Royal Canadian Navy Evaluation of Handheld Aerosol Extinguishers

by

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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.

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Abstract

Defence Research and Development Canada - Atlantic is currently under a project arrangement with Sweden and Holland to investigate new or emerging fire suppression technologies in naval applications. One possible outcome of this project arrangement could be the identification of a safe and effective Halon 1301 replacement suppression agent within the respective navies. The subject area Canada has agreed to investigate is aerosol fire extinguishing agent technologies. Although aerosols have been shown to be effective in suppressing demonstration fires, to date there has been little systematic scientific research into fire suppression using aerosol particulates. Therefore, there is a need for more in depth investigation of some of the commercial aerosol products available on the market to determine their fire suppression efficacy in naval applications, as well as any potential negative impacts that the aerosol may have on personnel, equipment and the environment. Aerosol suppression systems range from small handheld grenade extinguishers to large fitted and remotely activated aerosol dispersal units. The fire research and testing presented in this thesis looks specifically at the efficacy and safe use of two variants of the small handheld aerosol extinguishers, while also assessing aerosol agent suppression technologies overall.

The Royal Canadian Navy (RCN) currently uses a two tiered response to fire, consisting of first response by a Rapid Response Team (RRT), followed by full response by an Attack Team (AT). A Rapid Attack Team (RAT) has been introduced as an intermediate response team. To enhance efficiency of the RRTs or RATs, handheld aerosol units, in this evaluation the Dry Sprinkler Powder Aerosol (DSPA) and StatX fire knock down aerosol extinguishers, could potentially be stored throughout the ship or transported by the teams to a fire scene and used to control, suppress or even extinguish a fire prior to the AT arriving on the scene, particularly in the case of smaller enclosure fires. To fully evaluate their potential for use in this capacity, it is important to carefully study the suppression efficacy of these units under conditions similar to those in which they would be deployed, as well as to better understand their impact on a fire environment in terms of important parameters such as compartment temperature reduction, visibility, oxygen concentration, aerosol particulate dwell time, and toxicity. In terms of operational issues related to deployment of these pyrotechnic tools onboard RCN vessels, it is critical to assess the requirements for extinguisher safe storage and to gain an understanding of the incendiary potential of the units, as well as post suppression overhaul, smoke/agent clearing and compartment gas free certification.

The thesis includes a description of the experimental design, measurement techniques, and key results and conclusions for each of the 26 full-scale simulated marine enclosure live fire tests that were conducted. In general, handheld aerosol extinguishers have proven to be effective for fire control and even suppression under certain circumstances. They can improve the fire safety of RCN vessels when used correctly. Experimental data measured that relate to the consequences of accidental discharge and incendiary potential can also be used to ensure naval applications are safe and effective.

Acknowledgements

I would like to extend thanks and appreciation to Dr. Elizabeth Weckman for her constant advice and guidance throughout this entire project. Her expertise and strong motivation to deliver meaningful research to the Royal Canadian Navy have contributed greatly to this project, which in turn will ensure Canada and its allies have the data and information required to make sound procurement, procedural, and training decisions to improve the fire safety in naval vessels. Dr. Weckman always had my best interests and the best interests of the men and women who serve in the Royal Canadian Navy at heart and she worked tirelessly to keep this research project moving forward in the most meaningful and valid direction possible. Her dedication to her students and the quality of their education is admirable and, by extension, it directly benefits and improves the fire safety of such essential organizations as the Royal Canadian Navy.

I would also like to thank Mr. Gord Hitchman for his help and support in the setup and conduct of over 50 full-scale live fire tests. He is an essential asset to the Fire Research Lab who clearly has a passion for significant fire research and a desire to help students obtain the most useful and repeatable experimental data possible. It is certain that this research project would not have gone as far or achieved as much in the timeframe available had it not been for the expertise of Mr. Hitchman.

Dr. Al Strong also contributed to this research by imparting invaluable wisdom in terms of enclosure fire development and fire suppression, ensuring the data captured were precise and usable. He supported some of the live fire testing and guided some of the conclusions and recommendations made to the Royal Canadian Navy. He clearly has a wealth of fire science knowledge that he willingly gave in support of this important research.

Alen Topic, a fellow graduate student under the supervision of Dr. Weckman, needs to be thanked and appreciated for his willingness to accept the toxicity and corrosivity portion of aerosol fire suppression research, which was conducted in concert with the suppression testing reported in this thesis. Alen had a very difficult topic that had not been well defined in the scientific literature and he worked very hard to learn the issues and develop experiments while also supporting the suppression testing. The importance of his research cannot be overstated as it is directly related to the safety of sailors at sea and the safety of warship equipment that together provide an essential tool for the Canadian Government in the Defense of Canada at home and abroad.

Help in this research was also received by fellow graduate students Matt DiDomizio and Kai Mikkelsen by way of technical support, thermal imaging camera operation, and backup suppression teams. Their technical savvy and sense of humour were significant contributors that are difficult to measure at times but always easy to appreciate.

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1 Introduction

Fire safety and battle damage control in Royal Canadian Navy (RCN) warships is a complex and immensely important issue due to their peacetime and wartime roles in Canadian and international waters on behalf of the Government of Canada (GOC). Operational warships must be designed to enter into a threat environment whereby an enemy may attempt to inflict deliberate harm and damage. Fire safety design considerations then must cover both the requirements for safe peacetime transit as well as quite different requirements for combat. In one sense fire protection systems on warships are similar to those on merchant marine vessels in that they must be designed to prevent or suppress fires during peacetime operations so that damage and casualties are minimized and the mission can continue. The standards and certification criteria currently utilized for merchant marine vessels come from the International Maritime Organization (IMO) and various unified Classification Societies and are largely based around the requirements for Escape, Evacuation and Rescue (EER) and rarely consider fires and damage by deliberate attack. In addition to meeting fire safety requirements for peacetime operations, however, the fire protection systems on warships must be designed to mitigate fire damage and casualties as a result of a deliberate attack in a naval threat environment, allowing the vessel and crew to continue to float, fight and move until the mission is complete. In today's asymmetric threat environment the enemy is less predictable and less well known, requiring warships to adopt higher levels of force protection postures and awareness at all times in homeport, foreign port and at sea. Therefore, the fire safety and battle damage control capability onboard modern warships are critical, directly linked with operational capability and survivability of the vessel and therefore with a nation's ability to exert a naval influence anywhere in the world.

Warship survivability for fire must consider both peacetime and wartime fire scenarios and include design criteria for fire prevention, fire detection, fire suppression, and smoke and hot gas control. The various types of compartments in warships include but are not limited to storage rooms, electronics spaces, machinery rooms, ammunition magazines, food preparation (galley and pantries), dining halls (messes), workshops, accommodations, and manned operations rooms such as the Machinery Control Room (MCR). The peacetime fire scenarios will typically be due to equipment and electrical failures, human error or negligence, and collisions. In contrast, wartime fire scenarios can be a result of missiles, torpedoes, mines, bombs, rockets, and gunfire.

Extinguishing and suppression systems currently in use by the RCN employ many different agents, including Halon, Aqueous Film Forming Foam (AFFF), carbon dioxide inert gas, fine water mist, Karbaloy dry chemical, Sapphire halocarbon gas, and low pressure water sprinklers. Depending on the application, the systems are either fixed within a compartment as 'fitted' fire protection systems or are used in portable systems that can be moved to various locations on the vessel and deployed as necessary. In addition to having fire protection systems of various kinds, warships are also compartmentalized for watertight and gastight integrity. This often allows for oxygen starvation of the fire by confinement of the fire to an airtight compartment, which aids in suppression and even extinguishment of a fire. Confinement in warships also depends on whether there have been breaches to a compartment caused by enemy fire. In this context then, it is of interest to understand not only the efficiency of various fire suppression agents with respect to their possible use in fitted or portable systems, but also to investigate the effects of full or partial fire compartment confinement on the efficiency of a given fire suppression system.

Selection of warship fire suppression systems is further complicated by other factors related to the quite different concepts of deployment in peacetime and wartime. In addition to consideration of efficiency of fire suppression in fully and partially confined compartments, factors such as crew size, ease of automation, ratio of weight to relative extinguishing power, impact on the environment, toxicity to personnel, damage and/or corrosiveness to equipment, and cost of installation and maintenance must also be considered. There is seldom a single perfect system for use in a given compartment in modern warships and therefore new technologies are continuously evaluated to understand trade-offs in performance via qualitative and quantitative data from relevant and dependable sources. New agents for commercial applications form potential candidates, but these must be assessed from a military perspective to determine whether or not they are suitable for naval applications. For this reason, Defence Research and Development Canada –Atlantic (DRDC(A)) has partnered with Dutch and Swedish allies to conduct research into, and systematically assess and evaluate, new and emerging fire suppression technologies for naval applications. It is anticipated that some of these technologies will become potential candidates for upgrading current systems and for installation in future platforms within the respective navies.

In one application, new fire suppression technologies are being investigated for current vessels in the RCN mainly for the purpose of identifying a safe and effective replacement to Halon 1301, which is still used extensively for fire protection of machinery, electrical, and occupied operations compartments in frigates, destroyers and resupply tankers. Halon 1301 is an effective total flood gas suppression agent that does not displace oxygen. Primary and reserve banks of compressed Halon are stored in tanks outside designated spaces onboard ship. The gas is released either automatically upon heat and smoke alarms, remotely from the damage control headquarters, locally from a toggle switch outside the designated spaces, or manually by opening the valves on the storage tanks themselves. While efficient for fire suppression, Halon systems are expensive to maintain through life and Halon gas has a very high ozone depletion potential. According to the Montreal Protocol, an international treaty to protect the ozone layer, Halon production was banned in January 1994 due to its environmental impact as a greenhouse gas and an ozone depleting substance. Merchant vessels utilising Halon 1301 were legislated to retrofit replacement suppression systems by the December 2003 [1]. The RCN was permitted to continue to use Halon 1301 since the safety of sailors, the protection of naval assets and naval mission success outweigh the negative environmental impacts; however, as good environmental stewards the RCN is committed to finding a suitable retrofit alternative.

Research into new fire suppression technologies is also being conducted by the RCN with respect to major recapitalization efforts which will see replacement of the aging fleet of destroyers, frigates and replenishment ships. Technology, automation and crewing philosophy currently in use in the fleet will be 30 to 60 years outdated by the time the existing vessels are replaced. This presents an opportunity to leverage new technology whilst also reducing crew task loading throughout the ships. Automation and technology can reduce operator task loading for all seamanship and naval warfare evolutions, including battle damage control. With this opportunity comes a great challenge in integrating the optimum suppression agent technology and automated fire detection and protection systems and overcoming deep rooted cultural resistance to ensure the warships of tomorrow can have better damage control capability even if they have fewer sailors. This drives a need for additional investigation into new candidate fire suppression methods.

There are numerous new fire suppression technologies available that are marketed as safe Halon 1301 alternatives effective against all classes of fire in all types of marine compartments. They include but are not limited to halocarbon gas flooding agents similar to Halon 1301 but with fewer of the chlorine and bromine atoms that are responsible for ozone depletion, as well as high pressure water mist systems, compressed-air-foam generators, and aerosol generators [2]. One relatively new fire suppression technology, and the one that DRDC(A) has agreed to evaluate, is aerosol agents for fire suppression. These may be utilised either as handheld fire knock down extinguishers or as a remote fitted systems and are potentially scalable to any volume of compartment. The aerosol agents suppress fires in a similar way to larger particle dry chemical systems such as Purple K and in that sense their efficacy is fairly well understood even if the exact mechanisms of suppression are not. Aerosols essentially consist of smaller particles of sodium or potassium bicarbonate dry chemical extinguishing agent. In fact, some listings refer to aerosol suppression agents as Micro-K [3]; however, there are aspects of new generation aerosol fire suppression agents that require further investigation. One area of major interest for naval applications relates to the generation, dispersion and settling dynamics of the aerosol agents in a given volume or compartment. Others relate to the incendiary potential of aerosol generation and protocols required for post suppression overhaul, as well as smoke/agent clearing from the fire compartment. At present, published data in the literature does not fully justify the safety and efficiency of aerosol systems for naval applications, prompting the need for further investigation into these areas.

There are both theoretical and analytical methods by which to predict fire environments and the suppression efficacy of a particular agent or system. In general such techniques are limited by the assumptions and simplifications required to keep a particular analysis or model tractable. At the present time, there is really no substitute for live fire testing in terms of determining the efficacy of any suppression agent against a fire environment. Of course, this first requires an understanding of the fire scenarios against which the agent must work. Also, the key to the experiments is to ensure that the simulated fires challenge the suppression technology in meaningful and valid ways, allowing key performance criteria such as upper gas layer cooling, effect on compartment temperature, and impact on thermal stratification to be measured. It is this challenge that is to be addressed in the experimental design for the present research.

There are so many fire scenarios possible for a modern warship that it becomes difficult to develop universal evaluation criteria for new or emerging fire suppression technologies. Added to this, the enemy of the next four decades is relatively unknown so fire scenarios will continue to change. Finally, pressures to reduce the total cost of ownership (TOC) of warships are expected to grow and since personnel costs account for almost 50% of a ship's Operations and Maintenance (O&M) funding [4], it is expected that, similar to the United States Navy (USN), there will be significant pressure to reduce future crew sizes by up to 40% [5] [6].

Fewer crew members means there are fewer damage control personnel for firefighting. At the same time, the complexity of future ships is expected to increase. Therefore, the gap between smaller crews and the same or better battle damage control capability will need to be filled with the right combination of automated fire detection and suppression systems and firefighting strategies. In terms of strategy, the Royal Canadian Navy (RCN) currently uses a two tiered response to fire, consisting of first response by a Rapid Response Team (RRT), followed by full response by an Attack Team (AT). A Rapid Attack Team (RAT) has been introduced as an intermediate response team. The future role of this team in fire control will become more critical as crew sizes decrease and thus must be considered in an overarching assessment of future fire suppression technologies. One way to enhance the efficiency of the RRTs or RATs would be to locate handheld extinguishers at various key locations throughout the ship or transport the units to a fire scene for use to control, suppress or even extinguish a fire prior to the AT arriving on the scene. New handheld aerosol suppression units are a candidate technology that needs to be accurately assessed and evaluated for such rapid battle damage control.

Since it is difficult to predetermine all the possible fire scenarios in a naval warship, one starting point is to define the most likely and/or the most dangerous scenarios that might occur. Fire statistics for naval vessels, however, are not publically available. Based on the peacetime role of warships, though, it is reasonable to consider the statistics from merchant vessels. The Transport Safety Board (TSB) of Canada has tracked marine incidents in Canadian waters over the last ten years. The total number of marine incidents reported by TSB has trended downward from 485 to 322 between 2002 and 2011; however the number of incidents due to fire or explosion has remained at about 55 per year on average [7] despite an increase in awareness of fire prevention and fire safety onboard vessels. Det Norske Veritas (DNV), a major international marine classification society, recently published a report on marine fire statistics showing that almost two thirds of fires on cargo vessels originate in the engine room as shown in Figure 1-1 [1], while the remainder occur in the cargo spaces and accommodations. The report further breaks down the origin of fire in the engine rooms, associating the cause to be oil leakage, hot work accidents, electrical failure, component failure, and boiler incidents as shown in Figure 1-2 [1].

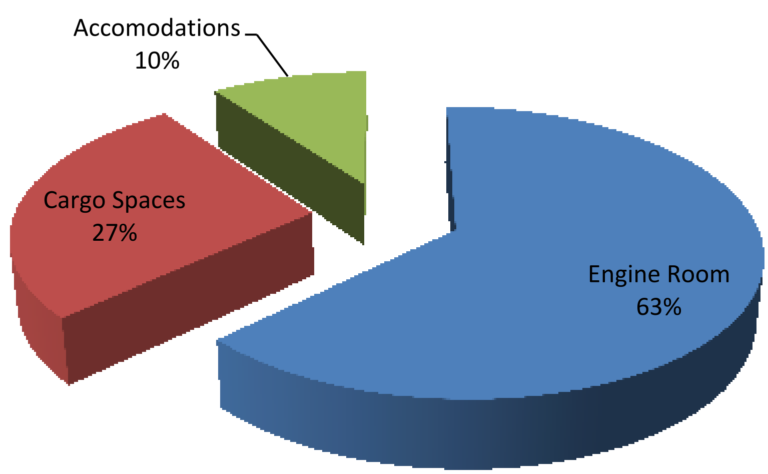

Figure 1-1. Statistical Breakdown of Fire and Explosion Locations in Merchant Cargo Vessels Reported by DNV.

