- If fitted on RCN vessels, evaluate how any facing product used with the fire insulation (such as sheet metal paneling) may affect the fire fighting tactics.

This list may not be exhaustive, and there are likely other areas on this topic that need to be better understood to quantify how this new design change will impact firefighting on marine vessels.

5.3 Conclusion

For the RCN, who is currently renewing the fleet with more modern ships, these results are not simply academic and have immediate implications as the new ships are entering operations. In short, the results mean that if fire insulation is installed at a boundary of compartment where there is a suspected fire, the surface temperatures on the unexposed side can not be used as a reliable indication of compartment fire conditions. This impacts both the initial and the follow on fire fighter response used in the RCN two-tiered procedure, which uses the surface temperature and associated visual indications on the painted structure to inform tactical decisions, and is part of the current training received by all personnel.

Effective fire fighting tactics require an understanding of the equipment, training and the context of the fire scenario, and it is critical that as one aspect changes, that consideration is given to the overall impact. While the addition of these fire divisions adds some significant safety benefits, and significantly reduces the risk of secondary fires in adjacent compartments by preventing that thermal conduction through steel structure, this means previous tactics that relied on the unexposed surface temperature need to be re-evaluated and adjusted accordingly. The recommendations above include some simple adjustments that can be made to the current training for the safety of personnel. Future experimental results may provide some additional insights that would allow for more efficient employment of personnel and prioritization of resources without increasing the overall risk to either personnel or equipment.

References

[1] Appendix 2: Thermophysical property data. In Gottuk et all Morgan. K Hurley, editor, *The SFPE Handbook*. National Fire Protection Association, 5th edition, 2016.

[2] email communication between P.O'Hagan, Francois LePage, John Caulk and Dr. James Huang, July 2020.

[3] AkzoNobel. International paint interlac 665 technical data sheet. Technical report, 2020.

[4] AkzoNobel. International paint interprime 234 technical data sheet. Technical report, 2020.

[5] Standard guide for heated system surface conditions that produce contact burn injuries. Standard, American Society for Testing and Materials, West Conshohocken, PA, Unites States, 2020.

[6] Statistics Canada. Fire statistics in Canada, Selected Observations from the National Fire Information Database2005 to 2014. Summary report, Prepared by the Canadian Centre for Justice Statisticsfor the Canadian Association of Fire Chiefs, 2017.

[7] Royal Canadian Navy Damage Control Manual. Standard, Royal Canadian Navy, 2016.

[8] Matthew Didomizio. *Experimental Study of Thermal Degradation of Fire Resisting Compartment Partitions in Fires.* PhD thesis, University of Waterloo, Ontario CA, 2017.

[9] Jennifer Ellingham. Measuring Smoke Evolution at Full-Scale with Video Recordings. Master's thesis, University of Waterloo, Ontario CA, 2021.

[10] IFSTA. *Marine Fire Fighting.* Fire Protection Publications, first edition, 2000.

[11] IFSTA. *Marine Fire Fighting for Land Based Fire Fighters.* Fire Protection Publications, third edition, 2019.

[12] United Nations Resolution MSC.307(88) International Code for Application of Fire Test Procedures, 2010 (2010 FTP Code). Standard, International Maritime Organization (IMO), 2010.

[13] Copper Development Alliance Inc. C83600 data sheet. Technical report, 2021.

[14] FLIR Systems Inc. User's manual flir tools/tools+. Technical report, 2017.

[15] Fluke Process instruments. Emissivity for metals. Technical report, 2021.

[16] Rockwool Technical Insulation. Searox marine and offshore insulation - technical guidelines. Technical report, 2018.

[17] Reaction to fire tests - Room corner test for wall and ceiling lining products Part 1: Test method for a small room configuration. Standard, International Organization for Standardization, Geneva, Switzerland, 2016.

[18] V.K.R Kodur and T.Z. Harmathy. Chapter 9: Properties of building materials. In *The SFPE Handbook*. National Fire Protection Association, 5th edition, 2016.

[19] Johns Mansville. John mansville minwool-1200® industrial board- data sheet. Technical report, 2020.

[20] Johns Mansville. John mansville minwool-1200® industrial pipe. Technical report, 2020.

[21] Nagy, Nicole. Determination Of Thermal Properties Of Mineral Wool Insulation Materials For Use In Full-Scale Fire Modelling. Master's thesis, University of Waterloo, Ontario CA, 2020.

[22] NATO Standard Allied Naval Engineering Publication 77: Naval Ship Code. Standard, North Atlantic Treaty Organization Standardization Office (NSO), 2019.

[23] NFPA 1005: Standard for Professional Qualifications for Marine Fire Fighting for Land-Based Fire Fighters. Standard, National Fire Protection Association, Qunicy, M.A., 2019.

[24] NFPA 1801: Standard on Thermal Imagers for the Fire Service. Standard, National Fire Protection Association, Qunicy, M.A., 20121.

[25] Obach, Matthew R. Effects of Initial Fire Attack Suppression Tactics on the Firefighter and Compartment Environment. Master's thesis, University of Waterloo, Ontario CA, 2011.

[26] Omega. Revised thermocouple reference tables. Technical report, 2021.

[27] Sheehan, Thomas D. Royal Canadian Navy Evaluation of Handheld Aerosol Extinguishers. Master's thesis, University of Waterloo, Ontario CA, 2013.

[28] Statistical Summary Marine Transportation Occurences in 2018. Summary report, Transportation Safety Board of Canada, 2019.

[29] The Pyramid School. Firefighter by the pyramid school from the noun project.

[30] Guide to Structural fire Protection. Standard, Transport Canada, Marine Safety Division, 1993.

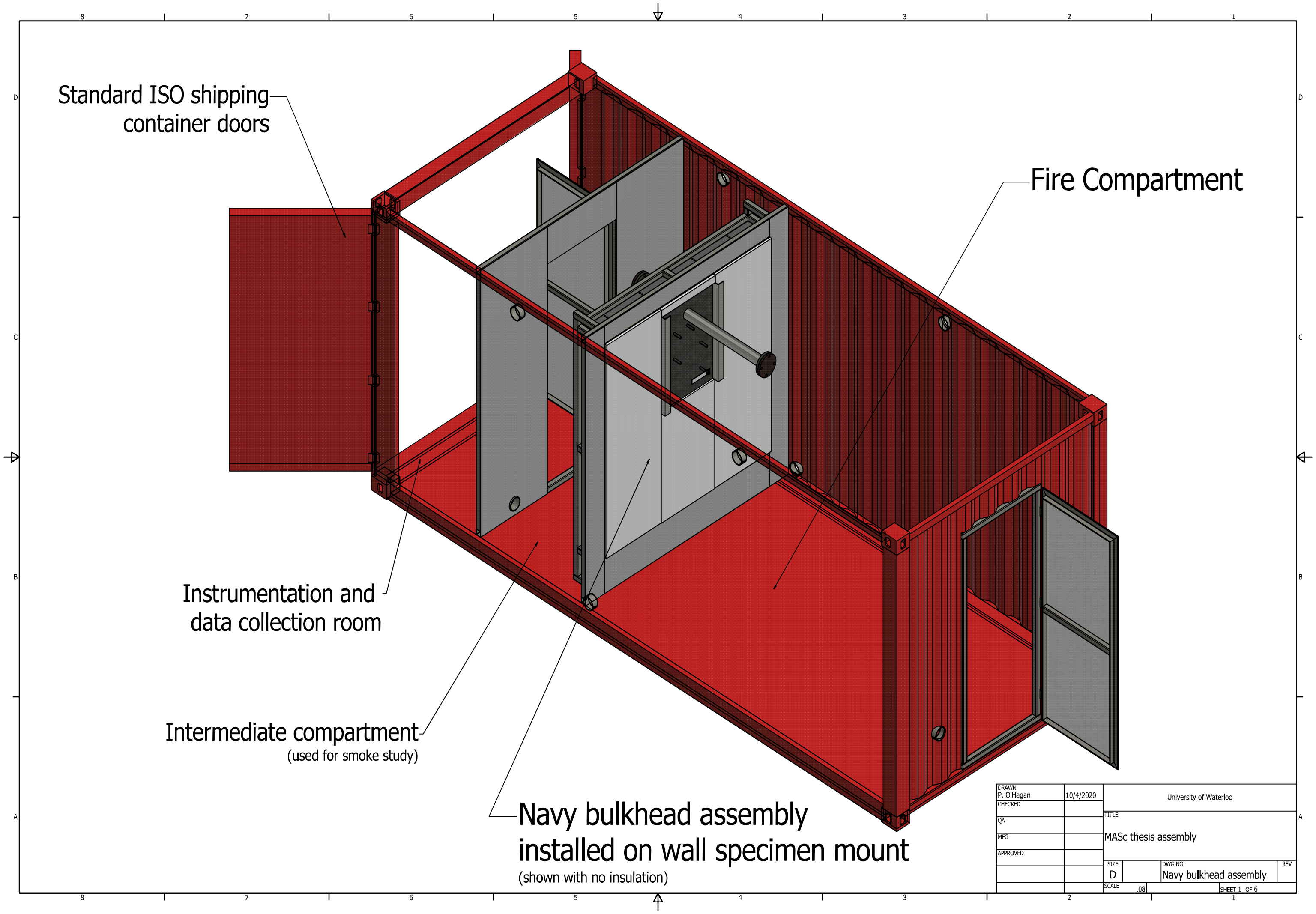
[31] Weckman, Elizabeth. Gas Flow Modeling and Simulation (Interim Report). Technical report, University of Waterloo, Fire Research group, March 2020.