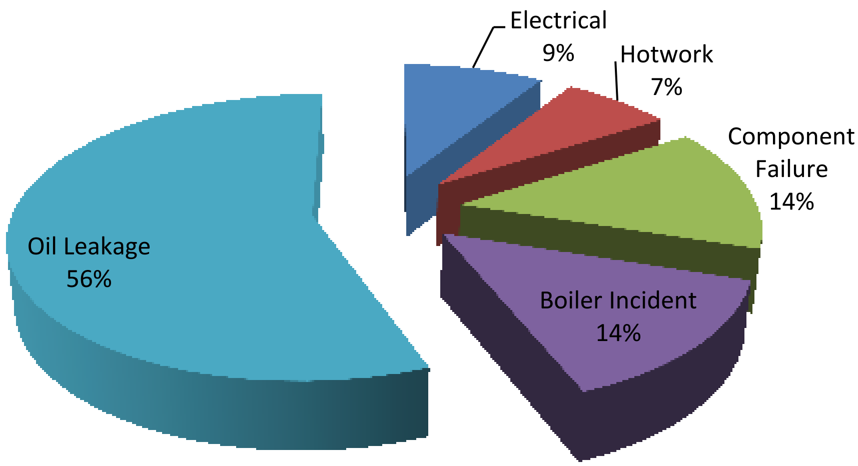

Figure 1-2. Origin and Cause Breakdown of Engine Room Fires Reported by DNV.

From these statistics, it is practical to consider engine room fires due to oil leakage as a 'most likely' marine fire scenario against which to evaluate a fire suppression agent. A warship machinery space can be massive, containing propulsion engine enclosures, transmission gearing and shafting, ancillary equipment, machinery control and signal conditioning cabinets, program logic control modules, electrical power generators, air/exhaust ducting (trunking), gangways and ladders. The amount of marine distillate fuel being pumped into the main gas turbine engines of an RCN destroyer at full power can exceed 600 ℓ/min. To burn this amount of fuel, the intake and exhaust systems need to move a stoichiometric equivalent volume of air and combustion gases. Therefore, the marine machinery space has the potential to present a significant challenge to a fire suppression system. For use of aerosol systems in this application, then, determination of the efficacy of the aerosol suppression method against a Class B, or liquid fuel fire, is essential. The types of Class B fires that might be envisaged include three-dimensional spray fires from fuel line ruptures, pool fires, bilge fires, and obstructed versions of the latter two when a fire occurs under a machinery enclosure. Since modern machinery spaces also include sophisticated platform management systems (PMS) for integrated machinery control and health monitoring, they must also be considered sensitive electronics spaces, meaning the impact of a suppression system on critical electronic equipment must also be investigated.

The second largest cause of fires on merchant vessels was in the cargo space. Warships do not typically have large cargo spaces so such fires are not considered here. Warships do, however, have crew sizes that are normally ten times those on commercial vessels, meaning accommodation spaces, the last reported fire source reported in DNV, should be a concern for suppression systems on a naval vessel. Accommodations spaces onboard warships contain mainly Class A fuels (solid combustible) so aerosol fire suppression agents should have good performance against Class A fuels in order to quickly minimize damage due to fire, smoke and hot toxic gases in accommodation fire scenarios.

There have been several tests and evaluations conducted using both fitted and handheld aerosol extinguishers that have helped to understand some aspects of their safe use on board ship as well as their suppression efficiency against both Class A and Class B fire loads for marine applications [8] [9] [10]. The compendium of results publically available on these tests leaves several key questions and concerns unanswered. For example, while there are visual accounts of the suppression of fires with aerosols, there is no data reported on actual or effective rates of cooling of the fire compartment. Similarly, the effects of compartment ventilation on the light aerosol particles has not been well studied, nor have key issues such as the relative contribution of the aerosol addition versus oxygen starvation when aerosols are discharged followed by confinement of the fire room. Finally, issues relating to safe use and storage of aerosol units on naval vessels as well as potential toxicity and corrosiveness of the aerosol agent and its residue have not been addressed. Many of these issues and concerns form the objectives of the present research on evaluation of aerosol systems for naval fire scenarios. Before outlining these objectives, though, summaries of the three main studies already conducted on aerosols by the Department/Ministry of Defence in Canada, the UK, and the Netherlands, and a fourth test conducted by an aerosol manufacturer, Fireway LLC, are provided to put the limitations of the existing information on aerosol agent suppression into further context.

In the winter of 2006, The Canadian Forces Fire Marshal's (CFFM) office conducted a test using the DSPS-5 knockdown tool, which is a handheld pyrotechnic aerosol extinguisher rated for use in a 60 m^3 compartment. The test utilised three fire scenarios in compartment sizes of 25 m^3, 36 m^3, and 126 m^3 respectively. The fuel used for each scenario was hay bales and wood cribs. The first test simulated a basement fire in the 25 m^3 room, where a DSPA-5 unit was activated after a 5 min 48 sec pre-burn. No compartment temperatures were recorded during this test, but it was noted that the unit knocked down the flames and the smoldering embers were extinguished with water 8 minutes after the start of the experiment. The 36 m^3 scenario was only to measure a relative amount of water required to suppress a hay and wood crib fire. For the third scenario, a DSPA-5 unit was activated in a 126 m^3 test room, which is double the volume for which the unit is designed and rated. Temperature readings were taken from one source at four stages during the test, but it is not clear how or where the data was collected. The remarks for this scenario state that the DSPA-5 suppressed the flames but did not extinguish the fire. The CFFM noted in his report that this test was not an in-depth trial and that further testing should be conducted on such units. With only two units tested against different scenarios on a -15^{o}C winter's day, with no characterization of the fire environment before or during suppression, and with suppression assessed largely on a visual basis, the true efficacy of the DSPA-5 was not fully determined in a repeatable or scientific manner. The test report does give expert accounts of the impact of the aerosol particles on visibility within the compartment. Normally a casualty can be seen under the smoke layer without a thermal imaging camera (TIC), but after aerosol activation the environment was fully obscured and a TIC was found essential for casualty rescue [11]. Further research building from this preliminary testing with Class A fuels should also include study of aerosol suppression of marine fire scenarios involving Class B fires, in a fully instrumented and characterized burn room, to obtain repeatable results of suppression efficacy. Impact of aerosol particulate on visibility within a compartment could be further investigated through examination of aerosol dispersion in compartments with and without fires present.

In 2010, the Royal Netherlands Navy (RNN) conducted four tests of the DSPA-5 in land-based replica marine enclosures using both Class A (wood) and Class B (low heat oil) fuel sources [12]. Similar to the CFFM tests described above, the burn rooms were not well instrumented and therefore did not provide a clear picture of changes in the fire environment during suppression testing. Some temperature measurements were taken by a firefighter thermal imaging camera (TIC) within the compartment but it is not clear which surface temperature was actually measured. Based on the reported results, none of the compartment temperatures exceeded 250°C prior to suppression; however it is difficult to ascertain an accurate compartment temperature from a TIC source. Also, the volumes of the compartments and the ventilation or leakage were not noted, making it difficult to understand the concentration of aerosol used or other important details of each scenario. The test report does provide good observational evidence of the success of DSPA-5 aerosol extinguishers against simulated marine fires in burn rooms of marine architecture, so from that respect provides valuable evidence in support of their use in naval applications.

The Royal Navy (RN) has been investigating aerosol fire suppression agents for use in the Type 45 Destroyer. This vessel is based on a fully integrated electric/electronic propulsion platform which has precipitated the move towards non-water based suppression systems [8]. Testing was conducted by the RN to evaluate the Ansul Micro-K pyrotechnic aerosol extinguishing agent for a marine machinery space and for gas turbine (GT) enclosures [9]. The large machinery space testing was conducted in accordance with the IMO MSC Circular 1007, which provides guidelines for the approval of fixed aerosol suppression systems similar to gas suppression systems in marine machinery spaces [13]. The GT enclosure tests were conducted in a purpose built apparatus to simulate something similar to a WR21 GT enclosure, including enclosure ventilation dampers. Cold discharge tests on the fitted aerosol systems within the IMO enclosure provided data on temperature and pressure increase within the compartment due to the pyrotechnic aerosol generation devices used in the systems under test. They also allowed for some qualitative assessments of deposition of aerosol residue on surfaces within the enclosure. Suppression tests in both the large marine machinery space and the GT enclosure tests met with varying levels of success. In most cases, failure to suppress test fires was attributed to compartment leakage and lack of ventilation control, which highlighted the importance of ventilation during use of aerosols to suppress fires. While the IMO protocol does specify design fires and size of enclosure, it does not specify thermal properties of the enclosure or the key aspects of the fire environment that must be established prior to suppression. These factors, along with enclosure leakage, will greatly affect the relative fire suppression challenge faced by an aerosol agent. Test to test variations in any of these factors will also make repeatable and comparative evaluation of fire suppression efficiency a challenge. Therefore, the somewhat qualitative information obtained from these tests provided limited data with respect to key issues such as the interaction between ventilation and aerosol agents, or the impact of aerosol particles on the compartment fire environment during and after discharge.

Fireway LLC conducted testing on their StatX 500E fitted pyrotechnic aerosol generators against simulated marine fire scenarios in an un-insulated 20 foot (6 m) ISO container [10]. These tests were designed to utilise similar fire loads as those specified for the large-scale IMO MSC/CIRC 1007 protocol, scaled to suit a 35 m^3 volume versus a 500 m^3 volume. The fires included open pool fires, hidden pool fires, tell telltale cans, and wood cribs. For each test conducted, the fires were allowed to grow, well ventilated, for a prescribed pre-burn period before the compartment was fully confined and the aerosol units were activated. There were 14 thermocouples installed in the compartment that show the upper gas layer temperatures exceeding 500°C prior to suppression for the Class B tests but only 114°C for the wood crib test. While these tests did provide more data than those previously outlined, it should be noted that

ISO containers are very well sealed, meaning that closing the door effectively confined the fire and starved it of oxygen immediately prior to aerosol activation. At the same time, the compartment was not well insulated so it is difficult, if not impossible, to discern the relative effect of through wall heat transfer or oxygen starvation of the fire versus that due to aerosol agent interaction with the fire and the compartment fire environment. Since full confinement may not always be possible in a warship due to compartment breach, the effects of ventilation on aerosol suppression need to be considered in future testing. In addition, tests should be conducted in which the fires are starved of oxygen by confining the compartment and not activating the aerosol suppression system. These data can then be compared to data that include compartment confinement and aerosol suppression to deduce the relative benefit or added suppression effect due to the aerosol particles.

In summary, the current research related to the evaluation of aerosol fire suppression technologies was derived from a base determination and understanding of the RCN need to improve fire survivability in current and future ships by the safest, most efficient method. Live fire testing and evaluation criteria for aerosols were developed from that need along with a requirement to design/develop accurate, repeatable, and well instrumented experiments commensurate with probable peacetime and wartime fire scenarios. The focus within the proposed test scenarios centred on key aspects of suppression efficacy and safety that have not been fully and completely investigated during testing by other defence, academic, and industry organizations. Due to the many possible situations that might be encountered on board navy ships, this broad direction was further refined to focus mainly on handheld aerosol technology.

1.1 Research Objectives

The primary objective of this research is to scientifically evaluate the fire suppression efficacy of two variants of handheld pyrotechnic aerosol extinguishers against simulated, repeatable, marine fire scenarios. This objective is met by setting up and characterizing an instrumented single fire compartment experiment with fuel loading and ventilation parameters set to produce a consistent and repeatable fully developed fire environment. Live fire suppression tests are conducted to evaluate key suppression parameters such as upper gas layer cooling rate, impact on thermal stratification, and total compartment cooling effect. Secondary objectives of the research relate to safety and safe storage of the pyrotechnically activated aerosol units, as well as the impact of evolved gases and aerosol particulate deposition on equipment. These are addressed respectively through dedicated tests to evaluate safe storage and incendiary potential of the units and via agent only (or cold compartment discharge) tests in the compartment. While the testing is designed to evaluate handheld aerosol extinguishers, the analysis, conclusions and recommendations pertain to the broader subject of pyrotechnically generated aerosol agents in general, both as possible Halon 1301 replacement agents or as may be scaled to suit multiple marine, and other similar fire, applications.

The next chapter of this thesis provides background information from the literature on aerosol suppression technology in general, followed by information more specific to pyrotechnic aerosol devices. In Chapters 3 and 4, the experimental design and techniques developed to test two variants of handheld aerosol extinguishers are also outlined in detail. Following this key test results are presented and discussed in Chapter 5 with conclusions and recommendations related to fire suppression using pyrotechnically generated aerosol agents summarized in chapter 9.

2 Aerosol Agent Suppression Background and Theory

An aerosol refers to a system of micron sized liquid or solid particles suspended in a gaseous medium. Several common aerosols include fumes, smoke, mists, fog and haze [14]. It is important to appreciate that there are several different classes of physical fire suppressants, such as fine water mist, that can be considered aerosols by definition. For the purpose of this thesis, the aerosol fire suppressants under investigation are those formed of micron-sized alkali metal salts such as potassium carbonate [15]. Alkali metal salts, in particular sodium and potassium bicarbonate, have been used as fire suppressants since at least the early 1940s. The first NFPA standard on them was issued in 1955 [15]. Their suppression efficacy has, therefore, been appreciated for many decades. During the 1980s to the present, attention and research efforts into aerosol fire suppression have focused on micron-sized alkali metal salts suspended and delivered to the fire environment in a gaseous medium, as the inverse relationship between particle size and suppression efficacy has been better understood [16]. Another reason for recent attention given to alkali metal salt aerosol extinguishers is that they are a relatively inexpensive technology [17] and have been identified by several organizations such as the United States Environmental Protection Agency as safe and suitable substitutes for Halon 1301 [3].

Aerosol fire suppression systems are marketed as environmentally friendly agents that do not displace oxygen from the compartment during suppression, although they do cause a minor oxygen dilution [10] [18]. Published data indicates they have an ozone depletion index of zero and produce minute amounts of greenhouse gas emissions [19]. It has also been shown in some experimental results that aerosol agents are non-toxic and are considered safe for use in normally unoccupied spaces, while certification for use in occupied spaces is still pending [20]. Additionally, some basic studies have demonstrated that aerosol agents are non-corrosive against materials such as copper 110, bronze 905, steel 1010, stainless steel 303, Aluminum 6061, galvanized steel, PC board (epoxy), nylon, PVC, and tin [21] [22]. It is from this basis that further background and theory of aerosol extinguishing agents was conducted and is reported in this Chapter.

In general, aerosol extinguishers do not cool the fire or fire environment as much as is the case during water suppression and they do not separate the fuel from the air as do foam agents. Instead, they achieve fire suppression by slowing the chemical reaction within the burning regions. Aerosols agents have been shown to suppress all classes of fire with varying degrees of effectiveness. They are least effective against Class A fires, and especially materials that char, as they are not as effective as foam or water at penetrating any unburned materials and reaching the deep burning embers [23]. Thus, while aerosols can knock down the flames in Class A fires, fire overhaul with water is normally still required to completely extinguish the fire.

There are typically three methods of delivering the aerosol suppression agent to the fire compartment: 1) piping in and dispersing prefabricated micron particles using a powerful ventilator such as a compressed inert gas system, 2) discharging, pulverizing and propelling prefabricated micron particles through a nozzle by an impulse generated from a small pyrotechnic charge, and 3) generating condensed micron particles in place through the thermal decomposition of a solid fuel tablet. The first method is typically referred to as a powder aerosol system, the second as a propelled aerosol system and the latter referred to as either pyrotechnically generated aerosol, encapsulated micron aerosol agent (EMAA) or condensed aerosol systems. There are advantages and disadvantages to all methods. For example, method 1, powder aerosols, require most of the same piping, nozzles and compressed gas cylinders as halocarbon or inert gas drenching systems, which are expensive to procure, install and maintain through service life. For methods 1 and 2, powder and propelled aerosols, production of the micron sized particles of potassium based agent is an expensive process and the particles tend to agglomerate in their storage canisters over time, reducing the reliability of the systems [24]. Pyrotechnic aerosol suppression agents (method 3) produce a large amount of heat during thermal decomposition of the solid fuel. Hot gases and, in some cases, flames that are ejected from the canisters during aerosol generation can be a significant thermal hazard [24]. Since the handheld units of interest in this research are based on pyrotechnically generated aerosols, generation of these agents, suppression mechanism, as well as some advantages and disadvantages of the technology are discussed in more detail in the following sections.