[32] Geoff Ziezulewicz. Navy will scrap fire-ravaged Bonhomme Richard. *Navy Times*, Nov 2020.

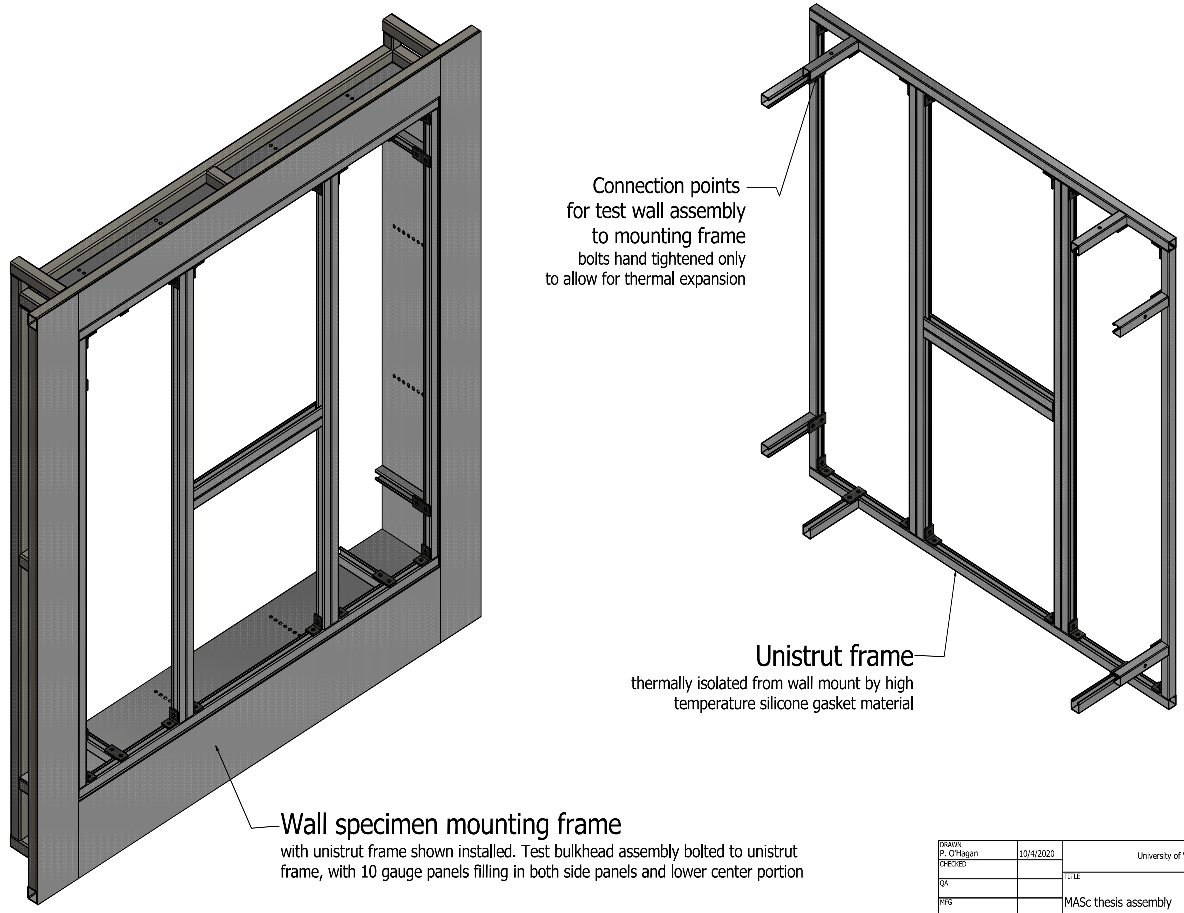
APPENDICES

.1 Appendix A - Construction Drawings

The construction drawings for the modified test wall are included below. The original construction drawings for the wall test unit and the test apparatus are available in [8].



DRAWN P. O'Hagan	10/4/2020	University of Waterloo		
CHECKED		TITLE MASc thesis assembly		
QA				
MFG				
APPROVED				
		SIZE D	DWG NO Navy bulkhead assembly	REV
		SCALE .08	SHEET 1 OF 6	



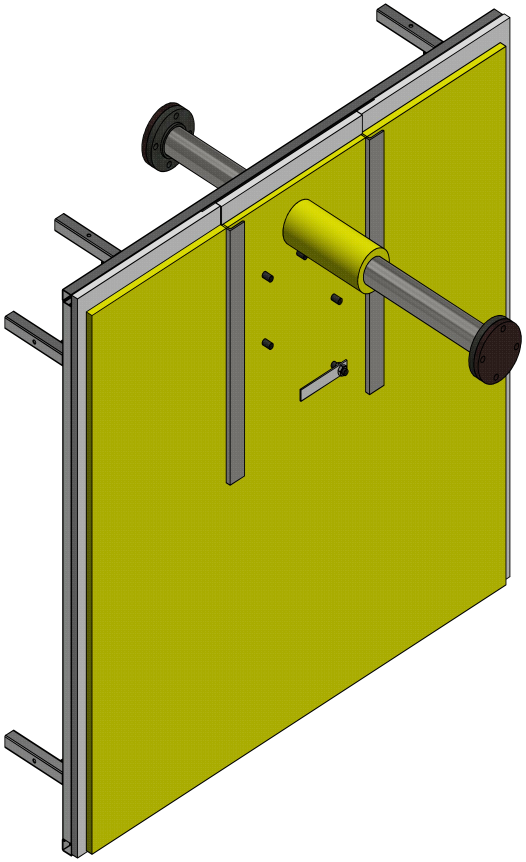
Connection points
for test wall assembly
to mounting frame
bolts hand tightened only
to allow for thermal expansion

Unistrut frame
thermally isolated from wall mount by high
temperature silicone gasket material

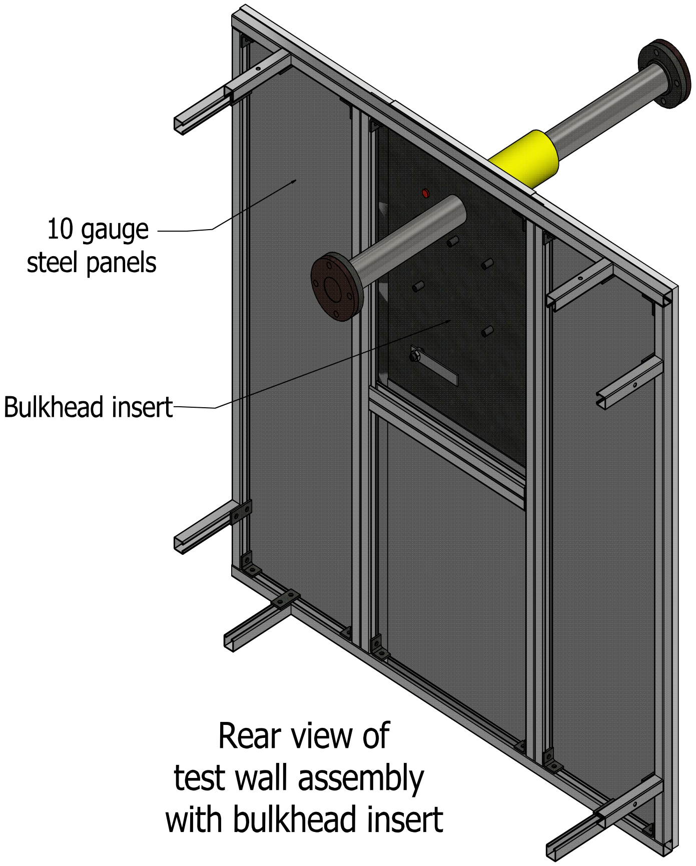
Wall specimen mounting frame
with unistrut frame shown installed. Test bulkhead assembly bolted to unistrut
frame, with 10 gauge panels filling in both side panels and lower center portion

DRAWN P. O'Hagan 10/4/2020
CHECKED
QA
MFG
APPROVED

University of Waterloo
TITLE MASc thesis assembly
SIZE D
DWG NO Navy bulkhead assembly
REV
SCALE .08
SHEET 2 OF 6

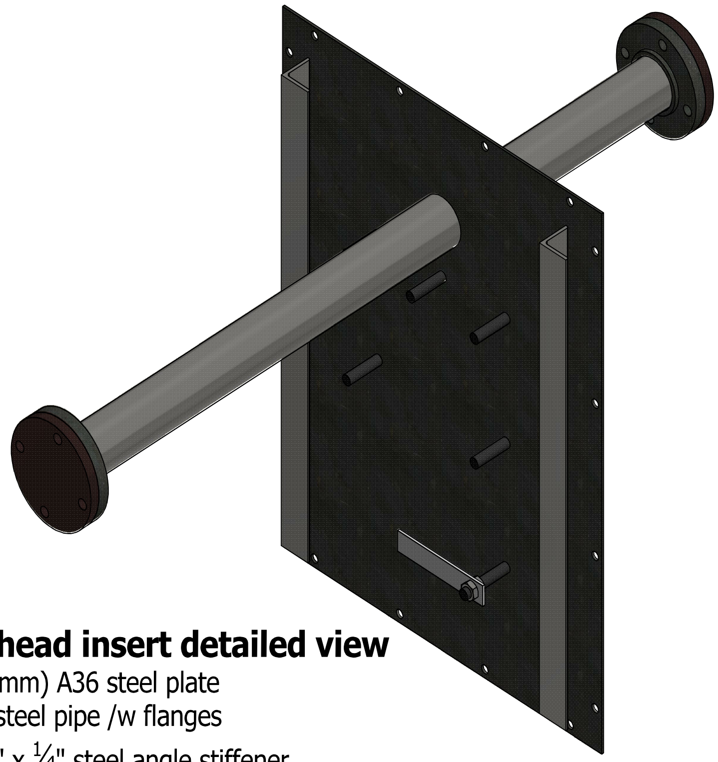


Front of test wall assembly with bulkhead insert
(insulated to IMO A15 standard)



Rear view of
test wall assembly
with bulkhead insert

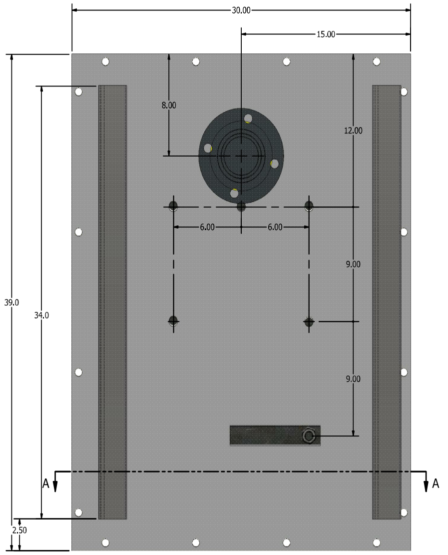
DRAWN P. O'Hagan	10/4/2020	University of Waterloo		
CHECKED		TITLE MASc thesis assembly		
QA				
MFG				
APPROVED				
		SIZE D	DWG NO Navy bulkhead assembly	REV
		SCALE .08		SHEET 3 OF 6



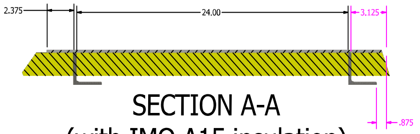
Test Bulkhead insert detailed view

-3/16" (~4.5 mm) A36 steel plate
-3" standard steel pipe /w flanges
- 2 ½" x 2 ½" x ¼" steel angle stiffener
-¾" coarse threaded rod for door dogs
-1 ½" steel flatbar for handle

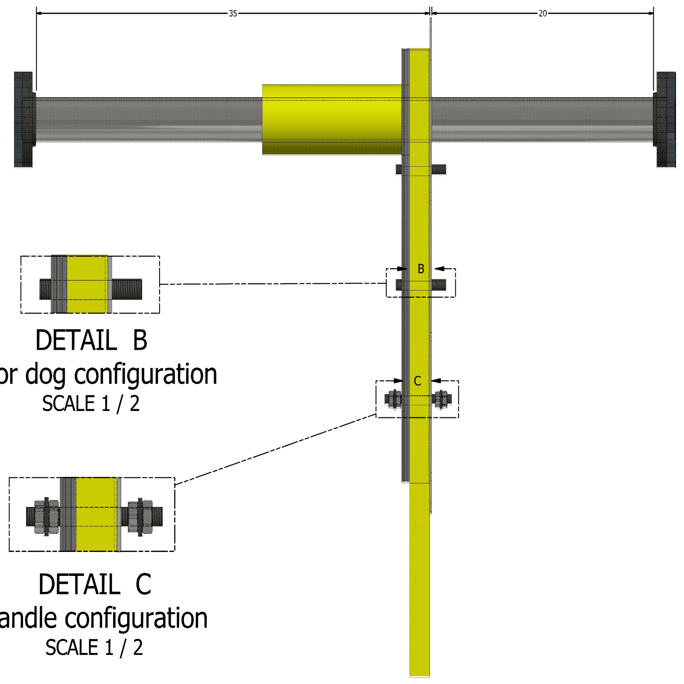
DRAWN P. O'Hagan	10/4/2020	University of Waterloo		
CHECKED		TITLE MASc thesis assembly		
QA				
MFG				
APPROVED				
		SIZE D	DWG NO Navy bulkhead assembly	REV
		SCALE 1 / 4		SHEET 4 OF 6



FRONT VIEW
(uninsulated)



SECTION A-A
(with IMO A15 insulation)



DETAIL B
Door dog configuration
SCALE 1 / 2

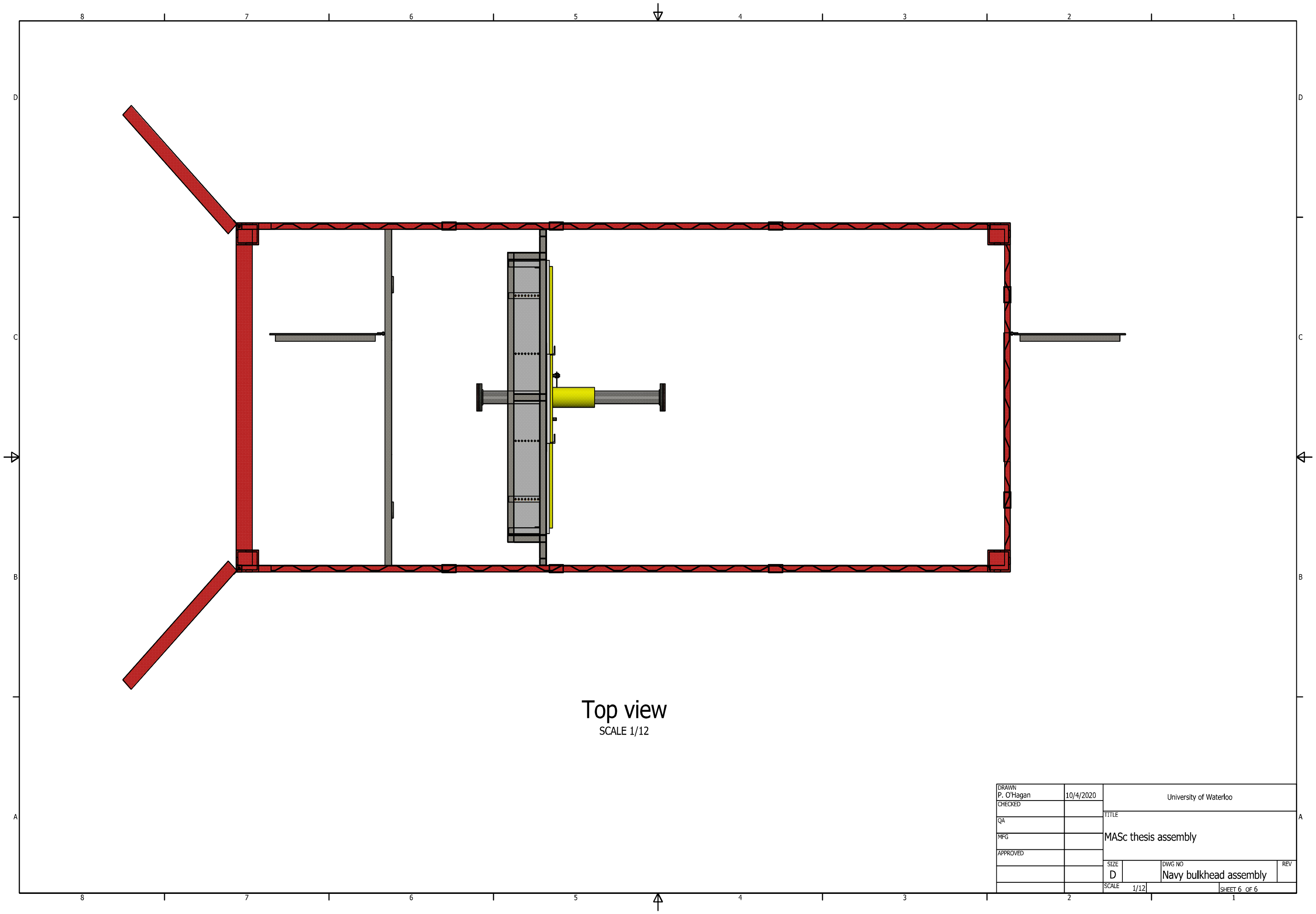
DETAIL C
Handle configuration
SCALE 1 / 2

SIDE VIEW of Bulkhead insert
(with IMO A15 insulation installed)