2.1 Pyrotechnically Generated Aerosol Suppression Agent

Pyrotechnically generated aerosols are produced by the combustion or thermal decomposition of a hermetically sealed solid active compound containing inorganic oxidizers and salts, and an organic or inorganic combustible that normally also serves as a binder [25]. The aerosol extinguisher canister basically contains solid rocket fuel that is thermally ignited by pyrotechnic fuse or resistive element and the products of the thermal decomposition process are the actual fire suppression aerosol agents [2]. There are numerous combinations of compounds currently in use to produce alkali metal-based aerosols for fire suppression. In most cases, the active compounds use an oxidizer that is either the nitrate or perchlorate of either sodium or potassium, while the fuel is an organic polymer [26]. Potassium based oxidizers have been shown experimentally to have a higher suppression efficacy [24] and are therefore more commonly used in the pyrotechnic compositions. Examples of the oxidizers in use include potassium nitrate, KNO_3, potassium perchlorate, $KClO_4$, and potassium chloride, KCl [25]. The fuel or combustible is typically a phenolic, polyester or epoxy resin [26].

Once the solid compound is ignited, the oxidizer reacts with the fuel and binder. This reaction is highly exothermic and produces alkali metal salts in gaseous form. These later cool and condense into extremely fine solid particles with a 1 μm mean diameter [26] suspended in product gases. The product gases are inorganic, including nitrogen, N_2, carbon dioxide, CO_2, and water vapour, H_2O. Depending on the oxidizer and the fuel binder used, other gas species may be produced as well, such as oxides of nitrogen and carbon monoxide. As an aerosol, the fire suppression agent is approximately 40% solid particles and 60% gases [14]. The thermal decomposition process associated with pyrotechnic solid compounds rapidly generates a large amount of hot gases that can increase compartment temperature and pressure. One way to appreciate this effect is to remember that motor vehicle airbags utilize similar technology, the combustion of a solid pyrotechnic tablet, to produce expanding gases that fill airbags in milliseconds [2].

2.2 Mechanism of Aerosol Agent Suppression

Any fire suppression system is designed to interrupt at least one of the factors shown in Figure 2-1 that are required to sustain a fire (heat, fuel, oxygen and chain reaction) [27]. While it is commonly understood that a fire requires fuel, oxygen and heat to exist and to persist, the fourth factor, chemical chain reaction, is less appreciated and less understood. Table 2-1outlines the factors governing fire propagation and some the mechanisms and methods commonly used in RCN warships to suppress fire [14]. While the table lists the major mechanisms of suppression, most suppression methods will also have minor effects on another element essential to fire propagation. Such interactions make comparisons of the relative suppression efficiency of various agents complicated.

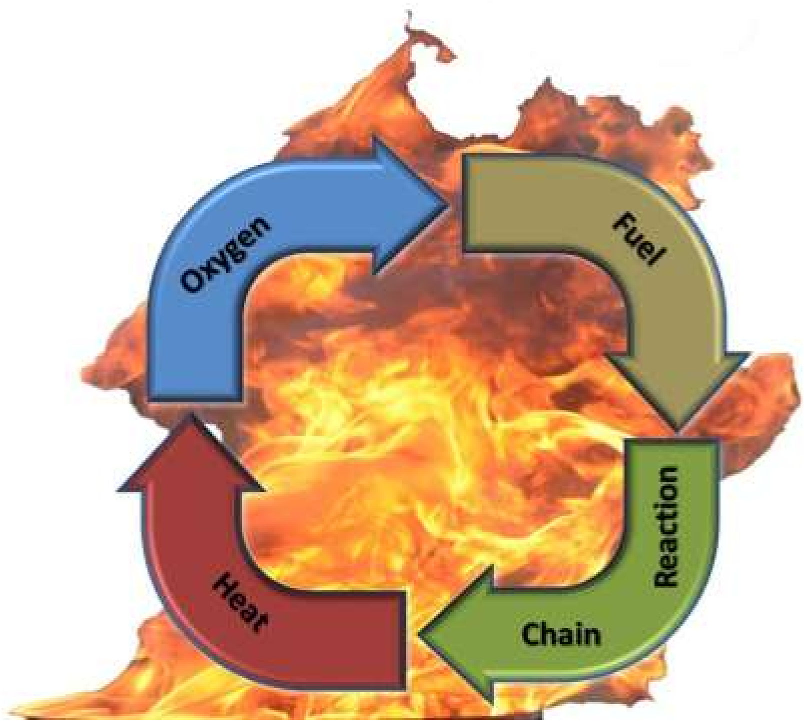

Figure 2-1. Factors Governing Fire Propagation

Table 2-1. Methods and Mechanisms to Interrupt Fire Propagation

Factor	Suppression Mechanism	Method	Example
Fuel	Removal	Vapour Seal	Foam
Oxygen	Exclusion	Smothering	Inert Gas Flooding
Heat	Absorbance	Cooling	Water Sprinklers
Chain Reaction	Inhibition	Stop Reactions	Halon

The pyrotechnically generated aerosol agent considered here is comprised of a mixture of approximately 40% micron-sized solid particles and 60% gases, the major components of which are water vapour and inert gases including nitrogen and carbon dioxide. For the present discussion, it will be assumed that the base pyrotechnic reactant is primarily potassium nitrate, KNO_3, such that the solid particulate phase of the aerosol suspension will be potassium carbonate, K_2CO_3.

An aerosol composed of the above particulate and gaseous compounds will work to interrupt three of the four factors that govern fire propagation. To varying degrees the aerosol mixture acts to absorb heat from the fire environment, inhibit chemical chain reaction within the reacting zones, and dilute the available oxygen in the compartment. As the aerosol agent is delivered to a fire environment heat will be absorbed from the fire and the fire environment due to the intrinsic cold mass of solid particles injected into the compartment, which is potentially further augmented by heat absorbed due to endothermic decomposition reactions of the K_2CO_3 molecules when exposed to the heat in the fire [15]. Some studies have shown that the heat absorbed by micron-diameter potassium carbonate particles as a result of such reactions is approximately 5.5 kJ/g [15], but it must be recognized that this value would also be directly proportional to the initial temperature of the aerosol [28]. The second mechanism of suppression key to aerosol systems is chemical inhibition. This takes place via the recombination of potassium radicals with the hydrogen, oxygen and hydroxyl radicals within the combustion zones to form stable molecules such as potassium hydroxide [25]. The hydrogen, oxygen and hydroxyl radicals are critical in sustaining combustion of most hydrocarbon fuels, so oxidation of the fuel (i.e. the fire) cannot be sustained when they are scavenged from the combustion zones. In the case of aerosols, the recombination occurs first heterogeneously on the surface of the potassium carbonate aerosol particles that are entrained into the flaming zones of the fire. Later, the recombination occurs homogenously as the particles are heated and sublime into a gaseous phase [22]. Figure 2-2 provides a pictorial representation of the chemical inhibition mechanism associated with aerosol suppression agents [18]. The third, less substantial mechanism of suppression due to aerosol agent interaction with a fire is oxygen exclusion in the vicinity of the fire. The water vapour and the inert nitrogen and carbon dioxide gases generated during formation of the aerosols dilutes the environment and therefore reduces the overall concentration of oxygen available to sustain the fire in the compartment.

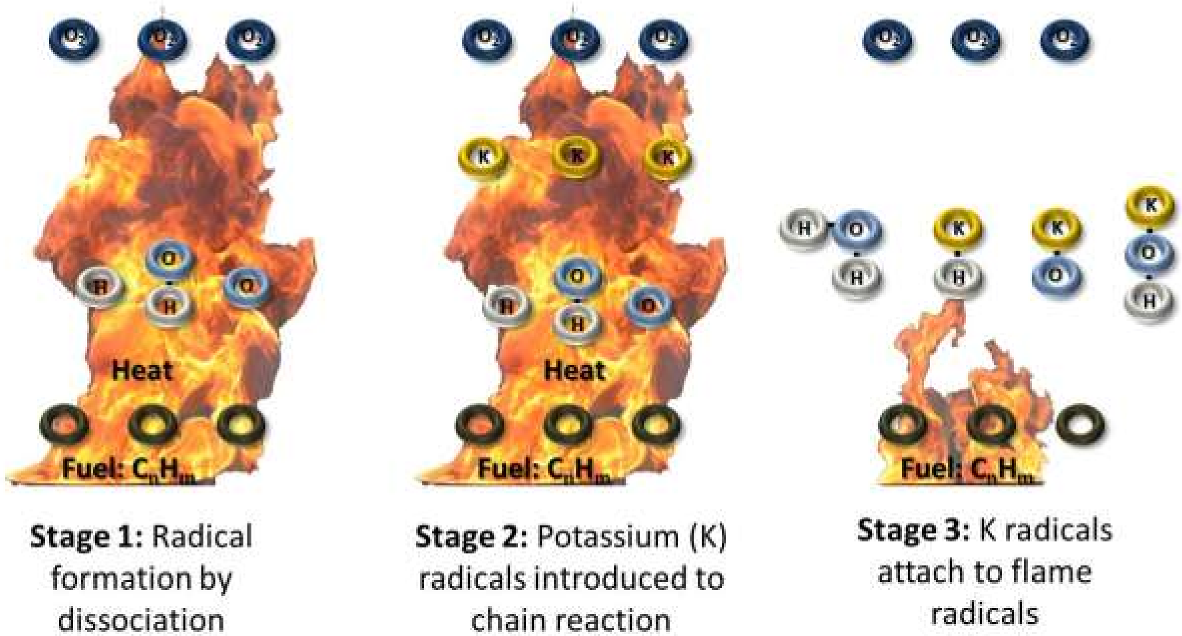

Figure 2-2. Chemical Inhibition within the Flaming Surface as a Result of Aerosol Suppression

The potassium carbonate particles propelled from aerosol extinguishers have a mean diameter of approximately 1 µm [16]. These small particles have a large surface area per unit mass. Since the heat absorption and the heterogeneous catalysis mechanisms by which aerosols work are both surface reactions, a greater surface area (smaller aerosol particles) should have a greater suppression effect [25] Additionally, Agafonov et al suggested that the aerosol particles formed via pyrotechnic action (newly condensed particles generated via combustion of a solid pyrotechnic tablet) have fresh and clean surfaces making the recombination process substantially more effective [25]. Therefore, there is expected to be an inverse relationship between suppression efficacy and aerosol agent particle size. In a real fire situation, however, there are other trade-offs that must be considered with respect to the efficiency of aerosol suppression as are discussed in the next section.

2.3 Aerosol Particle Dynamics

As discussed above, fire suppression efficacy of aerosol agents should be inversely proportional to particle size due to the greater surface area per unit mass of agent. Efficacy in this context, though, assumes that the aerosol particles are uniformly dispersed at a proper concentration throughout the compartment such that heat absorption and chemical chain inhibition occur at maximum efficiency on all surfaces and thereby particles are optimally sized to suppress a fire. There are, however, other key physical phenomena that must also be considered in determination of the actual interaction between aerosols and the hot gases and flaming zones in a compartment fire [29]. These relate to concentration and dispersion of the particulate in the compartment, each of which is discussed further below.

At one micron in size, pyrotechnically generated aerosol particles are sufficiently small that they should remain suspended in air for up to 60 min depending on ventilation [25]. Design guidelines are therefore set based on the requirement of achieving a minimum particle concentration in a space for effective suppression. The amount of aerosol needed for a given situation depends on compartment volume and ventilation. This requires the systems to be specifically designed to suit each space since the effectiveness of handheld or portable aerosol systems will be dependent on compartment size and ventilation. Experimental data available in literature suggests a fairly wide variation in the density of particulate that is required for fire extinguishment using aerosols. For most variants of aerosol agents, for example, the suggested particle density in the fire compartment is between 50 to 90 g/m^3 assuming direct material activation in an enclosed area [24]. Lower concentrations would be appropriate for hermetically sealed compartments or compartments with a high level of confinement, while the higher concentrations would be used for compartments that cannot be completely sealed or confined. Higher concentrations would also be required to reach the seat of the fire in situations that contain solid combustibles that char and smolder. In comparison to other agents, however, the density of aerosol agent required for fire suppression is low. For example, the required concentration of dry powder (potassium bicarbonate or Purple K) for suppression varies from 130 to 500 g/m^3, while brominated and chlorinated halon concentrations range from 160-340 g/m^3 [25].

As well as the density and suspension of the aerosol agent, the dispersion of the aerosol particulate within a fire compartment is important to efficient suppression of the fire. Dispersion is directly proportional to the mass of particles and the velocity with which the particles are issued into the space, while the suspension or dwell time (once they have been dispersed) of the particles is inversely proportional to the particle mass and surface area. In general, larger particles with more momentum will be better able to penetrate turbulent gas flows encountered in well-developed compartment fire environments, yet they will fall out of suspension earlier. Smaller particles have a greater surface area relative to their mass, and will have a lower settling velocity since the particle buoyancy and viscous air resistance or drag is closer to the force of gravity acting downward, allowing for a longer suspension times [15]. A formula for settling velocity is provided below [30]:

$$v_s = \frac{2}{9} \cdot \frac{(\rho_p - \rho_f)}{\mu} \cdot g \cdot R^2 \qquad [1]$$

where: v_s is the particle settling velocity (m/s), g is the gravitational acceleration (m/s^2), ρ_p is the mass density of the particle (kg/m^3), ρ_f is the mass density of the fluid (kg/m^3) and R is the particle radius.

For example, the settling velocity of a spherical particle of potassium carbonate with a diameter of 10 μm is approximately 5 mm/s, while the settling velocity of 1 μm particle is approximately 0.05 mm/s [15].

Smaller lighter particles may have a longer dwell time and greater suppression efficacy, however, it is not clear whether they will have enough momentum to carry them against the flows in a fully developed fire scenario and allow them to get to the flaming surfaces of the fire. The concern is whether the smaller aerosol particles are more easily impacted by ventilation, buoyancy and turbulence within a fire environment such that they are more easily carried away from the fire before acting to suppress the flames. This is less of a concern in situations where compartments can be completely confined prior to aerosol activation, as the agent is contained and suppression by oxygen starvation works in conjunction with the action of the aerosol. In unconfined compartments, the inverse relation of particle size to suppression efficacy may be negated by the fact that particle momentum is insufficient for good dispersion throughout the fire environment. To better understand these interactions, one can look towards research related to determining the optimum water droplet sizes needed for suppression. In research to find optimum water droplet size, a balance has been found between the momentum needed from larger droplets (i.e. 5 mm diameter) to penetrate a fire plume, and the benefits of smaller water droplets (i.e 0.5 mm diameter) that vaporize more rapidly and absorb heat to cool the entire environment [31] [32]. Smaller droplets, as with aerosols, are more easily overcome by the turbulent gas flows within a fire environment. Research by Back et al has shown that fine water mist may be more effective for small confined spaces, while larger droplets may be more effective in larger compartments [33]. For water systems, previous research has appreciated the physical influence of the fire plume and other ventilation pathways on water droplet size particularly when minimizing the use of water while achieving fire suppression is a key factor [34]. The physics and lessons learned for water droplets may to some degree be valuable when evaluating the limitations of micron-sized aerosol agents as well, although comparisons such as these have not been reported in the literature to date. Instead, much of the information on interaction of aerosols with fires is of a more qualitative nature, presenting fairly general information on the advantages and disadvantages of their use. Key points related to this are discussed in the next two sections.

2.4 Advantages of Pyrotechnically Generated Aerosol Agents

Pyrotechnically generated aerosol extinguishing systems are marketed as offering several key advantages for use in naval applications. Manufactures bring focus to the high effectiveness of aerosols in terms of weight to extinguishing power ratio. This advantage is what makes a lightweight handheld aerosol extinguisher possible and practical. It is also a significant advantage for large fitted systems where canisters can be easily installed and distributed to protect compartments of any size without the piping, nozzles, pumps, accumulators, foam proportioners, or compressed gas cylinders needed for many alternative suppression systems. As such, a pyrotechnic aerosol fire protection system is relatively simple and inexpensive to install as either a retrofit or in new construction. The materials used to form the solid active tablets are also readily available and affordable. Further, the pyrotechnic canisters have a shelf life of 10-15 years with minimal preventative or planned maintenance requirements, reducing through-life costs and operator workload. The reduced maintenance requirements can also be viewed as an advantage in terms of greater system reliability. A recent (2012) National Fire Protection Agency statistical study has shown that 44% of all non-water-based automatic suppression system failures were due to a lack of or incorrect maintenance being performed [35]. It stands to reason, then, that if an automatic system requires less maintenance there will be fewer operator injected faults, increasing the system reliability. Despite these advantages, however, there are also some concerns with use of these aerosol suppression systems as discussed in the following section.

2.5 Common Concerns Associated with Pyrotechnically Generated Aerosol Agents

2.5.1 Toxicity

Although marketed as environmentally friendly agents, there are concerns over potential toxic hazards associated with fire extinguishing aerosols. This is an important performance characteristic, especially in the context of a relatively confined marine or naval application. Even if such extinguishing agents are only utilized in normally unoccupied spaces, there is still potential for human exposure either by improper confinement or by accidental release.