NOTE: All measurements are in inches unless noted otherwise

Materials:
Pipe: 3" SCHD 40 Steel /w standard flanges and blanks
Plate: $\frac{3}{16}$ " (0.188) Steel
Stiffeners: $2\frac{1}{2}$" x $2\frac{1}{2}$" x $\frac{1}{2}$" Steel Angle
Threaded Rod - ¾" - 10 TPI Steel rod

DRAWN P. O'Hagan	10/4/2020	University of Waterloo
CHECKED		TITLE MASc thesis assembly
QA		
MFG		
APPROVED		SIZE D · DWG NO Navy bulkhead assembly · REV
		SCALE 1 / 4 · SHEET 5 OF 6



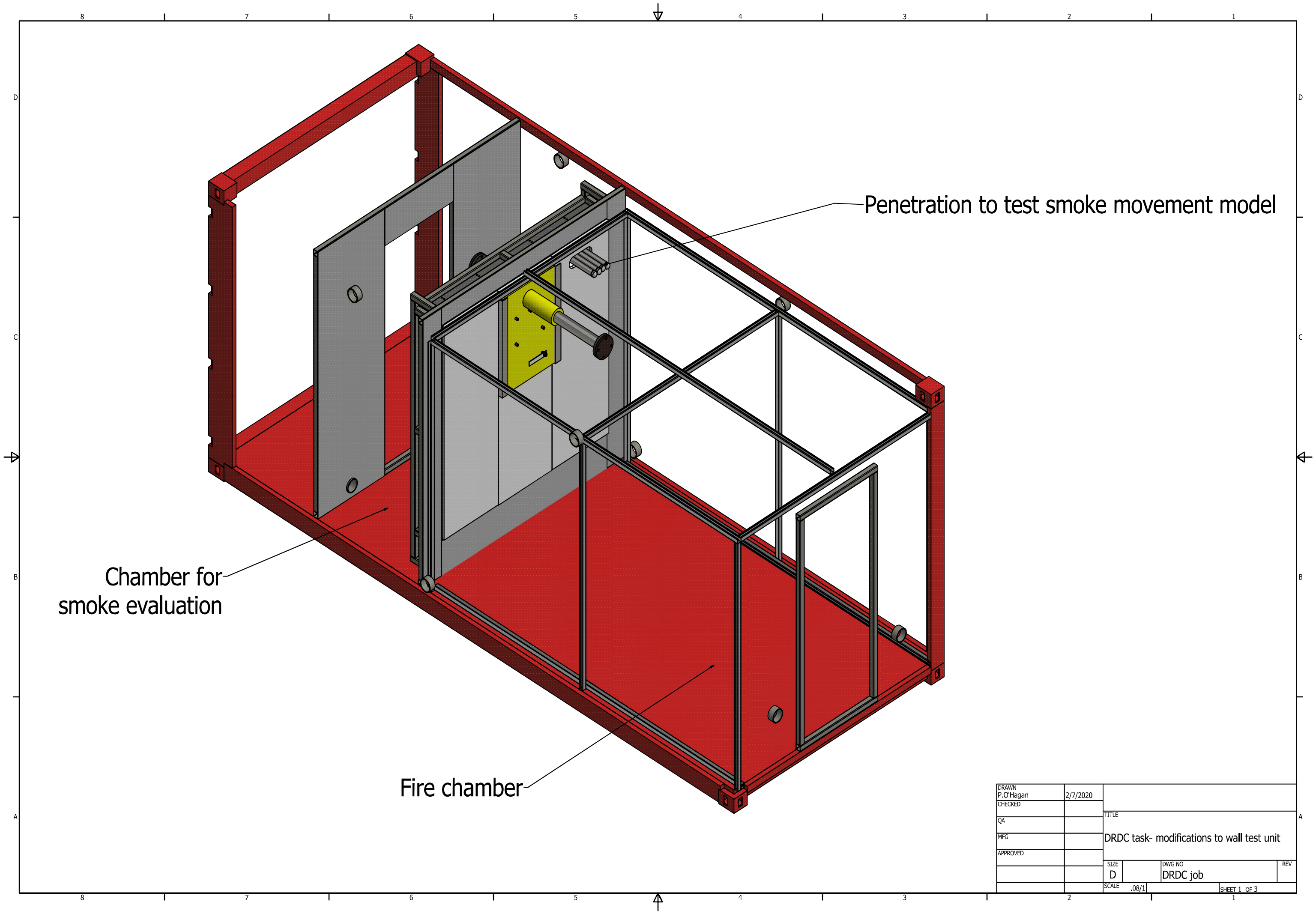
Top view
SCALE 1/12

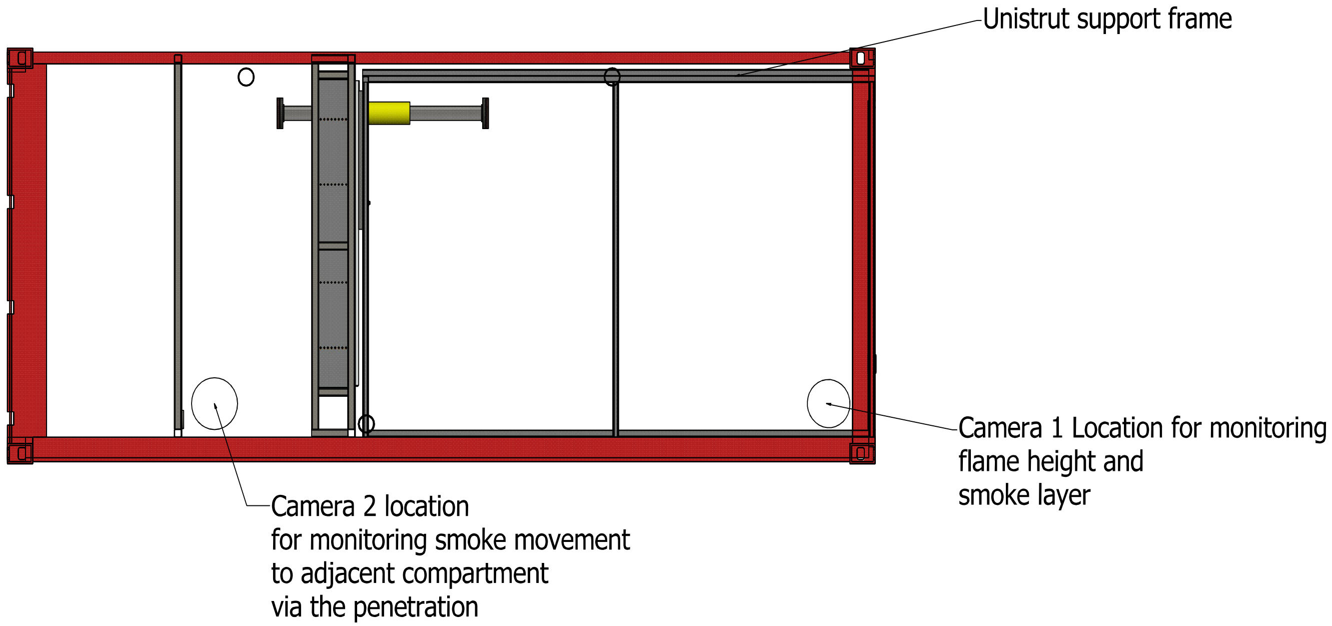
DRAWN
P. O'Hagan 10/4/2020
CHECKED
QA
MFG
APPROVED

University of Waterloo

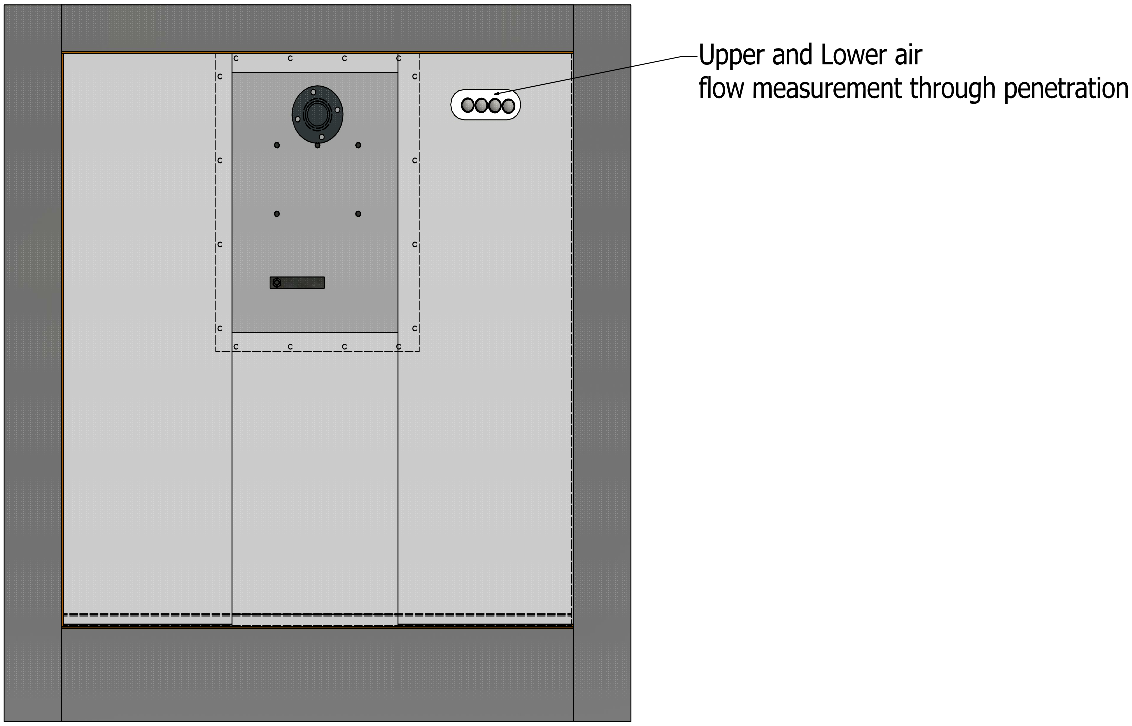
TITLE
MASc thesis assembly

SIZE D
DWG NO Navy bulkhead assembly
REV
SCALE 1/12
SHEET 6 OF 6


Penetration to test smoke movement model
Chamber for smoke evaluation
Fire chamber
DRAWN
P.O'Hagan
2/7/2020
CHECKED
QA
MFG
APPROVED
TITLE
DRDC task- modifications to wall test unit
SIZE
D
DWG NO
DRDC job
REV
SCALE .08/1
SHEET 1 OF 3
8
7
6
5
4
3
2
1
A
B
C
D

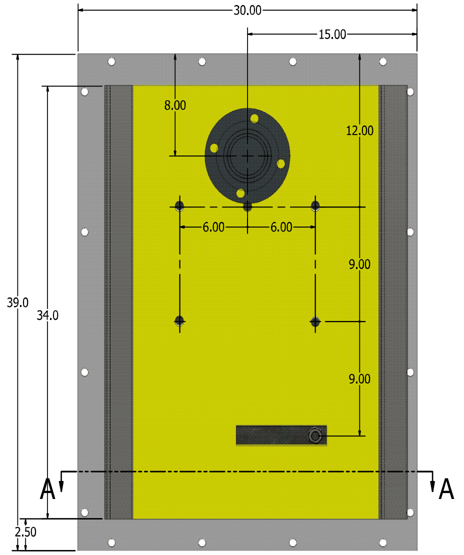


DRAWN P.O'Hagan	2/7/2020			
CHECKED		TITLE DRDC task- modifications to wall test unit		
QA				
MFG				
APPROVED		SIZE D	DWG NO DRDC job	REV
		SCALE .08/1	SHEET 2 OF 3	

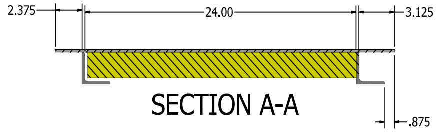


Installed Wall View
SCALE .15

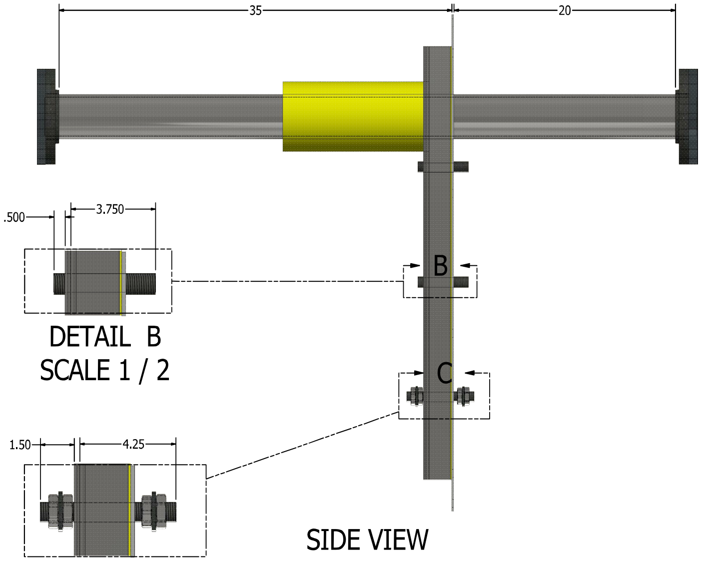
DRAWN P.O'Hagan	2/7/2020			
CHECKED		TITLE DRDC task- modifications to wall test unit		
QA				
MFG				
APPROVED				
		SIZE D	DWG NO DRDC job	REV
		SCALE .15		SHEET 3 OF 3



FRONT VIEW



SECTION A-A



DETAIL B
SCALE 1 / 2

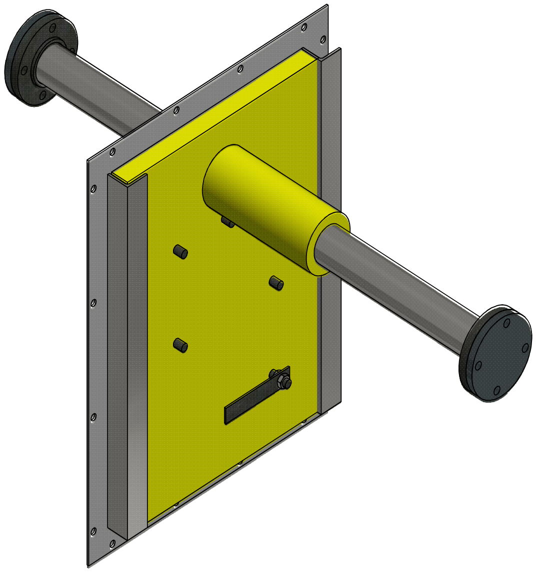
DETAIL C
SCALE 1 / 2

SIDE VIEW

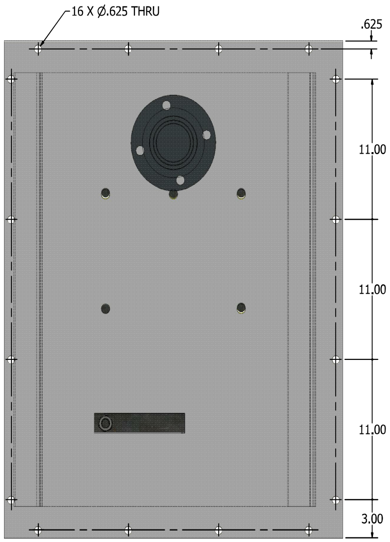
NOTE: All measurements are in inches unless noted otherwise

Materials:
Pipe: 3" SCHD 40 Steel /w standard flanges and blanks
Plate: $\frac{3}{16}$ " (0.188) Steel
Stiffeners: 2 $\frac{1}{2}$" x 2 $\frac{1}{2}$" x $\frac{1}{2}$" Steel Angle
Threaded Rod - ¾" - 10 TPI Steel rod

DRAWN Peter O'Hagan	2/4/2020				
CHECKED		TITLE Steel Test Wall - with penetrations for naval firefighting tactics			
QA					
MFG					
APPROVED					
		SIZE D		DWG NO Navy test wall	REV
		SCALE 1 / 4		SHEET 1 OF 5	

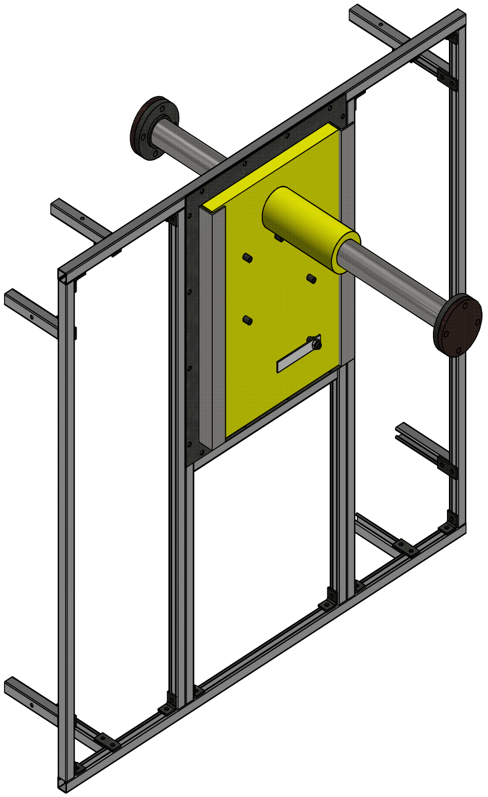


ISOMETRIC

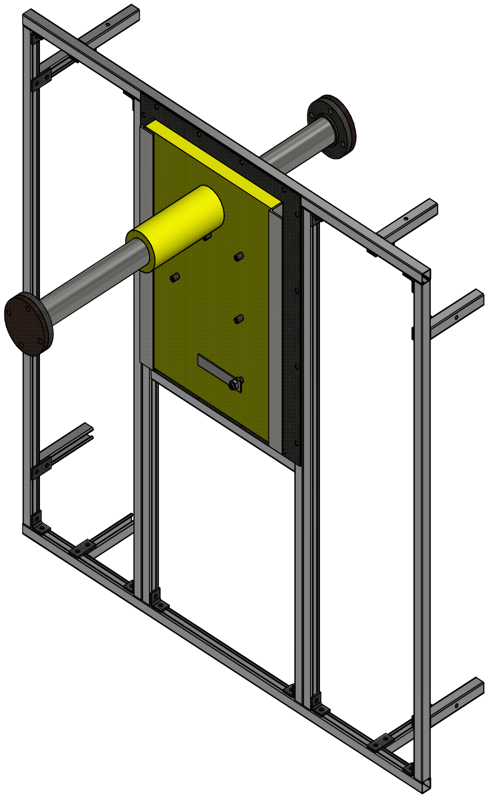


BACK VIEW

DRAWN Peter O'Hagan	2/4/2020	
CHECKED		TITLE Steel Test Wall - with penetrations for naval firefighting tactics
QA		
MFG		
APPROVED		SIZE D · DWG NO Navy test wall · REV
		SCALE 1/4 · SHEET 2 OF 5