The thermal decomposition of the pyrotechnic aerosol forming compounds produces gas species composed mainly of CO_2, N_2, and H_2O vapour which mix with the ambient air; however, the literature suggests there is a potential for the production of other toxic species such as oxides of nitrogen (NO_x or NO and NO_2) and carbon monoxide, CO [15]. For example, Kidde International Research found that KNO_3 based pyrotechnic aerosols produce NO concentrations between 300-600 ppm [26] and CO between 350-3000 ppm [36]. Pyro-aerosols have also been shown to produce trace amounts of hydrogen cyanide (HCN) between 10-15 ppm [36]. Additionally, irritation and possible interference with pulmonary function of human mucus membranes can occur after penetration of ultra-fine solid particles of potassium salts, especially when combined with low concentrations of CO and NO_x [36]. Potassium carbonate, for example, is an irritant to human mucus membranes, particularly the eyes, and needs to be flushed immediately upon contact [37]. By way of setting possible benchmarks for later comparison with measurements, it is of interest to compare measured levels to some of the existing standards for NO_x, CO and HCN exposure outlined in occupational health and safety literature.

In the case of nitrogen oxides (NO_x), toxicological concentration thresholds are generally specified with respect to measured values of NO_2 since better data is available for toxicology of NO_2 and NO_2 is most often used as an indicator for the presence of nitrogen oxides (NO_x). In addition, NO_2 is five times more acutely toxic than NO [38]. That said, it should be noted that there is little consistent evidence of long term health effects with exposure to NO_2 and there is still significant uncertainty in human exposure-response data for both acute (< 3 hour) and long term exposure [39]. According to the World Health Organization (WHO), sub-chronic or acute exposures to concentrations of NO_2 of as little as 2 ppm can have some physiological impacts particularly in the case of children between the ages of 5 and 12, and asthmatic adults [39]. As such, the levels of exposure proposed in the WHO guidelines are 0.1 ppm for continuous 1-hour exposures and 0.02 ppm for long term exposures [39]. In contrast in the USA, the Occupational Safety and Health Administration (OSHA) has set a higher 15-minute exposure limit of 5 ppm for NO_2 in workplace air, with an IDHL of 20 ppm [40]. They also indicate a permissible exposure limit of 25 ppm NO averaged over an 8-hour work shift, with an IDHL of 100 ppm [40]. Other published levels suggest ten minute exposure levels for NO_2 of 5 ppm; while exposure to several hundred ppm over the course of minutes is purported to cause deep lung irritation leading to pulmonary edema or fluid buildup in lungs, which can also lead to death [38]. Although not as pertinent to this work, the EPA has established that the average concentration of NO_2 in ambient air in a calendar year should not exceed 0.053 ppm for outdoor exposures [41]. Therefore, the overall lack of sound toxicological data for nitrogen oxides and consequent uncertainty in potential threshold and exposure values may make it difficult to assess the toxicity of the NO_x production of pyrotechnically generated aerosols [40].

Since the binding resin in the pyrotechnic tablet is polymer based it is a hydrocarbon fuel, which accounts for the production of CO_2 and other common exhaust gases during combustion. Incomplete combustion of hydrocarbon fuels leads to production of carbon monoxide, CO, which is a clear, colourless and poisonous gas. Existing short-term exposure guidelines published by the National Research Council (NRC) set Emergency Exposure Guidance Levels (EEGLs) for CO as follows: 10-minute EEGL: 1,500 ppm, 30-minute EEGL: 800 ppm, 60-minute EEGL: 400 ppm, and 24-hour EEGL: 50 ppm. NRC has also set the lethal concentration to humans at 5000 ppm for 5 min [42]. The National Institute for Occupational Safety and Health (NIOSH) has set the Time Weighted Average (TWA) for CO at 35 ppm with a ceiling of 200 ppm [43]. CO levels produced from pyrotechnically generated aerosol units vary widely based on the solid tablet composition. Kopylov et al studied the CO production from five different pyrotechnic aerosol combinations, all about 1 kg in initial mass. The study revealed that the concentrations of CO varied between 572 and 4000 mg/m^3, which based on the molecular weight for CO of 28 g/mol equates to approximately 464 to 3243 ppm [36]. The range of CO concentrations observed in these experiments highlights how dependent the production of CO is on the initial pyrotechnic tablet composition, and also that CO production should not be overlooked in a naval application. Based on the potential for high levels of CO production, the RN Institute of Naval Medicine has approved pyrotechnic aerosols for use in unmanned compartments only, stating that personnel must be able to vacate within about two minutes before CO levels become prohibitive [8].

Hydrogen cyanide, HCN, is toxic to humans at relatively low levels. Once again turning the WHO, HCN is listed as fatal to humans if inhaled at the concentrations and for the durations listed in Table 2-2 [44]. The literature reviewed does not report measurements of HCN levels due to pyrotechnically generated aerosols that exceed the acute toxicity levels listed by the WHO. Nonetheless, the danger associated with HCN should dictate a high standard of care and vigilance in understanding the potential for lethal concentrations. Though no the subject of the present work, further research and testing into this aspect of pyrotechnic aerosol forming compounds should be conducted prior to their consideration for use in manned naval applications.

Table 2-2. Time to death following hydrogen cyanide inhalation in humans [44]

Dose		**Time to Death**
mg/m3	**ppm**	
150	135	30 min
200	180	10 min
300	270	Immediate

Generally speaking, there is sufficient variability in the public literature on the toxicity of pyrotechnically generated aerosol systems to warrant a more stringent, thorough, and independent toxicology study prior to procurement or use by the RCN.

2.5.2 Heat and Flame Ejection

The thermal decomposition or combustion of solid pyrotechnic fuel tablets is known to generate significant heat, flames, and rapidly expanding hot gases (some inert and some flammable such as CO) in a short period of time [15]. The combustion temperature of a KNO_3 based solid tablet is between 1200-2100°C [14]. Agafonov et al published results suggesting that the exit temperature of aerosols produced pyrotechnically will typically be in the range of 500 to 600°C without a cooling medium and 100 to 200°C with a cooling medium [28]. While it is understood that an effective fire suppression agent is being produced in conjunction with the generation of such heat and flames, pyrotechnically generated aerosols do pose a significant thermal hazard that needs to be appreciated. Depending on container design, even handheld pyrotechnically generated aerosol units can eject flames up to 1 m from the canisters and render their own metal surfaces red hot [26]. These effects can be reduced through system design whereby a cooling medium is installed between the solid fuel tablet and the ejection ports to suppress the flames and absorb some of the temperature. Insulation can also be utilized to reduce the external surface temperatures of activated canisters. These mitigating strategies, however, are not practical for small handheld aerosol extinguishers as they increase cost and would render the units too heavy and bulky for effective storage and transport. Good system design for fitted systems can ensure that the thermal hazards due to pyrotechnic generation of aerosols are mitigated by the aforementioned insulating and cooling media and proper spatial separation from combustible and flammable materials. Handheld systems on the other hand are thrown into compartments and may come into direct contact with various fuel sources. In addition, the units can pose a significant hazard to casualties if the units are activated in close proximity. Therefore, in this research it is of interest to qualitatively measure the heat and flame projection from the two variants of handheld aerosol extinguishers.

2.5.3 Corrosion Potential

Pyrotechnically generated aerosol fire suppression agents produce a buoyant mixture of micron-sized particles carried in a gaseous medium that consists of a range of decomposition and oxidation products. For effective suppression, this mixture is well dispersed throughout the compartment and therefore, both the particulate and the gases will come into contact with surfaces and equipment there. In the case of a modern naval application, even machinery spaces contain thousands of electronic devices that are critical for platform systems management and control and therefore survivability of the vessel. In this respect, the deposition of the aerosol particulate onto surfaces is of interest, as is the potential corrosivity of the mixture to sensitive electronic equipment and devices.

The deposition of the aerosol residue onto electronics and samples of various metal and polymer materials commonly used in electronics has been evaluated, but not in sufficient depth to fully appreciate any possible long term effects [22] [26]. Examples of materials tested include copper 110, bronze 905, steel 1010, stainless steel 303, Aluminum 6061, galvanized steel, PC board (epoxy), nylon, PVC, and tin [22]. In a fully developed fire scenario, exposure of equipment to heat, flames and hot toxic gases produced from the burning fuels certainly has the potential to cause damage. Suppressing the fire by the quickest means will minimize the damage due to the fire, but with aerosol agents, there may be the potential for corrosion or deposition of residue due to suppression. Further, in the case of accidental discharge of fitted aerosol systems, or activation of fitted aerosol systems for very small fires in large compartments, the resultant residue may be of considerable concern. Therefore, issues such as particle deposition and the potential corrosive by-products from the aerosol agents must be examined in scientific detail as they may not be considered acceptable trade-offs, particularly when there are several candidate suppression systems for a given application. Technical white papers outlining tests on some pyrotechnic aerosol extinguishers note that after the fire is suppressed most of the suppression agent can be exhausted in the same manner as smoke, but results do indicate that there can be a slight film on surfaces [10] [19]. The manufacturers recommend removing any aerosol residue deposited on equipment and electronics using a damp cloth, vacuum or compressed air. In the case of large compartments with thousands of sensitive electronic devices, however, this process could prove expensive and time consuming. Some manufacturers postulate that aerosol agents are non-corrosive, citing studies conducted in the early 1990s [45]. These reported that aerosol agents were found to be non-corrosive to electrical and structural materials, although the included references could not be found and therefore were not reviewed as part of this work. Jacobson et al conducted a corrosion study on the GreenSol aerosol material and found that the agent was non-corrosive against 12 common metal and polymer materials [22]. In this study, the exact composition of the agent tested was not published and unfortunately, the composition of the aerosol has been demonstrated to make a significant difference. For example, pyrotechnically generated aerosols based on perchlorates of nitrogen produce potassium chloride, which is known to be corrosive to aluminium and certain grades of steel [26]. In other units, the major aerosol generation component is listed as KNO_3, but details of the composition of the resulting aerosol particles and gases are not precisely known. In many cases of thermal decomposition of potassium nitrate, the resultant powder residue is comprised mainly of potassium carbonate which alone has been shown to be non-corrosive to most metals and alloys [46], but when dissolved in water results a medium strong basic solution [37]. In addition, there could be other corrosive agents present that have not as yet been identified and since potassium carbonate reacts violently with acids and other compounds such as chlorine triflouride [37], corrosive potential exists. If the suppression agents do lead to any corrosion, the consequences could be significant in the context of large marine compartments containing thousands of critical electronic devices. For this reason, studies should be conducted both into the corrosivity of the aerosol and into aerosol deposition on electronic devices and firefighter PPE to gain a better understanding of post suppression impact of the agent for naval applications.

The above review of the literature indicates that while there is basic theoretical understanding and some observational evidence of the efficacy of pyrotechnically generated aerosols as fire suppression agents, there are still many outstanding issues. These drive the present research which seeks to undertake a more detailed scientific evaluation of the efficiency and potential impacts of fire suppression using two variants of handheld pyrotechnic aerosol extinguishers against repeatable, fully developed marine fire scenarios. In the first instance, it is important to undertake controlled experiments to determine key suppression parameters, such as upper gas layer cooling rate, impact on thermal stratification, and total compartment cooling effect to more clearly understand the interactions between the aerosol agent and the fire compartment environment. Further, a review of existing information relating to advantages and disadvantages of aerosol suppression points to the need to conduct additional agent only (or cold compartment discharge) tests, dedicated safe storage experiments and incendiary potential evaluations to assess the safety of pyrotechnically generated aerosols, as well as to identify potential impacts of post suppression aerosol residue or corrosivity on equipment in the fire compartment.

The next stage in this research was to design a series of unique experiments in order to meet the scientific requirements listed above. Background procedures and protocols used in the experimental design, as well as the final layout, instrumentation and experimental methodology used in the investigations are discussed in the next two Chapters.

3 Aerosol Suppression Experimental Design and Techniques

Based on the RCN need to improve fire safety and survivability in current and future warships, the handheld aerosol extinguishers needed to be tested under fire scenarios designed to simulate the most challenging fire environment. In contrast to previous demonstrations of aerosols against fires in the early stages of growth, testing against a fully developed fire situation was deemed most appropriate in this work in order to better understand how and whether aerosol suppression agents work against a range of possible fire situations. Since statistically speaking, engine room or marine machinery space fires due to oil leakage are commonly considered the most likely fire scenarios, the burn room, fuel loads and configurations used for aerosol evaluation sought to simulate this scenario as closely as possible. This consisted of simulating a marine machinery space of the rated volume for the two variants of aerosol extinguishers and designing open diesel pool fires, obstructed diesel pool fires, and obstructed diesel bilge fires for repeatable and comparative suppression testing. Additionally, due to the large percentage of accommodation space onboard naval vessels, commonly with Class A fuel loads, softwood crib fire scenarios were designed using the same burn room and instrumentation for evaluation of the aerosol units against this category of fire.

From lessons learned in previous testing on aerosols, it was considered important to start suppression testing once the fires had reached the fully developed, or steady state, which is the worst case for compartment hot layer temperature and turbulent flow development while also being the most consistent from a repeatability standpoint. Although the final fire protection goal will be to utilise the aerosol suppression units as early in real fire growth as possible in order to minimize damage, choosing such a point from one test to another is challenging and inconsistent, and it does not allow for the aerosol technologies to be tested against the worst, or fully developed, fire environment.

Another aspect from lessons learned in previous testing is to utilize ample temperature measuring devices to accurately assess the fire environment in all three dimensions, as information from one TIC or from just a few thermocouples can misrepresent what is happening across the entire fire compartment. Finally, because oxygen starvation is a very effective fire suppression method, it was decided that aerosol suppression needed to be assessed in isolation from this method in order to appreciate the mechanism on its own. This meant that suppression test fires needed to be well ventilated throughout the pre-burn and the aerosol suppression testing period by not altering the ventilation configuration of the experimental burn room. The added advantage of this technique was the ability to assess the aerosol agent's efficacy against fully developed and unconfined marine fires. While it is understood that confinement will normally be coupled with aerosol suppression, the ability to fully confine a naval compartment fire depends on the functionality of doors, hatches, and ventilation dampers. It also depends on the integrity of the bulkheads which may have penetrations either by design, poor maintenance, or even due to breaches caused by enemy fire. Evaluation of aerosol suppression agents against unconfined fires, then, is of importance. Manufacturers of aerosol suppression agents that are protecting a given compartment will overdesign in order to account for a ventilation leakage factor; however, temperatures, pressures, and turbulent flow in a fully developed fire environment can be underappreciated and cause a light chemical suppression agent to be much less effective than anticipated.

In the first phase of the work, described in this Chapter, the fuel loads for the suppression tests were designed and characterized to provide a steady heat release rate and a fully developed fire environment at the onset of aerosol agent suppression, allowing comparison among the various repeatable tests. Next, the fully developed compartment fire environments for each scenario were characterized using both computer simulations and live compartment fires to confirm fuel loading and to understand temperature profiles, stratification and distribution of soot and hot gases prior to suppression testing. Following this, aerosol extinguishers were systematically discharged into the fire environments using different placements. Based the variability of the results due to aerosol extinguisher placement in the preliminary suppression testing, it was decided to fix the point of activation within the burn room to limit that variability. Upon completion of compartment characterization and preliminary aerosol testing, which are described in Chapter 4, a total of 18 live fire suppression tests were conducted to scientifically evaluate aerosol suppression efficacy in terms of upper gas layer cooling rate, impact on thermal stratification, and total compartment cooling effect. The live fire suppression tests also allowed for comparative analysis of the suppression efficacy of aerosol agents on their own without the added suppression effect of oxygen starvation, the results of which are contained in Chapter 5.

To improve on the RN cold discharge tests; two agent only tests (one for each variant) were conducted in the same burn room as the suppression tests. These tests were designed to qualitatively and quantitatively understand the aerosol agent distribution, aerosol agent suspension, compartment obscurity, re-ignition prevention, compartment temperature, oxygen dilution and carbon dioxide production, effect and residue distribution on electronics, and effect and residue distribution on firefighter breathing apparatus and protective ensemble. The experimental technique and applicable results of these tests form Chapter 6.