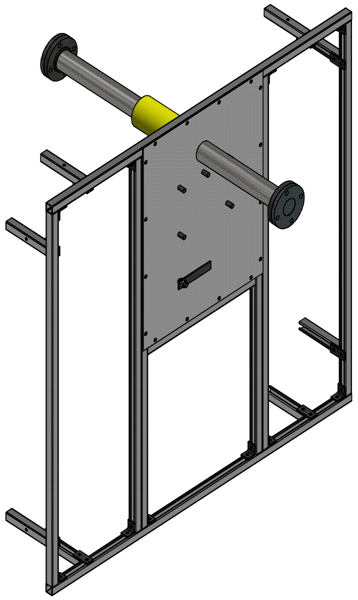
VIEW OF MOUNTED AND INSULATED WALL



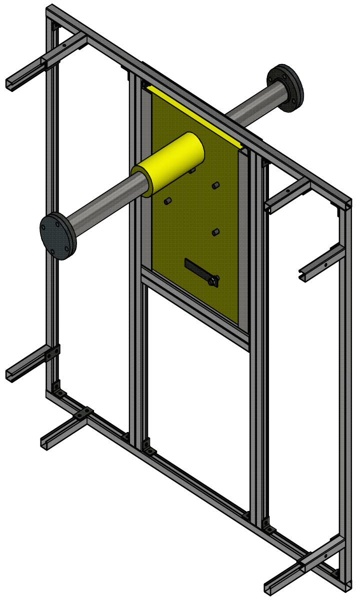
ALTERNATE

NOTES:
-existing unistrut frame shown with minor modifications
-high temp gasket to be installed between unistrut and wall mount to prevent heat transfer
-openings to be framed in and fireproofed with concrete board and fibrefrax
-bolt holes on edge of test wall to be covered with concrete board and fibrefrax
-sensor location on pipe and plate to be confirmed and added to drawing

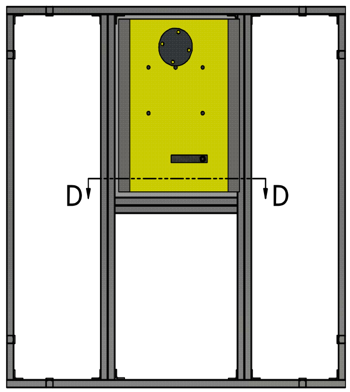
DRAWN Peter O'Hagan	2/4/2020	
CHECKED		TITLE Steel Test Wall - with penetrations for naval firefighting tactics
QA		
MFG		
APPROVED		
		SIZE D · DWG NO Navy test wall · REV
		SCALE 1/6 · SHEET 3 OF 5



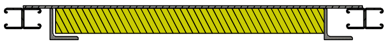
REVERSE MOUNT VIEW



BACK VIEW OF REVERSE MOUNT

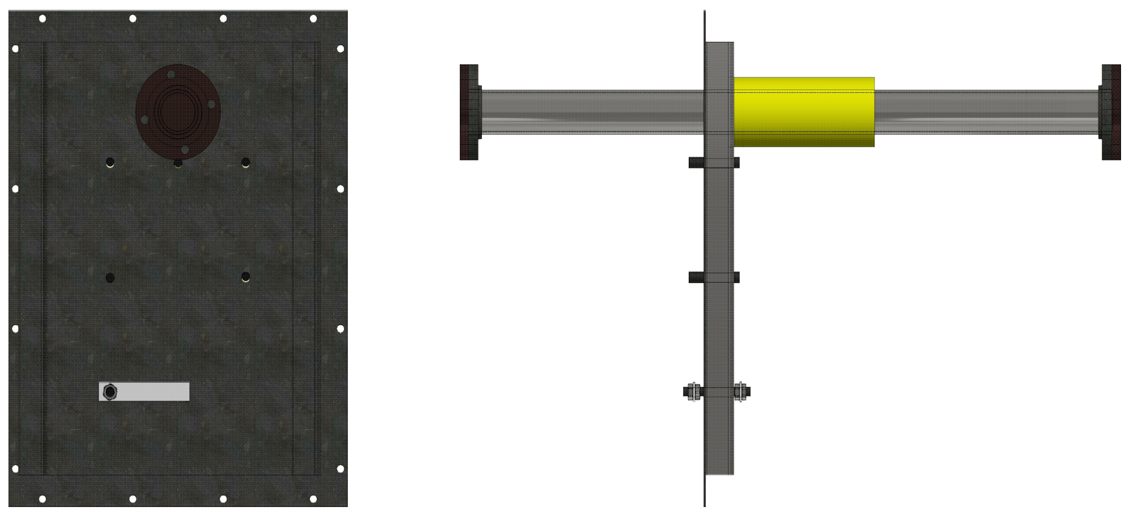


WITH INSULATION



SECTION D-D
SCALE 1/4

DRAWN Peter O'Hagan	2/4/2020	
CHECKED		
QA		TITLE Steel Test Wall - with penetrations for naval firefighting tactics
MFG		
APPROVED		SIZE D DWG NO Navy test wall REV
		SCALE 1/8 SHEET 4 OF 5



DRAWN
Peter O'Hagan 2/4/2020
CHECKED
QA
MFG
APPROVED

TITLE
Steel Test Wall - with penetrations for naval firefighting tactics

SIZE D
DWG NO Navy test wall
REV
SCALE 1 / 4
SHEET 5 OF 5

.2 Appendix B - Instrumentation Details

.2.1 Labeling Convention

The standard data acquisition setup used two separate backplanes (labeled DAQ 1 and 2) that was fitted with different modules for the thermocouples as well as analogue outputs for the gas flow transducers and the Novatech gas montitoring outputs. Each module had 8 channels, using the numbering convention of channels 0 through 7. For the Tests 2, 3 and 4 where the Novatech system was used to perform gas analysis, a third backplane (DAQ 3) with a single module was used.

To ensure consistency of the data capture with the physical connection points, each output was labeled with the convention 'Dxx Mxx C xx'. This corresponds with the back plane (DAQ 1 or 2), module (1-8) and channel (0-7). For example, D1M2C0 corresponds with the signal on back plane number 1, module 2, channel 0 (which is the ceiling thermocouple in the fire compartment on Tree number 2).

.2.2 Diagrams showing thermocouple locations

Figure 1 shows the location of the thermocouple fitted in the fire compartment, in the intermediate compartment (labeled as the back room) and on the wall mounting frame. All thermocouples are located on back plane number 1, as shown in Tabel 1.

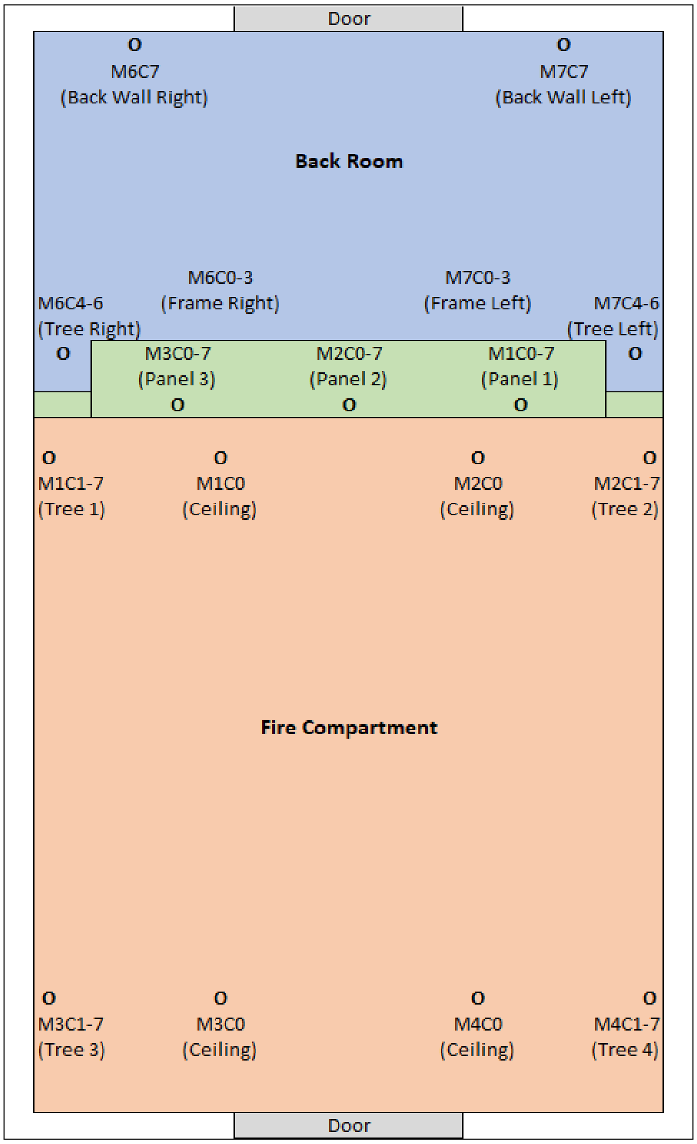


Figure 1: Instrumentation overview for the apparatus- top view [8]

Figure 2 shows the location of the thermocouple fitted on the unexposed side of the steel wall, in the same standard locations used by DiDomizio [8]. All thermocouples are located on back plane number 2, as shown in Tabel 2.