In addition to the 18 live fire suppression tests, 5 safe storage and 3 incendiary potential tests were conducted on the two variants of pyrotechnically generated aerosol extinguishers using purpose built and instrumented test rigs for a total of 26 aerosol units tested and evaluated. The solid fuel compound in pyrotechnically generated aerosols can produce significant amounts of heat and flame and as such are currently under scrutiny from Canadian Forces (CF) ammunition safety personnel. Normally, pyrotechnic devices such as flairs and smoke grenades are stored in floodable steel lockers on the upper decks of warships do to their incendiary potential if improperly used. While it is understood that pyrotechnic aerosols generate an effective fire suppression agent at the same time as they produce heat and flames, the thermal risk and hazard is still considerable. For handheld aerosol fire extinguishers to be effective in warships, they will need to be accessible throughout the ship. Understanding the consequences of an accidental discharge within supplied storage cases is important in the development of safe operating procedures and the design the storage racks. Additionally, the consequence, in terms of incendiary potential, of activating extinguishers in compartments that have a high ventilation turnover and/or are much larger than the rated volume for the units also need to be understood. Prior to procurement, Quality Ammunition Technical Authorities (QATA) in the CF will need to be satisfied that pyrotechnic aerosol suppression systems are safe for use as either fitted systems or has handheld extinguishers. The safe storage testing technique and results are contained in Chapter 7, while the incendiary potential testing technique and results may be found in Chapter 8.

3.1 Handheld Pyrotechnic Aerosol Extinguisher Test Method

There is currently no standard test procedure for the evaluation and approval of handheld aerosol extinguishers, therefore, a series of unique tests were designed that were adapted from various protocols, standards and best practices in order to meet the research objectives outlined in Section 1.1.

The main existing method for testing the effectiveness of aerosol suppression systems in the marine context is the "Test Method for Fire Testing of Fixed Aerosol Fire-Extinguishing Agents" contained as an Appendix in the larger IMO MSC Circular 1007 Machinery Space Test Protocol [MT-3] [13]. The full protocol specifically pertains to design, testing and approval of large fitted aerosol extinguishing systems for fire protection of enclosures with sizes on the order of 500 m^3, stating that "it is to be applied to evaluate whether fixed aerosol fire-extinguishing systems for use in machinery spaces have the same reliability which has been identified as significant for the performance of fixed gas fire-extinguishing systems" [13]. It is intended for direct comparison of large fitted aerosol systems against similar fitted gaseous fire protection and suppression systems so that the enclosure details and fire sources are defined accordingly. This said, the IMO MSC/Circ.1007 Protocol provides an excellent framework and guidelines to follow in testing of any aerosol extinguishing system against machinery space fires as defined by the International Convention for Safety of Life at Sea (SOLAS) [47].

In the present context of evaluation of potential handheld aerosol fire knock-down tools for RRTs and RATs, it is critical to ensure that the evaluation is conducted under conditions similar to those that will be encountered in the fire scenarios against which the handheld units will be deployed. Due to the design sizes and intended use of the handheld units for fire knockdown, they must be tested against fires in spaces significantly smaller than those for which the fixed fire protection systems covered in the protocol would be used. Further, particular emphasis in the present study is to be placed on evaluation of the units for use against engine enclosure and accommodation fires, in particular Class A fires, as well as open and hidden Class B fires. After full review of the protocol in light of the research requirements, details of the protocol were adapted in some aspects to better apply to evaluation of small handheld aerosol extinguishers. The overall framework, as well as some of the guidance and details for instrumentation, testing and approval of aerosol extinguishers against simulated engine enclosure fires (hidden Class B pool fires with and engine mock-up) have been adopted directly. This is discussed in further detail in Section 3.3 after a description of the aerosol extinguishing systems under study.

3.2 Handheld Aerosol Extinguisher Specifications

The handheld pyrotechnic aerosol units tested were the StatX First Responder (Figure 3-1 left hand side) and the DSPA 5-4 Manual Firefighter (Figure 3-1 right hand side). These specific models were selected for testing based on their comparable sizes and applicability for fire suppression in the compartment sizes used in the experiments, as well as the willingness of the respective companies to collaborate in the research project.

Figure 3-1. Left: StatX First Responder, Right: DSPA 5-4 Manual Firefighter

The specifications for each unit as taken from the respective manufactures' publications are outlined in Table 3-1 to [48] [49] [50].

Table 3-1. Characteristics and Specifications of the StatX FR and DSPA 5-4 Aerosol Extinguishers

Characteristics	**StatX FR**	**DSPA 5-4**
Active Substance	0.5 kg	0.9 kg
Discharging Time	20 sec	25 sec
Maximum Temperature at 50 cm	Unknown	75°C
Diameter	80.89 mm	165 mm
Height	174.6	94 mm
Weight	1.22 kg	2.0 kg
Capacity (based on 50 g/m^3)	20 m^3	18 m^3
Fuse Delay Timer	3.5-5 sec	6-10 sec
Storage Life	10 years	5 years
UL/ULC Listing for fixed systems		
Class A (or not hermetically sealed)	97 g/m^3	96.4 g/m^3
Class B	67 g/m^3	32.1 g/m^3

The solid, aerosol forming, oxidizing agent in each of the two variants of handheld units tested in this research is potassium nitrate, KNO_3, which is an ionic salt and a natural solid source of nitrogen [51]. Other common uses for KNO_3 include fertilizers, food preservatives, rocket propellants, and fireworks

[51]. The oxidation process is initiated thermally by a fuse in each unit, with a timed delay of 3.5-5 seconds for the StatX FR unit and longer at 6-10 seconds for the DSPA 5-4 unit. After activation, each aerosol unit produces and expels the alkali metal, potassium carbonate, K_2CO_3, in gaseous form. Subsequently, the gas condenses into ultra-fine particles suspended in a gaseous medium of mainly nitrogen, carbon dioxide, and water vapour. Discharge times are listed at 20 seconds for the StatX FR and longer, at 25 seconds, for the DSPA 5-4 unit. Although temperatures of the discharging aerosol are listed as only 75^{o}C at 50 cm from the DSPA 5-4 unit (and not listed for the StatX FR), the combustion temperature of the KNO_3 based solid tablet is expected to be in the range of 1200-2100^{o}C [14].

The DSPA-5 Material Safety Data Sheet (MSDS) shows that solid compound ingredients are potassium nitrate (60-70%), dicyandiamide (15-25%) and phenol-formaldehyde resin (5-15%). The exact phenol resin is not identified by Chemical Abstracts Service (CAS) number on the MSDS. The MSDS for the DSPA compound is attached as Appendix A.

The StatX First Responder MSDS does not provide percentages of the various ingredients by weight, but shows that the solid compound ingredients are potassium nitrate, dicyandiamide, and an organic resin. The CAS number associated with this organic resin on the MSDS is 9003-35-4, which represents phenol-formaldehyde resin. The MSDS for the StatX compound is attached as Appendix B

All aerosol units tested in this work were supplied by the manufacturer together with design criteria, operating instructions, drawings and technical data. The respective company representatives personally delivered the aerosol units to UW and provided training and technical support in their use to ensure proper and repeatable activation per manufacturers' instructions. UW maintained a collaborative relationship with both industrial partners throughout the testing.

3.3 IMO MSC Circular 1007 Machinery Space Test Protocol Modifications

There were two key aspects of the protocol that were not considered applicable to the evaluation of handheld aerosol knock down tools that would be typical of those used by RCN RRTs and RATs against small machinery enclosure fires. These were the overall size of the test enclosure specified in the protocol, as well as the details of several of the specified fire scenarios. The protocol requires a test volume of 500 m^3. Appropriate use of handheld units against fires in an enclosure of this size would necessitate simultaneous triggering of between 25 and 50 handheld aerosol units in each test (less larger capacity units, but at significant cost in unit weight and against the requirement of ease of transportation by an RAT or RRT). Further, handheld aerosol extinguishing units are not appropriate for 'knock down' operations against engine fires in such large spaces due to their design capacity and weight, the typical numbers of personnel on RRTs and RATs, and the very rapid fire growth characteristic of engine fires in large machinery spaces. For these reasons the very large enclosure specified in the protocol was adapted to a compartment volume of 20.2 m^3 for the present experiments (see Section 3.5 for a full description of the compartment and layout).

The second aspect of the protocol that was adapted for the present test plan involves the details of the specific design fires. The protocol specifies good performance of the suppression agent against telltale fires such as those that might persist after a larger engine room fire, against diesel/fuel oil fires with and without engine enclosure, against class 'A' wood crib fires ignited using small heptane pool fires, and against three-dimensional fuel spray fires that simulate ruptured fuel lines that have ignited, as well as, in a more recent version, against fires from a range of polymeric materials [13]. While the latter two scenarios (fuel spray and polymeric materials) can be accommodated by a smaller fire test facility, these are not typical of fires against which RRTs or RATs would deploy handheld aerosol units for knock-down. Therefore, these fires were considered to be beyond the scope of the research and were not evaluated here. The other fires are more characteristic of general fires and smaller machinery space fires likely to be encountered by RRTs and RATs on RCN vessels and were included, with particular emphasis on engine enclosure fires involving hidden B class fires.

With these two basic adaptations to the IMO test protocol, other aspects of the experiments were designed to address the objectives of the present research. Key design parameters as well as instrumentation and test procedure are discussed in order below.

3.4 Fire Development

While the IMO protocol discussed above does provide good guidance for the evaluation of aerosol suppression systems against simulated marine machinery space fires, it does not give direction on the fire environment that needs to be attained prior to suppression. The protocol is very specific in terms of fire design and engine enclosures or mock-ups to obstruct the fires; however, the fires specified will not necessarily produce a fully developed fire environment, which is considered to be the most challenging and also the most repeatable test fire scenario. Since the goal for this research is to test the handheld aerosol units against fully developed, repeatable, fuel controlled marine fire scenarios, it is necessary to identify the salient features of the fire environment of interest and then design fuel loadings to accomplish this goal. The resulting compartment fire environment must then be carefully characterized as the reference against which to conduct the suppression tests. To set the stage for the ensuing discussion, some key aspects of fire growth and enclosure fire dynamics are outlined below.

The normal stages of fire development follow a cycle of fuel ignition, fire growth, steady state burning and fire decay. At any point during this cycle, a fire can either be fuel controlled or ventilation controlled [52]. A fuel controlled fire has all the oxygen it needs to burn. The growth rate, length of the steady state burning period and the decay are all dependent on the amount and the types of fuel feeding the fire. Conversely, a ventilation controlled fire cannot burn all the available fuel freely since it is starved of oxygen to some extent. In both cases, as a fire grows, there is a build-up of hot gases that are buoyant and rise to the top of the enclosure or compartment. A boundary, which is commonly referred to as the interface height, forms between hot gases situated near the ceiling and cold gases closer to the floor [52]. In a fuel controlled fire, ventilation pathways allow hot gases to escape (normally from higher points of ventilation within the compartment) and cool air to enter, providing ample oxygen to the fire. In contrast, a ventilation controlled fire does not have sufficient ventilation to supply the fresh air needed to sustain the required level of oxygen to keep the fire burning.

In a burn room that only has one rectangular door the mass transfer of hot combustion gases and cool combustion air occurs through the same ventilation passage. Hot gases are expelled at the top portion of the door and cool air is drawn in at the bottom and the neutral plane between layers coincides with the interface height of the hot and cold gas layers within the compartment. In this case, the compartment door can be used to control the rate of mass transfer of the hot combustion products from the fire relative to the cold incoming air and thereby hold the interface height at a given level throughout the compartment.

The hot gases that build up in the upper gas layer within a compartment fire increase the amount of heat that is transferred to all surfaces inside the compartment. If some of the internal surfaces are flammable materials not already involved in the fire, heat transfer from the hot gas layer onto those materials will cause them to off gas and release flammable vapours into the environment [53]. As the depth and temperature of the upper gas layer build, the radiant heat it generates can ignite all the available fuel in the room creating what is often referred to as a fully developed fire [54]. Another definition of a fully developed fire is when the average upper gas layer temperatures reach values typically between 500-600^{o}C, with peaks up to 800^{o}C [55]. Following full development of the fire, the fuel burns out, the fire decays and eventually goes out.

Krasnyansky suggests that automatic pyro-aerosol systems are suitable for fire prevention or extinguishment only in the first few minutes after ignition [24]. As such, small handheld aerosol extinguishers such as the StatX First Responder and the DSPA 5-4 Manual Firefighter are intended for use as early in the fire growth stage as possible. On the other hand, there is evidence to suggest that it is reasonable to assume that compartment fires onboard naval vessels will be fully developed prior to activation of handheld aerosol extinguisher units. Babrauskas conducted a study in which it was determined that the average time taken for compartments containing a wide variety of natural or synthetic fuels to reach a fully developed state is 3.5 minutes [56]. Taking into account the normal response times of either a RRT or a RAT (1-4 minutes), a fully developed marine fire scenario is not unlikely. From an experimental view, determining a single repeatable point in the fire growth stage, is challenging and not very consistent.. Therefore, it was decided the probable and repeatable marine fire scenario for the present tests was a fully developed compartment fire as defined based on upper layer temperature above; however, it must be recognized that this does pose a challenging fire environment for handheld aerosol units.

Details of the compartment, fuel load and instrumentation used for the tests are discussed in turn in the following sections.

3.5 Compartment Setup

The fire compartment used to simulate a small marine machinery space in the aerosol suppression testing conducted at University of Waterloo is a modified 6.1m (20ft) ISO shipping container as shown in Figure 3-2 and Figure 3-3. This enclosure is similar in dimension and thermal properties to an emergency generator space onboard a navy ship.

Figure 3-2. University of Waterloo Standard Shipping Container

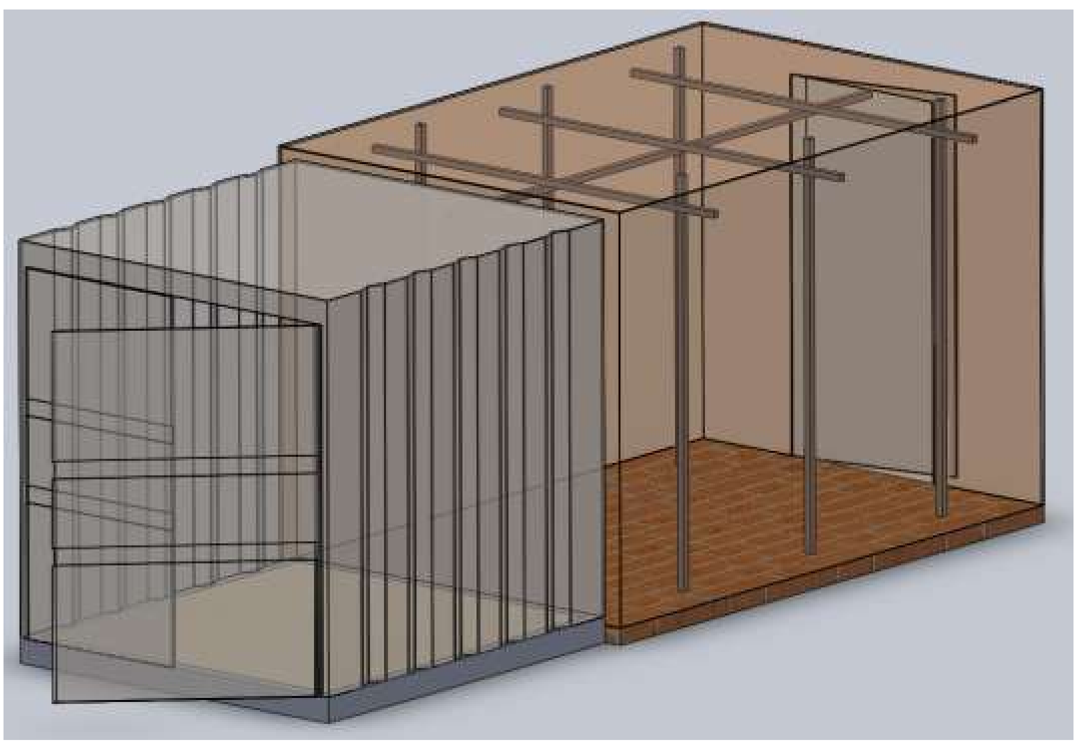

Figure 3-3. 3-D Computer Aided Rendering of UW Shipping Container Burn Room

The shipping container has been divided into a burn room and a control room. The control room houses the data logger and other test support instrumentation. It measures 2.4 m wide x 2.6 m long x 2.4 m tall and utilises the standard cargo doors for access. The burn room itself measures 2.4 m wide x 3.5 m long x 2.4 m tall to give a floor area 8.4 m^2 and a compartment volume of 20.2 m^3. There is a single door at the end of the burn room that measures 0.91 m wide x 1.75 m tall and is 0.05 m off the compartment floor to simulate the marine door to the machinery space.

The dimensions and thermal properties of the burn room were designed to be similar to an ISO 9705 test room [57]. ISO 9705 is used for standardized testing of wall lining materials, for example, and as such, it prescribes a burn room with good thermal properties for repeatable fire testing [58]. The shipping container walls and ceiling are 2 mm thick Corten steel. On the outside of the burn room, the walls are insulated with 25.4 mm thick layer of Fiberfrax Durablanket S™ high temperature ceramic fibre insulation, then a 25.4 mm air gap, and covered with a 18-gauge (1.25 mm) aluminum sheet. The ceiling is insulated with 50.8 mm of Fiberfrax Durablanket S™ insulation and is also covered with 18-gauge sheet aluminum [59]. This composite construction is similar to that utilised in navy ships for noise and heat insulation (noise and heat signature reduction is of importance for missile avoidance) which was considered to add to the realism of the suppression test study. Finally, the floor of the burn room is covered in fire brick.