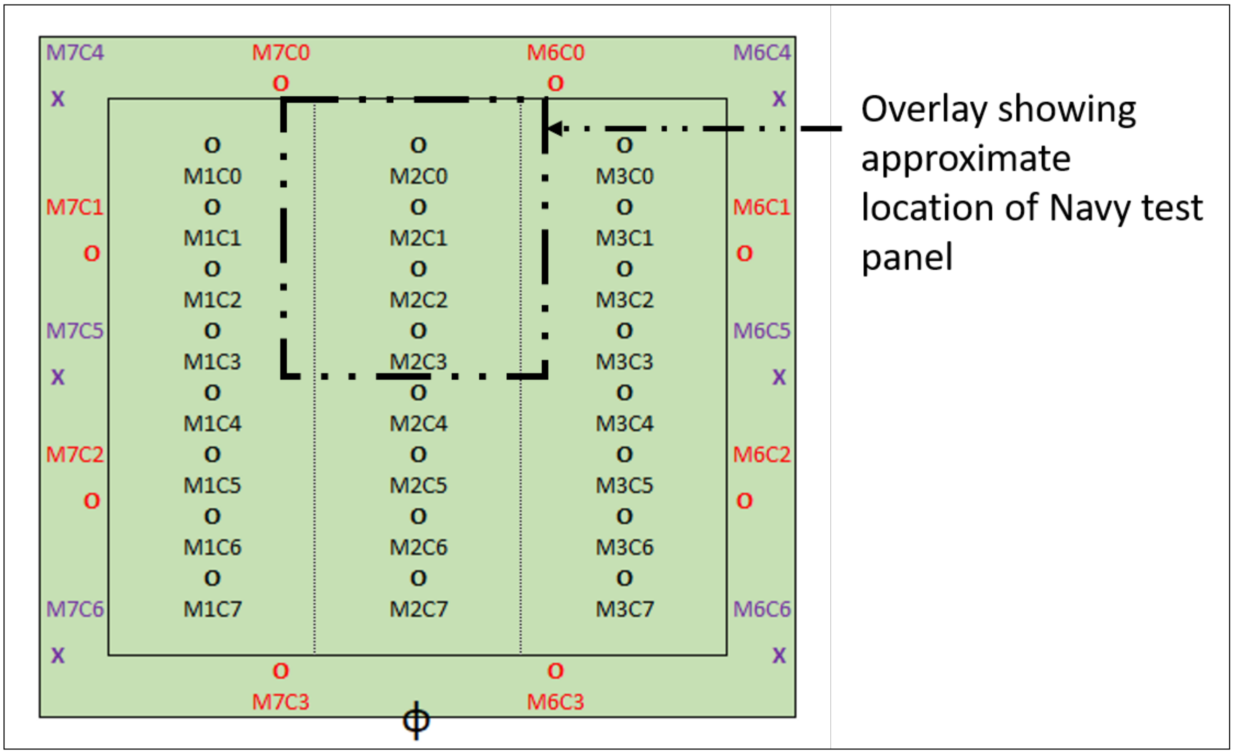


Figure 2: Wall thermocouple location- rear view [8] with overlay showing approximate location of the Navy bulkhead test panel

Figure 3 shows the location of the additional thermocouples fitted onto the unexposed side of the test wall, which included monitoring points at the stiffener connection points, the bolts used to simulate door holdbacks and key monitoring points for the plate, with the items that are required for the IMO testing marked in blue. All thermocouples are located on back plane number 2, as shown in Tabel 2.

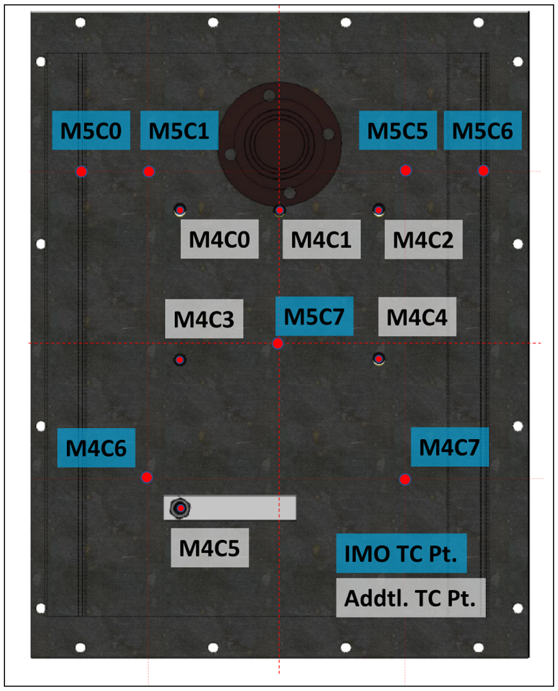


Figure 3: Navy Test wall thermocouple location. (IMO required thermocouples indicated in blue)

Figure 4 shows the location of the additional thermocouples fitted onto the unexposed side of the pipe, at a distance of 2.5 cm, 10 cm and 25 cm from the wall, with the IMO required monitoring point marked in blue. All thermocouples are located on back plane number 2, as shown in Tabel 2.

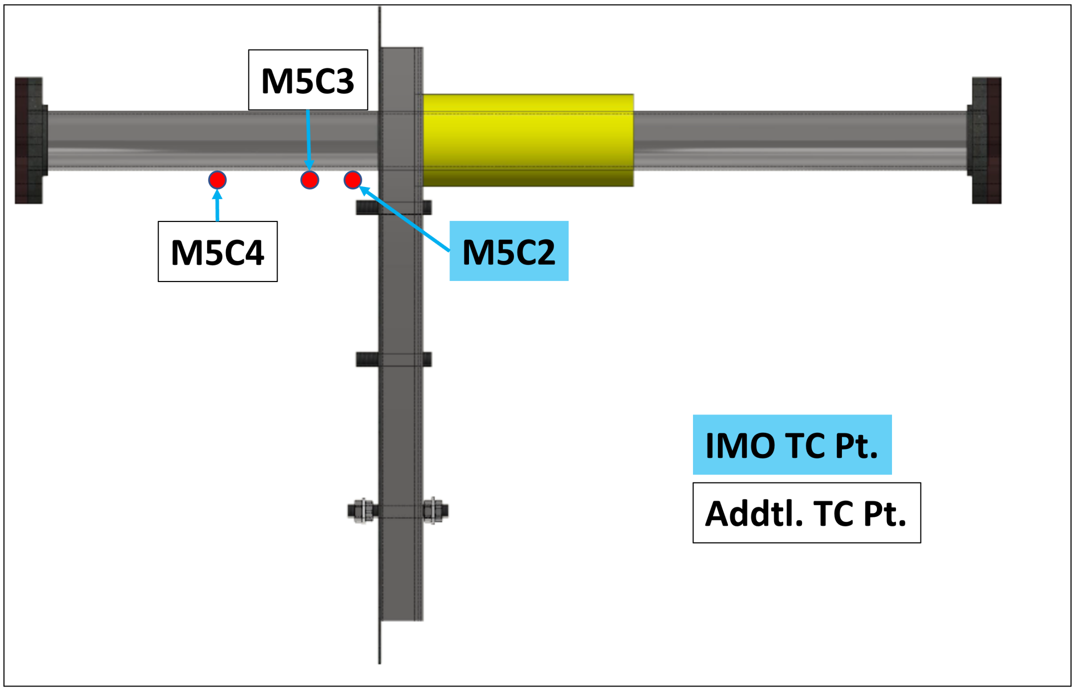


Figure 4: Pipe penetration thermocouple location

Figure 5: Thermocouple locations on the unexposed side of the pipe. (IMO required thermocouple indicated in blue)

.2.3 Full list of Data Acquisition signals

Table 1 is the full list of thermocouple inputs that was recorded in the backplane 1, and includes all the thermocouple rakes in the fire compartment and the intermediate compartment. This setup was used for all 10 Tests.