Initial thermal characterizations of the facility were conducted to help determine the design fire loads and ventilation required to obtain a fully developed fire environment in the compartment. This was accomplished using calorimetry to measure various Class A and Class B fuel loads, in combination with simulations done using the mathematical model CFAST, a commercially available computational tool used for fire modelling [60]. After a description of the engine fire mock-up, fuel loads are defined and general instrumentation layout for the experiments are discussed in Sections 3.6, 3.7, and 3.8 respectively. Model formulation, input and results, as well as characterization of the final compartment fire environment, are presented and discussed in Chapter 4.

3.6 Engine mock-up

An engine mock-up of size 1.4 m x 1.3 m x 0.46 m (width x length x height) was constructed of sheet steel of nominal thickness 5 mm. The structure was suspended 40 cm above the burn room firebrick floor to simulate an engine enclosure obstructing the diesel pan fire as shown in Figure 3-4. The distance between the top of the fuel surface and the underside of the engine enclosure was 21 cm. This represents typical equipment that might be found in smaller marine machinery spaces, such as emergency generator enclosures, on board RCN vessels. An obstructed pan fire (0.82 m^2) in the center of the shipping container directly under the engine mock-up simulates fuel accumulation under an engine in a marine machinery space.

Figure 3-4. Mock Engine Enclosure used in Obstructed Diesel and Bilge Fire Suppression Tests

3.7 Fuel Loads

Design of the fuel loads for the various fire scenarios was critical to ensuring the fully developed fire environment required for repeatable fire suppression testing. Fuel loads for the two main fires, diesel fuel (Class B) and softwood cribs (Class A), were determined using analytical heat release rate calculations and confirmed using a full-scale oxygen consumption calorimeter of test fires. Hand calculations formed a basis for fuel load design, while the oxygen calorimeter was used to obtain the free burn (or well ventilated burn) characteristics of the chosen diesel and softwood fuel loads. For diesel characterization tests, the 0.82 m^2 fuel pan was filled with 10 ℓ of diesel floated on 105 ℓ of water (reducing the freeboard to 1 cm), while for softwood, an 8 kg softwood crib was tested. Each fuel was placed on a load cell under the hood of the lab calorimeter and ignited. Fuel mass rate of burning was measured and combustion gases were collected to determine heat release rate via oxygen consumption calorimetry [61]. These free burn characteristics were important as input to the fire simulation and modelling, as well as to interpreting results from the suppression tests, particularly with respect to the secondary effects that ventilation and heat losses have on the fire in the burn room. They are discussed in more detail for each fuel type in the following sections.

3.7.1 Diesel Fuel

The primary fuel load for aerosol suppression testing was the diesel pool fire, as this is one of the most likely fuel sources in a marine machinery space. Therefore, the main characteristics of this fuel source are discussed in more detail here. These parameters were also used to define the fire input used in the CFAST model described in Section 4.1.

To estimate the HRR of the diesel pan fire, the heat of combustion of the diesel fuel was first calculated. Using the average formula for marine diesel fuel of $C_{12}H_{23}$, the stoichiometric reaction equation can be balanced to indicate the combustion products produced. This equation assumes complete combustion and provides an estimate for the quantities of major products only:

$$C_aH_b + 4.77(a + {}^1/_4\,b)air \rightarrow aCO_2 + {}^1/_2\,bH_2O + 3.77(a + {}^1/_4\,b)N_2 \quad [2]$$

$$C_{12}H_{23} + 84air \rightarrow 12CO_2 + 11.5H_2O + 66.9N_2 \quad [3]$$

$$C_{12}H_{23} + 17.8O_2 + 66.9N_2 \rightarrow 12CO_2 + 11.5H_2O + 66.9N_2 \quad [4]$$

With the moles of the major combustion products known, the heat of combustion of the fuel may be calculated using the respective heats of formation [54]. From the heats of formation of diesel (-174 KJ/mol), carbon dioxide (-393.5 KJ/mol), and water (-241.83 KJ/mol) the heat of combustion of diesel is calculated:

$$\Delta H_{C_{Diesel}} = \eta_{CO_2} h_{fCO_2} + \eta_{H_2O} h_{fH_2O} + \eta_{C_{12}H_{23}} h_{fC_{12}H_{23}} \quad [5]$$

$$\Delta H_{C_{Diesel}} = 12\left(-393.5\frac{KJ}{mol}\right) + 11.5\left(-241.83\frac{KJ}{mol}\right) + \left(-174\frac{KJ}{mol}\right) \quad [6]$$

$$\Delta H_{C_{Diesel}} = 7677\frac{KJ}{mol} \ or \ \frac{7677\ KJ/mol}{167\ g/mol} = 45.97\frac{KJ}{g} = 45.97\frac{MJ}{kg} \quad [7]$$

This calculation is based on an average molecular weight for the fuel as well as the assumption of ideal combustion of the diesel. A more realistic figure is 45 MJ/kg as found in the SFPE handbook [62]. The diesel fuel pan used was 0.905 m x 0.910 m x 0.140 m (width x length x depth). Based on the average properties of diesel fuel with a molecular formula of $C_{12}H_{23}$ and molecular weight of 167 g/mol, and the area of the fuel pan, the maximum heat release from the fire was estimated to be 908 kW using:

$$\dot{q} = \lambda \dot{m}_b A \Delta H_c \quad [8]$$

Where λ (efficiency factor) was assumed to be 0.7 due to the sooty nature of the diesel fire [63] the surface area was A = 0.823 m^2, the burning rate was taken to be 0.035 kg/m^2s [63], and the heat of combustion was taken to be ΔH_c = 45 MJ/kg [62].

For this testing, a 3 min burning time was desired in order to obtain a fully developed fuel controlled fire with sufficient unburned fuel remaining to ensure the fire would not decay prior to aerosol suppression. Using the stated pan area and burning rate for the fuel yields a requirement for at least 6.3 kg of fuel for each test run. Dividing by an approximate specific gravity of 0.85 for the fuel then gives a volume of 7.4 ℓ. For ease of testing and repeatability, it was decided to use 10 ℓ (or 0.01m^3) of fuel for each run to ensure a minimum 3 min burning time. As shown below, the burning time for 10 ℓ of fuel will be approximately 5 min:

$$Burning\ Time = \frac{Mass\ of\ Fuel}{Area * Mass\ Burning\ Rate} = \frac{8.5kg}{0.823m^2 * 0.035\frac{kg}{m^2 \cdot s}} = 295\,\text{sec} \cong 5\ min \quad [9]$$

The thickness or depth of fuel in the pan was determined to be:

$$Fuel\ Thickness = \frac{volume\ of\ Fuel}{Area\ of\ Pan} = \frac{0.01m^3}{0.823m^2} = 0.0122m = 1.22cm \qquad [10]$$

The estimated heat release rate was validated and the free burn characteristics of a 7 ℓ diesel fuel load were obtained via the UW full-scale oxygen consumption calorimeter. A typical heat release rate versus time curve is shown in Figure 3-5. This confirms that the average HRR for this fuel load was 903 kW and the well ventilated burning time was 3.5 min. Further it substantiated that, while diesel pool fires may be difficult to ignite, they grow quickly to high heat release rates and then also decay very quickly.

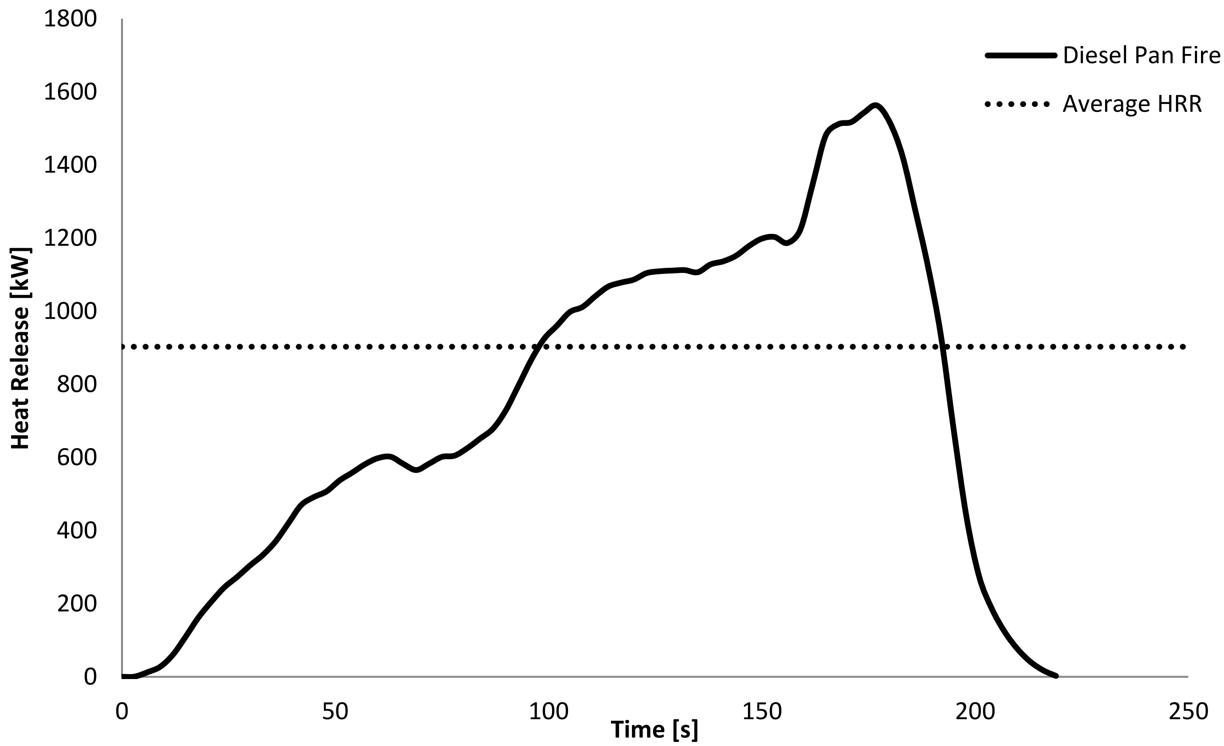

Figure 3-5. Heat Release Rate of Diesel Pan Fire as measured in Large Scale Oxygen Calorimeter

3.7.2 Softwood Cribs

As the second main fuel load in these tests, the main characteristics of the softwood crib fuel source are discussed in this section. Each softwood crib was constructed to be similar to those specified in the ISO Standard 14520, Gaseous fire extinguishing systems, Part 1: General Requirements (2000) [64]. Using 8' lengths of construction grade spruce 2x2's, each length was cut into 4 equal pieces nominally 2' long. Crib modules, 6 layers deep, were made by evenly spacing 6 pieces of 2x2's per layer, with each layer nailed such that the pieces lay orthogonally to those in the previous layer. Each 6-layer crib consisted of nine 8' lengths of 2x2s and was nominally 2' square and 9" high (6 layers x 1.5" per layer) and weighed about 16 kg after drying indoors for a least 2 weeks at a relative humidity of 40%. The cribs were ignited using 0.2 ℓ methanol in a 0.1-0.2 m^2 pan. During the pre-burn, the cribs were centred at a position 300 mm above the top of ignition fire pan. It should be noted that the contribution of ignition source (methanol) to the overall heat produced by the cribs is insignificant.

To confirm the heat release rate from the softwood cribs and determine the free burn characteristics, one-half crib weighing 8.2 kg was burned in the large calorimeter, producing an average heat release of 56 kW as shown in Figure 3-6.

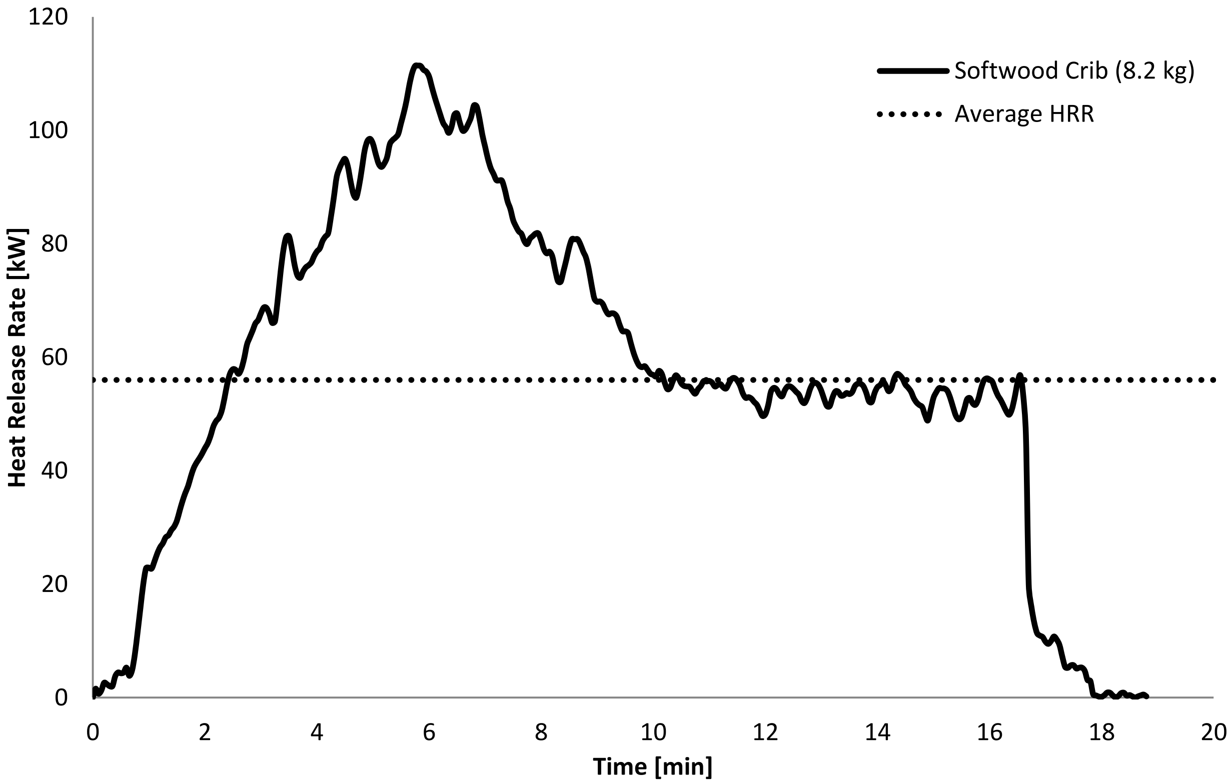

Figure 3-6. Heat Release Rate of Softwood Cribs as measured in Large Scale Oxygen Calorimeter

Based on the calorimeter results, a 4-crib fuel load was chosen for these tests to produce an average heat release of approximately 500 kW and provide a fully developed fire environment after a 4-6 min pre-burn period. Figure 3-7 shows the final 4-crib fuel load configuration in the shipping container burn room with ignition tray beneath.

Figure 3-7. 4-Crib Softwood Fuel Load Configuration

3.8 Instrumentation and Data Acquisition

The UW burn room is instrumented to measure gas temperatures internal and external to the compartment, internal and external compartment surface temperatures, and gas concentration in the upper hot layer of the compartment.

Compartment gas and surface temperatures were measured using Inconel-sheathed, ceramic wrapped Type-K (chromel-alumel) thermocouples, which are well suited for measurement in post-flashover or fully developed fires [65]. Each thermocouple has a bead diameter of approximately 1 mm. The two wires of each thermocouple were individually wrapped with mica insulation for moisture resistance, then with ceramic fibre insulation for heat resistance, and lastly, the assembly was covered with braided Inconel sheathing to provide overall abrasion resistance. These thermocouples were rated for 980°C continuous and 1090°C short-term service [66]. In previous burns undertaken by U of W fire researchers, these thermocouples have survived fire environments well over 1050 °C [67].

Internal compartment gas temperature distributions were measured using 80 thermocouples, mounted on 10 rakes, four horizontal and six vertical, as shown in Figure 3-8. The rakes were configured such that they did not obstruct gas flow in the compartment and also to leave a 1.8 m unobstructed region to facilitate free gas flow from back to front along the centre of the compartment. Surface temperatures were measured on the bulkhead, side walls, and ceiling of the compartment using thermocouple beads directly attached to the internal steel surfaces and the external aluminum surfaces respectively. Thermocouple data was acquired using a National Instruments Compact Field Point distributed data logging system that allowed remote placement of the analogue to digital (A/D) signal conversion hardware. A conventional Ethernet protocol was used to communicate with multiple A/D units and to transfer the digitized signals back to a central computer located in the burn facility control room. This system had many advantages including: reducing the required lengths of expensive thermocouple wire; minimizing the travel distance of analogue signals for improved noise immunity; and allowing the control and data acquisition computer to be located tens of meters from the experiment. The sample to sample time used for these experiments was 1125 milliseconds (0.89 Hz). All temperature channels were recorded simultaneously.