Table 1: Full list of sensor outputs to Data Acquisition system - Back plane 1

Table 1: Data Acquisition Back plane 1 signals			
DAQ	MODULE	CHANNEL	DESCRIPTION
1	1	0	Fire compartment, TC rake 1, TC0 (top).
1	1	1	Fire compartment, TC rake 1, TC1.
1	1	2	Fire compartment, TC rake 1, TC2.
1	1	3	Fire compartment, TC rake 1, TC3.
1	1	4	Fire compartment, TC rake 1, TC4.
1	1	5	Fire compartment, TC rake 1, TC5.
1	1	6	Fire compartment, TC rake 1, TC6.
1	1	7	Fire compartment, TC rake 1, TC7 (bottom).
1	2	0	Fire compartment, TC rake 2, TC0 (top).
1	2	1	Fire compartment, TC rake 2, TC1.
1	2	2	Fire compartment, TC rake 2, TC2.
1	2	3	Fire compartment, TC rake 2, TC3.
1	2	4	Fire compartment, TC rake 2, TC4.
1	2	5	Fire compartment, TC rake 2, TC5.
1	2	6	Fire compartment, TC rake 2, TC6.
1	2	7	Fire compartment, TC rake 2, TC7 (bottom).
1	3	0	Fire compartment, TC rake 3, TC0 (top).

Continuation of Table 1			
DAQ	MODULE	CHANNEL	DESCRIPTION
1	3	1	Fire compartment, TC rake 3, TC1.
1	3	2	Fire compartment, TC rake 3, TC2.
1	3	3	Fire compartment, TC rake 3, TC3.
1	3	4	Fire compartment, TC rake 3, TC4.
1	3	5	Fire compartment, TC rake 3, TC5.
1	3	6	Fire compartment, TC rake 3, TC6.
1	3	7	Fire compartment, TC rake 3, TC7 (bottom).
1	4	0	Fire compartment, TC rake 4, TC0 (top).
1	4	1	Fire compartment, TC rake 4, TC1.
1	4	2	Fire compartment, TC rake 4, TC2.
1	4	3	Fire compartment, TC rake 4, TC3.
1	4	4	Fire compartment, TC rake 4, TC4.
1	4	5	Fire compartment, TC rake 4, TC5.
1	4	6	Fire compartment, TC rake 4, TC6.
1	4	7	Fire compartment, TC rake 4, TC7 (bottom).
1	5	0	Fire compartment, open.
1	5	1	Fire compartment, open.
1	5	2	Fire compartment, open.
1	5	3	Fire compartment, open.
1	5	4	Fire compartment, open.
1	5	5	Fire compartment, open.
1	5	6	Fire compartment, open.

Continuation of Table 1

DAQ	MODULE	CHANNEL	DESCRIPTION
1	5	7	Fire compartment, open.
1	6	0	Back room, wall frame, TC0 (top-right).
1	6	1	Back room, wall frame, TC1 (right-top).
1	6	2	Back room, wall frame, TC2 (right-bottom).
1	6	3	Back room, wall frame, TC3 (bottom-right).
1	6	4	Back room, rake 1 (right), TC4 (top).
1	6	5	Back room, rake 1 (right), TC5 (middle).
1	6	6	Back room, rake 1 (right), TC6 (bottom).
1	6	7	Back room, back wall (right), TC7.
1	7	0	Back room, wall frame, TC0 (top-left).
1	7	1	Back room, wall frame, TC1 (left-top).
1	7	2	Back room, wall frame, TC2 (left-bottom).
1	7	3	Back room, wall frame, TC3 (bottom-left).
1	7	4	Back room, rake 2 (left), TC4 (top).
1	7	5	Back room, rake 2 (left), TC5 (middle).
1	7	6	Back room, rake 2 (left), TC6 (bottom).
1	7	7	Back room, back wall (left), TC7.
End of Table			

Table 2 is the full list of thermocouple inputs that was recorded in the backplane 2, and includes all the thermocouples fitted on the unexposed side of the steel wall. This setup was used for all 10 Tests. Additionally, for Tests 1 through 4, an analogue signal module was fitted in slot number 7 to record the pressure transducer outputs. Using a known calibration curve for the specific sensor, this gave the gas flow reading across the top and bottom of the opening between the fire compartment and the intermediate compartment.

Table 2: Full list of sensor outputs to Data Acquisition system - Back plane 2

Table 2: Data Acquisition Back plane 2 signals			
DAQ	MODULE	CHANNEL	DESCRIPTION
2	1	0	Steel wall, panel 1, TC0 (top).
2	1	1	Steel wall, panel 1, TC1.
2	1	2	Steel wall, panel 1, TC2.
2	1	3	Steel wall, panel 1, TC3.
2	1	4	Steel wall, panel 1, TC4.
2	1	5	Steel wall, panel 1, TC5.
2	1	6	Steel wall, panel 1, TC6.
2	1	7	Steel wall, panel 1, TC7 (bottom).
2	2	0	Steel wall, panel 2, TC0 (top).
2	2	1	Steel wall, panel 2, TC1.
2	2	2	Steel wall, panel 2, TC2.
2	2	3	Steel wall, panel 2, TC3.
2	2	4	Steel wall, panel 2, TC4.
2	2	5	Steel wall, panel 2, TC5.
2	2	6	Steel wall, panel 2, TC6.
2	2	7	Steel wall, panel 2, TC7 (bottom).
2	3	0	Steel wall, panel 3, TC0 (top).
2	3	1	Steel wall, panel 3, TC1.
2	3	2	Steel wall, panel 3, TC2.

Continuation of Table 2			
DAQ	MODULE	CHANNEL	DESCRIPTION
2	3	3	Steel wall, panel 3, TC3.
2	3	4	Steel wall, panel 3, TC4.
2	3	5	Steel wall, panel 3, TC5.
2	3	6	Steel wall, panel 3, TC6.
2	3	7	Steel wall, panel 3, TC7 (bottom).
2	4	0	Bolt 1 (B1, top left)
2	4	1	Bolt 2 (top centre)
2	4	2	Bolt 3 (top right)
2	4	3	Bolt 4 (middle left)
2	4	4	Bolt 5 (middle right)
2	4	5	Bolt 6 (handle)
2	4	6	Bottom left centre (IMO req)
2	4	7	Bottom right centre (IMO req)
2	5	0	Left stiffener (upper .75 of length, IMO req)
2	5	1	top left centre (IMO req)
2	5	2	pipe, 1” from wall (IMO req)
2	5	3	pipe, 4” from wall
2	5	4	pipe, 10” from wall
2	5	5	top right centre (IMO req)
2	5	6	right stiffener (upper .75 of length, IMO req)
2	5	7	centre of plate (IMO req)
2	6	0-7	Not used

Continuation of Table 2			
DAQ	MODULE	CHANNEL	DESCRIPTION
2	7	0	pressure transducer (flow sensor)
2	7	1	pressure transducer (flow sensor)
2	7	2	empty
2	7	3	empty
2	7	4	empty
2	7	5	empty
2	7	6	empty
2	7	7	empty
End of Table			

Table 3 lists the output from the Novatech unit, which was used to monitor the gas concentrations in the intermediate compartment. An analogue module was used to output the raw signal for each channel, which was converted to the output values using a calibration curve for each signal. The calibration curve was created using the procedures for the Novatech unit, and was done prior to the start of Tests 2, 3 and 4. The Novatech unit was unavailable for Test 1. These signals measured the unburned Total Hydrocarbons, concentrations of Oxygen, Carbon Dioxide and Carbon Monoxide in percentages, as well as the parts per million concentraion of Carbon Monoxide and total Nitrous oxides, Nitrous Monoxide and Nitrous Dioxide.

DAQ	MODULE	CHANNEL	DESCRIPTION
3	7	0	Total Hydrocarbons (THC) [ppm]
3	7	1	Carbon Monoxide (CO) [ppm]
3	7	2	Oxygen (O2) [%]
3	7	3	Carbon Dioxide (CO2) [%]
3	7	4	Carbon Monoxide (CO) [%]
3	7	5	Total Nitrous Oxides (Nox) [ppm]
3	7	6	Nitrous monoxide (NO) [ppm]
3	7	7	Nitrous dioxide (NO2) [ppm]

Table 3: Data Acquisition Back plane 3 signal list - Novatech outputs

.3 Appendix C - Full experimental results

The temperature data from the large scale testing and the small scale test results have been made available on 'Scholars Portal Dataverse' under

"Replication Data for: MASc Investigation on the implications of passive fire barriers on the fire fighting tactics of the Royal Canadian Navy by Peter John O'Hagan"

Please refer to https://dataverse.scholarsportal.info/

The video, IR images and photographs are not included due to the file size but are available upon request from the author.

Glossary

bulkhead marine terminology for a wall division 1

bunker gear (or turnout gear) firefighting protective ensemble that includes a jacket, pants, boots, a helmet and leather gloves. Normally worn with a Self Contained Breathing Apparatus (SCBA), which consists of a facemask with an air regulator and an air cylinder carried in a dedicated harness on the back. 28

deck marine terminology for a floor 1

deckhead marine terminology for the ceiling 1

hatch vertical opening through a floor (deck) or ceiling (deckhead) 1

pipe A pipe is a general announcement made over a ship's public address system; for emergencies this follow the alarm bell and provides information such as the location of the fire alarm onboard the ship 26