Each rake of thermocouples consisted of up to 8 thermocouples mounted inside a Uni-Strut steel channel, with the individual sensing points (thermocouple beads) protruding about 5 cm beyond and at a right angle to the channel. The thermocouples were spaced at regular spatial intervals along the channel to form a rake of thermocouples. The rakes were installed either vertically or horizontally in the fire compartment to measure a temperature profile across a line of interest.

Six thermocouple rakes were mounted vertically on each side of the fire compartment to document the thermal stratification at the rear, middle and front of the compartment. Four thermocouple rakes (one longitudinal from front to back and three transfers) were mounted horizontally 2.15 m above the floor of the compartment to document the homogeneity of the thermal layer. Figure 3-8 shows a three dimensional view of the thermocouple rakes positioned within the burn facility. The exact location of each thermocouple along with the associated data file naming system used in the excel spreadsheets can be found in Appendix C.

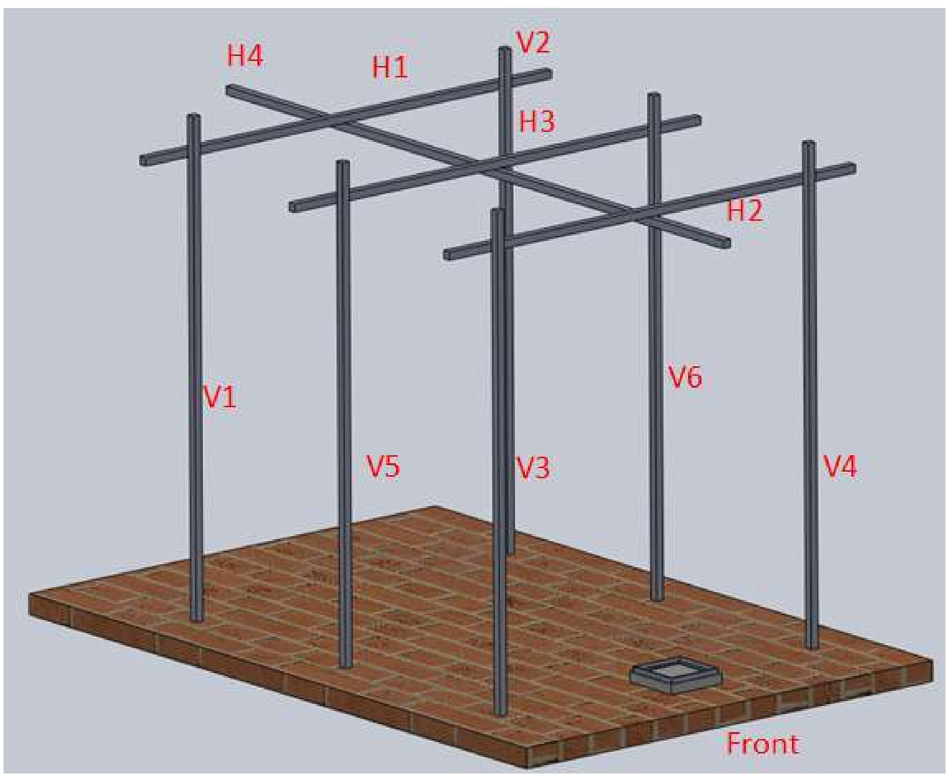

Figure 3-8. 3-D Rendering of the Thermocouple Rakes inside the Shipping Container

Concentrations of O_2, CO, CO_2, NO, and NO_2 were measured during the test using a Novatech P-695 gas analysis system with Servomex Servopro 4900 infrared (IR) and paramagnetic analyzers. The sampling was done through a heated, Teflon coated tube, maintained at a temperature of 150^{o}C to prevent condensate formation in the lines [68].

At the time of aerosol suppression testing, UW was also in the process of evaluating a prototype volume sensor on behalf of Defense Research and Development Canada. This sensor suite (Figures 3-9a and 3-9b) was positioned to gather UV, IR, near IR, acoustic, colour video and low wavelength video data during the aerosol suppression testing. Still photography was also employed to record burn room set up, live fire testing and post-suppression evidence.

Figure 3-9a. Prototype Volume Sensor

Figure 3-8 b. Volume Sensor Suite as Installed

Colour video was taken from outside, looking into, the compartment during testing to track fire development and early stages of suppression. Still photography was also employed to record burn room set up, live fire testing and post-suppression evidence. Finally, external air temperature and relative humidity were recorded via Cole-Parmer weather sensors.

3.8.1 Temperature Uncertainty

The type K, 24-gauge, thermocouples had a standard manufacturer's uncertainty of ±2°C and an expanded uncertainty of ±4°C when including the complete data acquisition system. The response time for a 24-gauge exposed bead thermocouple was measured to be less than 1 second in air moving at about 20 m/s [66]. Ignoring any flow variations due to turbulence, this would represent a conservative limit for these experiments assuming that the buoyant air movement produced by the fire was the main convective effect acting on the thermocouples during the live fire tests.

4 Characterization of the Compartment Fire Environment

In response to the considerations discussed in Chapters 1 and 3, it was determined that a compartment environment similar to that expected during a fully developed fire was required in the burn room prior to activation of the DSPA 5-4 Manual Firefighter and StatX First Responder aerosol units. After the initial fuel load was chosen (Section 3.7), a numerical fire model was used to investigate the interactions between the fire, compartment and ventilation conditions expected in the UW shipping container burn room. Results are presented in Section 4.1 below. After the fire was modeled, preliminary full-scale compartment fire characterization tests were conducted in order to better define the actual heat losses and upper and lower gas layer temperatures and interface heights that could be expected during the suppression tests. Using the model and test results, the optimum compartment ventilation during the initial growth period of the fire was determined along with the effects on the fully developed compartment fire environment of oxygen starvation by closing the burn room. The combined characterization test data was then used to develop repeatable methods of assessing aerosol suppression efficiency via determination of the effect of the aerosol on the fire compartment including: upper gas layer cooling rates, impact on thermal stratification, and total compartment cooling effect. In this Chapter, appropriate justifications and sensitivity analysis are also included to justify the choice of average compartment temperatures used in subsequent data analysis, as well as measured thermal properties of the UW shipping container burn room.

4.1 CFAST Model

Prior to conducting live fire testing in the UW shipping container, fire simulation software was used to model the fire scenario and predict the compartment environment. The goal of this modelling effort was to predict whether a repeatable and sustained fully developed fire environment could be established for the suppression testing, given the thermal properties of the container and the diesel fuel load estimated above. In this experimentation, a fully developed fire is defined as a uniform upper gas layer temperature at or above 500-600^{o}C [52]. A secondary goal of the model was the determination of the optimum opening fraction of the door to provide the highest compartment temperatures without starving the fire of oxygen.

The software used was the Consolidated Fire and Smoke Transport (CFAST) model developed by the National Institute for Standards and Technology. CFAST is a zone model, meaning that it divides the fire compartment into a uniform hot upper layer and cold lower gas layer and solves mathematical equations for the conservation of mass and energy; with the fire plume acting effectively as an enthalpy pump [60]. A zone model is useful to represent geometries of relatively simple enclosed volumes and establish global equations that predict key aspects of fire behaviour (average temperature, effect of ventilation). The UW shipping container is a rectangular box with one door, which is ideally suited for analysis using a zone model. More complex geometries may be better represented through the use of a field model, such as FDS, where thousands of smaller control volumes are utilized to discretize the space and solve fire related flows, but these require more time and computational power than a zone model and the increased detail in output was considered of little benefit for the present simulations [69].

4.1.1 Model Development

As discussed in Section 3.5, the UW shipping container has been divided into a burn room and a control room, shown in Figure 3-3. The burn room measures 2.4 m wide x 3.5 m long x 2.4 m tall to give a floor area 8.4 m^2 and a compartment volume of 20.2 m^3. One rectangular door was added at the end of the burn room that measures 0.91 m wide x 1.75 m tall and is 0.05 m off the compartment floor [59]. This door simulates a marine door to a small machinery space. The geometry of the burn room and door were input into CFAST to represent the exact compartment volume and ventilation (the door), while the control room was neglected.

As described in Section 3.5, the ISO shipping container walls and ceiling are 2mm thick Corten steel. On the outside of the burn room, the walls are insulated with a 25.4 mm thick layer of Fiberfrax Durablanket S high temperature ceramic fibre insulation, then a 25.4 mm air gap, and covered with a 18-gauge (1.25 mm) aluminum sheet. The ceiling is insulated with 50.8 mm of Fiberfrax Durablanket S insulation and is also covered with 18-gauge sheet aluminum. For the purpose of CFAST modelling and fire characterization, the effective thermal properties of these composite walls/ceiling was determined. The properties of each component the composite wall/ceiling materials are listed in Table 4-1 below taken from the SFPE Handbook [62].

Table 4-1. Thermal Properties of the UW Shipping Container Burn Room Walls and Ceiling

Thermal Property	**Steel**	**Air**	**Fibrefrax**	**Aluminum**
Thermal Conductivity (W/m-K)	43	0.026	0.07	204
Specific Heat (kJ/kg-K)	0.473	1.003	0.7	0.896
Density (kg/m^3)	7801	1.1	64	2707
Thickness (m)	0.002	0.0254/0.0	0.0254/0.0508	0.00125
H_k=k/L (W/ m^2·K)	21500	1.02/0.0	2.75/1.38	163200

4.1.2 Burn Room Effective Thermal Properties Values for Composite Walls and Ceiling

The effective heat transfer coefficient for the composite walls and the ceiling were calculated using the equation [54]:

$$h_{keff} = \frac{1}{\frac{1}{h_{ksteel}}+\frac{1}{h_{kfair}}+\frac{1}{h_{kfibre}}+\frac{1}{h_{kaluminum}}} \quad [11]$$

The result for the composite wall was 0.746 W/m^2·K. Multiplying by the total wall thickness of 0.05405m yields an effective thermal conductivity, k_{eff}, of 0.0403 W/m·K. The result for the composite ceiling was 1.38 W/m^2·K. Multiplying by the total ceiling thickness of 0.05405m yields an effective thermal conductivity, k_{eff}, of 0.075 W/m·K.

The burn room wall is 3.7% steel, 47% Fibrefrax insulation, 47% air, and 2.3% sheet aluminum. The ceiling is 3.7% steel, 94% Fibrefrax insulation, and 2.3% sheet aluminum. These percentages were utilised to calculate weighted, effective densities and specific heat values for the walls/ceiling as follows:

$$\rho_{eff_{wall}} = (0.037)(7801) + (0.47)(1.1) + (0.47)(64) + (0.023)(2707) = 381\ kg/m^3 \quad [12]$$
$$\rho_{eff_{ceiling}} = (0.37)(7801) + (0.94)(1.1) + (0.023)(2707) = 410\ kg/m^3 \quad [13]$$

$$C_{p\ eff_{wall}} = (0.37)(0.473) + (0.47)(1.003) + (0.47)(1.13) + (0.023)(0.896) = 1.037\ kJ/\text{kg·K} \quad [14]$$

$$C_{p\ eff_{ceiling}} = (0.37)(0.473) + (0.94)(1.13) + (0.023)(0.896) = 0.969\ kJ/\text{kg·K} \quad [15]$$

For the model design fire, the diesel pan fire was located in the center of the ISO container. The pan dimensions were input exactly as measured, 0.905 m x 0.910 m x 0.140 m (width x length x depth) and discussed in Section 3.7.1.

The pan fire was input into CFAST as the Fire of Origin (FOO) with an estimated heat release rate (HRR) temperature versus time profile. Diesel pool fires are difficult to ignite, but they grow rapidly to high values of HRR for a period of time and decay quickly. This was simplified to a top hat shaped profile using the estimated maximum steady state HRR of the actual pan fire calculated to be 908 kW in Section 3.7.1 and then adding an ultrafast growth and decay profile. Using an average formula for diesel of $C_{12}H_{23}$ gives a molecular weight of 167 g/mol, which is an input requirement for the CFAST model fire object properties. With the fire load calculations made, the properties of the fuel and HRR curve were entered into the fire properties file, as shown in Figure 4-1, and the model was run to simulate the enclosure fire.

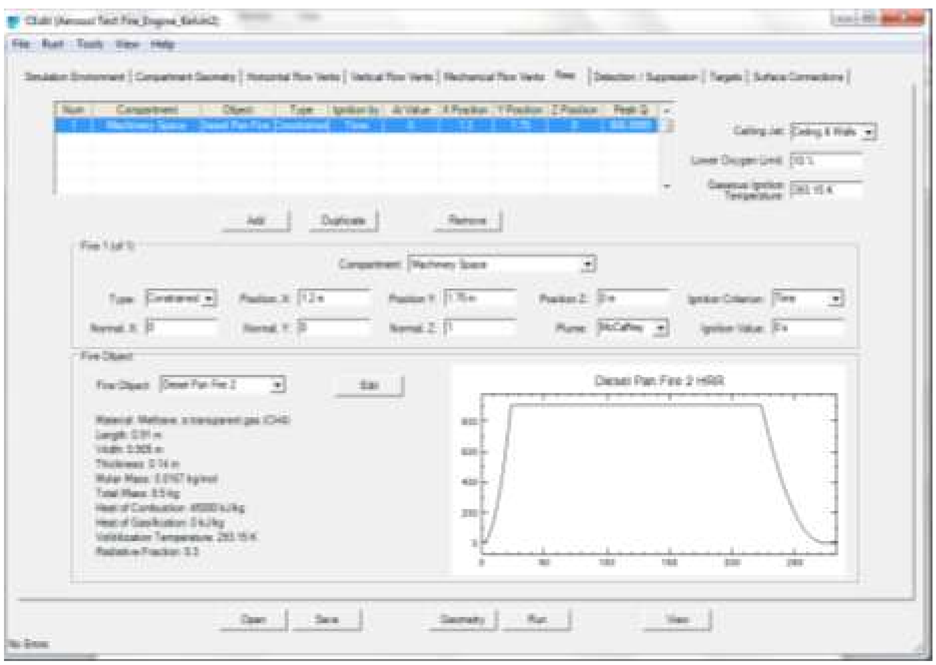

Figure 4-1. CFAST Design Diesel Fire Properties to Represent Open Diesel Pan Fire

4.1.3 CFAST Model Results

Figure 4-2 shows one image from a Smokeview animation of the simulated fire plume, interface height and mass transfer of gases through the compartment door for a CFAST model run using the actual burn room geometry and effective thermal properties with the FOO defined to simulate a 0.823 m^2 diesel pan fire as a 908 kW fire lasting 3 min. The figure represents the fire compartment development at 150 seconds after ignition with the door opening fraction set at 33%. The Smokeview animations for the fire model were useful in gaining a visual appreciation for the predicted fire plume height and flame impingement, the way the hot gas layer develops, the interface height and the mass transfer of gases through the door.

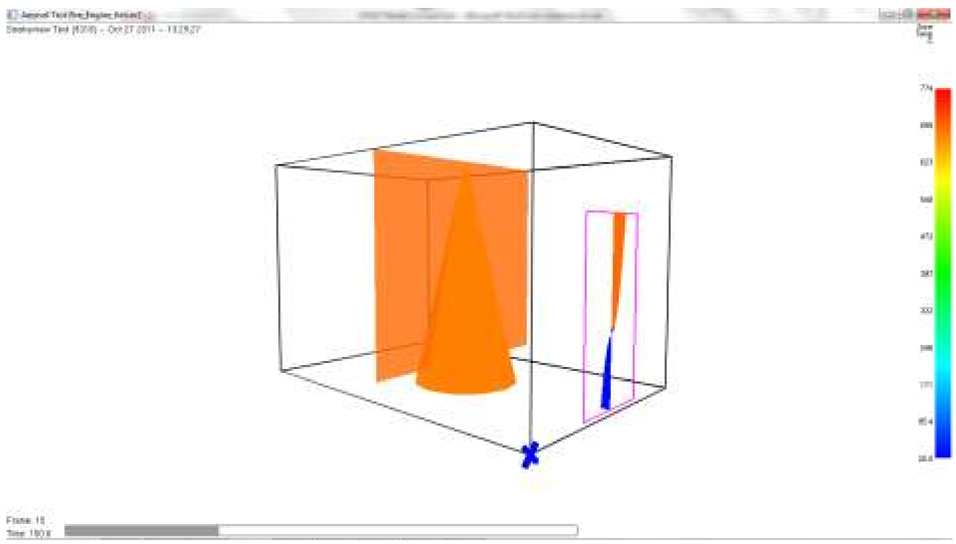

Figure 4-2. CFAST Model Smokeview Animation Showing the Diesel Fire Plume, Interface height and Gas Mass Transfer through the Compartment Door 150 seconds after Ignition

Figure 4-3 shows results of simulations in which the opening fraction of the burn room door was iteratively altered. Examination of the plot of average upper layer temperature versus percent opening fraction, indicates that as the door opening fraction is increased from 25%-33%, the peak temperatures increase after which they level off for opening fractions between 33% and 40% and finally decrease again for fractions larger than 40%. From the results, it was determined that the optimum door opening fraction should be on the order of 33% since larger or smaller opening fractions resulted in lower predicted gas temperatures.

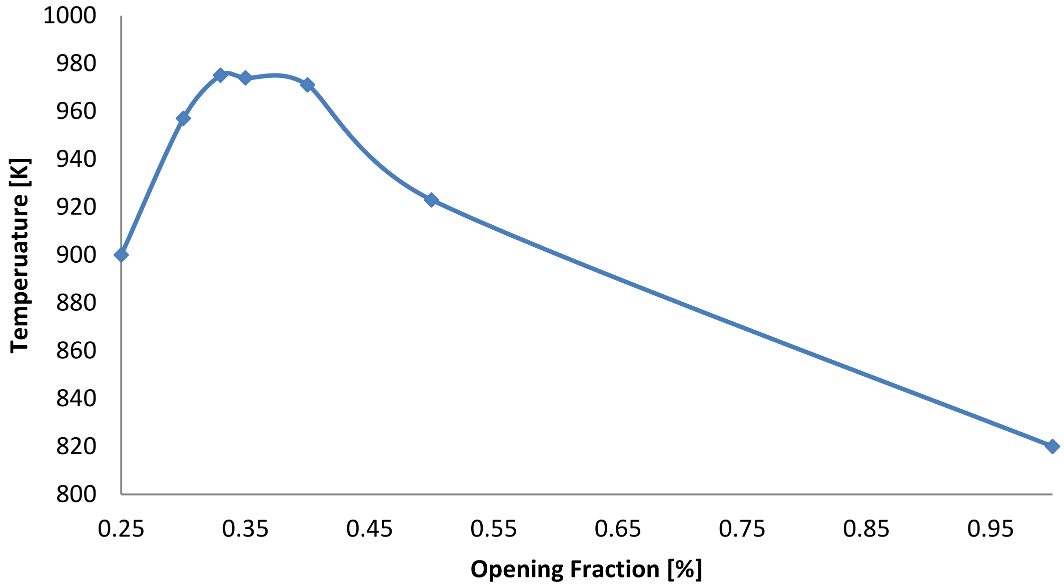

Figure 4-3. Prediction of average upper layer temperature for various door opening fractions as determined using CFAST Model

The upper and lower gas layer temperatures and interface height were plotted for the simulation conducted with a door opening of 33% and are shown in Figure 4-4. The figure indicates that the upper gas layer temperatures in the burn compartment would reach 600^{o}C in 70 sec after ignition and continue climbing to a peak of 763^{o}C after 210 sec, after which they would decay again as the fuel load burned out. At the same time, the predicted lower layer average temperatures rose quickly to 300^{o}C after 30 seconds and continued on a steady climb, peaking at 490^{o}C in 210 sec. The interface layer height was predicted to drop to the floor within the first 20 sec after ignition, which did not seem realistic and is not desirable for suppression testing. Whether this result was realistic had to be confirmed later through the compartment characterization fires discussed in Section 4.2. These results indicated that the design fire would be sufficient to provide a sustained fully developed fire environment with peak temperatures being obtained at a compartment door opening fraction of 33%, which corresponds geometrically to the burn room door being held open at 30 cm.

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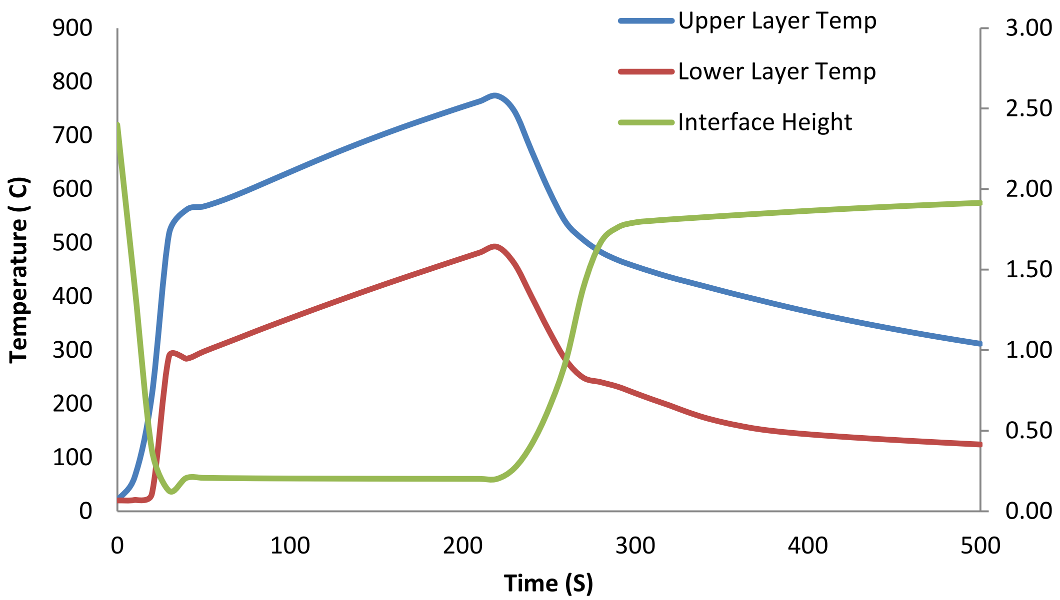


Figure 4-4. Upper and Lower Gas Layer Temperature Evolution and Interface Height [m] of CFAST Model Diesel Fire Simulation

4.2 Characterization Tests

With the free burn data from the large calorimeter and the predicted results from the CFAST model complete, fire characterization testing in the burn room was conducted with all instrumentation running as a final stage before aerosol extinguisher testing. The characterization tests were conducted to confirm the fuel load, fire size and burning time, test the instrumentation under fire conditions, and better determine the actual compartment environment that was developed for a 33% opening fraction of the burn room door.

The average upper layer gas temperatures measured with time during the four characterization tests conducted at a door opening fractions of 30 cm (33%), 40 cm (44%), 50 cm (55%), and 60 cm (66%) respectively are shown in Figure 4-5. It can be seen from the figure that the initial growth stage from ignition to 60 sec is similar for all four door openings between 30 and 60 cm. After the first minute, the temperatures rise faster and the fuel burns out more quickly with larger door openings. Therefore, this testing revealed an opposite trend in comparison to results predicted using the CFAST model, as it indicated hotter upper gas layer temperatures with increase in the door opening fraction over 33%. However, the total burning time of the fuel was the trade-off, so an opening of 30 cm was chosen as the final test configuration. In addition, several other factors were considered in the final choice of door opening used in the aerosol suppression tests. These are discussed in more detail below.

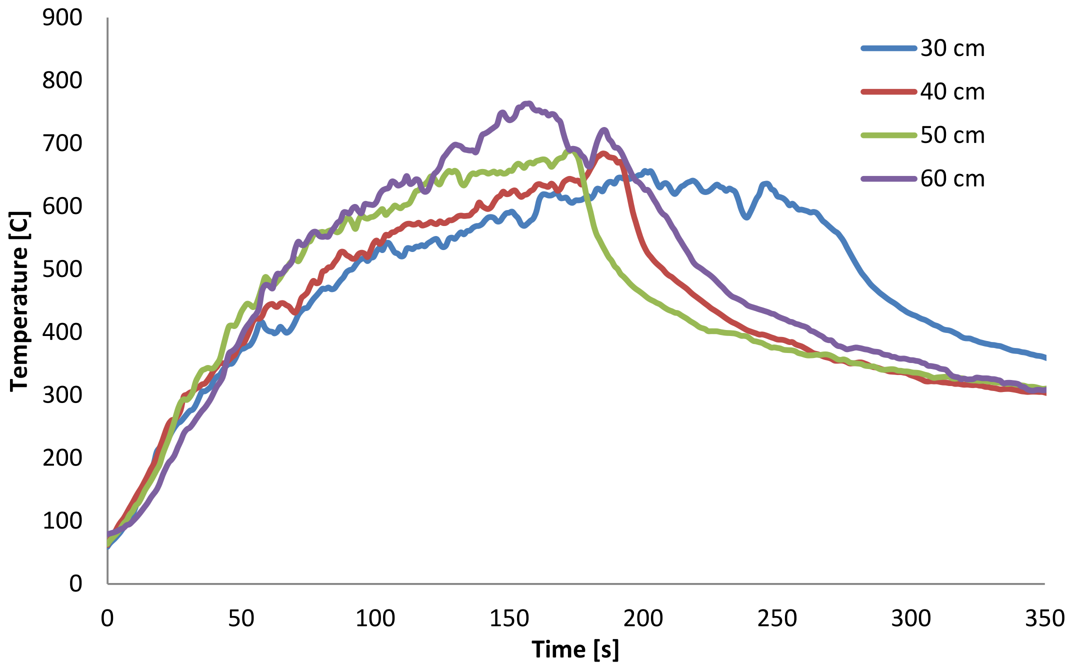


Figure 4-5. Measured Average Upper Layer Gas Temperatures at 2.0 m from the floor for Various Door Openings

The IMO protocol and the expected naval SOP both require the burn room to be confined, i.e., the burn room door to be closed, immediately following activation of an aerosol unit and its insertion into the fire compartment. To aid in better determining the test conditions and door opening required for the present suppression tests, an additional test was conducted to understand the impact on the fire of closing the compartment door without discharge of an aerosol unit. This test was conducted for comparative reasons as well, since it was considered critical to understand the effect of ventilation control on the fire so that the effect of the aerosol agent by itself could be better quantified. Figure 4-6 below shows plots of average temperature versus time at various heights in the compartment during an open diesel characterization fire with the door opening set at 30 cm (33%). The fire was allowed to grow and reach the fully developed stage, and then the compartment door was closed, at 180 seconds after ignition. It is clear from the Figure that for this door opening, the upper layer gas temperatures reached 700^{o}C (2.0 m) while lower layer temperatures reached 320^{o}C (0.5 m). In addition, closing the door resulted in fire extinguishment and a consequent rapid decrease in the average temperature across all eight horizontal planes within the compartment. Based on these results, it was decided that the impact on a fire of aerosol extinguishing methods should be assessed in the situation when the compartment ventilation configuration was not altered during the test to ensure that the suppression effects identified were attributable largely to the effect of the aerosol agents alone. For this, it was decided to use a 30 cm door opening, which equates to approximately 33% of the fully open position. A 30 cm door opening was the minimum opening that provided a fire environment with the longest steady state burning period and upper gas layer temperatures above 500^{o}C. At this opening, the quantity of aerosol agent that could escape during suppression was also minimized. Finally, a 30 cm opening is the minimum opening that allowed placement of an extinguisher unit inside the compartment without opening and closing the door.

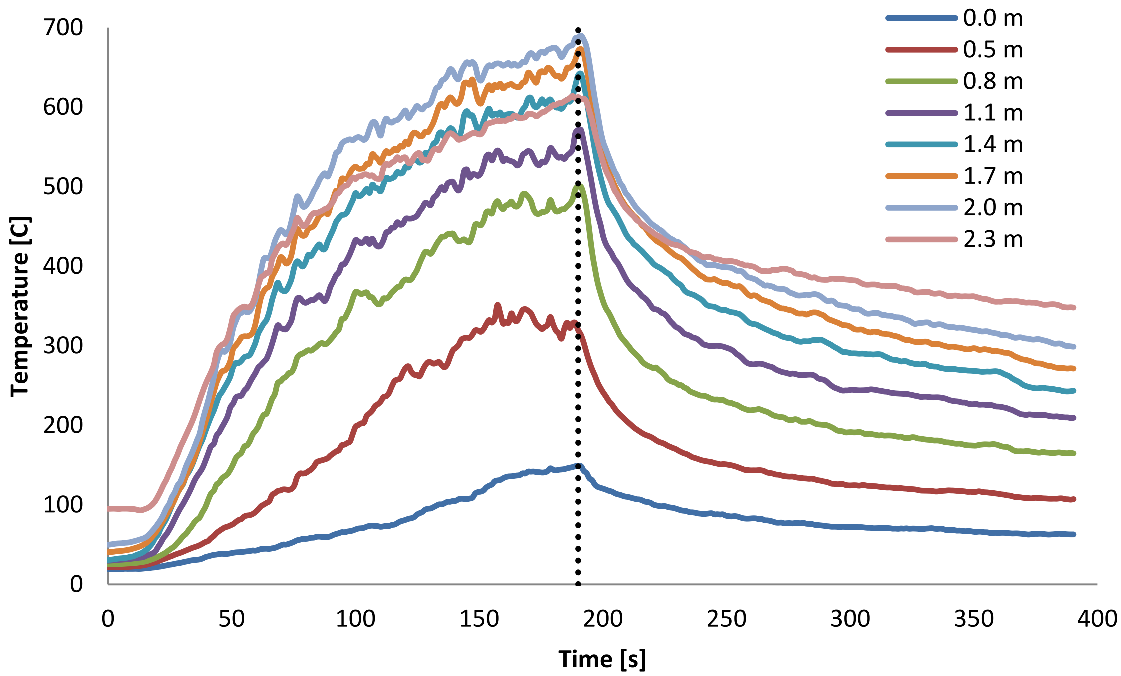


Figure 4-6. Effect of Closing the Compartment Door during an Open Diesel Fire as measured via average compartment temperature at different heights within the compartment

4.3 Assessing Suppression Effects

Another key reason for conducting a series of compartment characterization tests was to aid in the development of measures by which the effectiveness of aerosol suppression could be determined. Development of a standard procedure for measurement of suppression 'effectiveness' was required to allow comparison of results across various tests. Three measures were investigated for this evaluation. These are: the cooling rate of the average upper gas layer, the cooling effect on the compartment, and the effect of aerosols on the average thermal stratification within the compartment. Each is discussed in its own section below. The challenge in each case was to establish the correct average temperatures for valid, consistent and repeatable comparison. The decisions made and methods chosen for assessing suppression effects are explained and justified below in subsections 4.3.1 to 4.3.5.

4.3.1 Average Upper Gas Layer

The greatest rate of cooling during live fire suppression of a fully developed compartment fire is seen in the upper gas layer where buoyancy has taken the majority of the hot fire gases. As such, the rate of cooling of the upper layer gases forms an excellent benchmark against which to compare the impact of various suppression methodologies. To evaluate this cooling rate across the entire upper gas layer in these studies, several measures of average temperatures were assessed. This was necessary to be sure that any test-to-test variability in the large-scale motions of the hot layer and/or flame impingement on the compartment ceiling was not negatively impacting the values of average upper layer temperatures. From comparisons of average upper gas layer temperatures calculated from characterization fire data, the simplest and most consistent methods of averaging data across thermocouples were 1) taking the average of all six of the vertical TCs at a height of 2.0 m above the compartment floor and 2) taking the average of all 32 of the horizontal TCs at 2.1 m above the compartment floor. Figure 4-7 shows plots of each of these average temperatures versus time for an open diesel characterization fire, revealing that although the average of the 32 horizontal thermocouples was consistently 13% higher than that of the six vertical thermocouples, both sets of data for average temperature exhibit the same trends with time. The higher temperatures measured via the horizontal thermocouples are due to the fact they are positioned 10 cm higher above the floor of the compartment than the others and also that the values include some effects of direct flame impingement on the thermocouples for those thermocouples positioned directly above the diesel pool fire. The fact that both average values of upper layer temperature consistently follow the same profile across time suggests that either set of average temperatures could be used to assess a valid cooling rate in a repeatable manner. It also shows that the effects of flame impingement on the averages across the horizontal TCs are not particularly adverse. Conversely, this comparison shows that the average of the six TCs positioned at 2.0 m above the compartment floor on the vertical rakes represents a good average upper gas layer temperature. The positioning of the vertical rakes within the burn room is such that they measure accurate gas temperatures without being adversely effected by heat losses to the side walls. For ease of data analysis across all tests, it was decided to utilise the average temperatures determined from the six TCs on the vertical rakes to represent the average upper gas layer temperature on the horizontal plane 2.0 m above the floor of the burn room. This average temperature was therefore used in all assessments of upper layer temperature cooling rates during suppression testing.

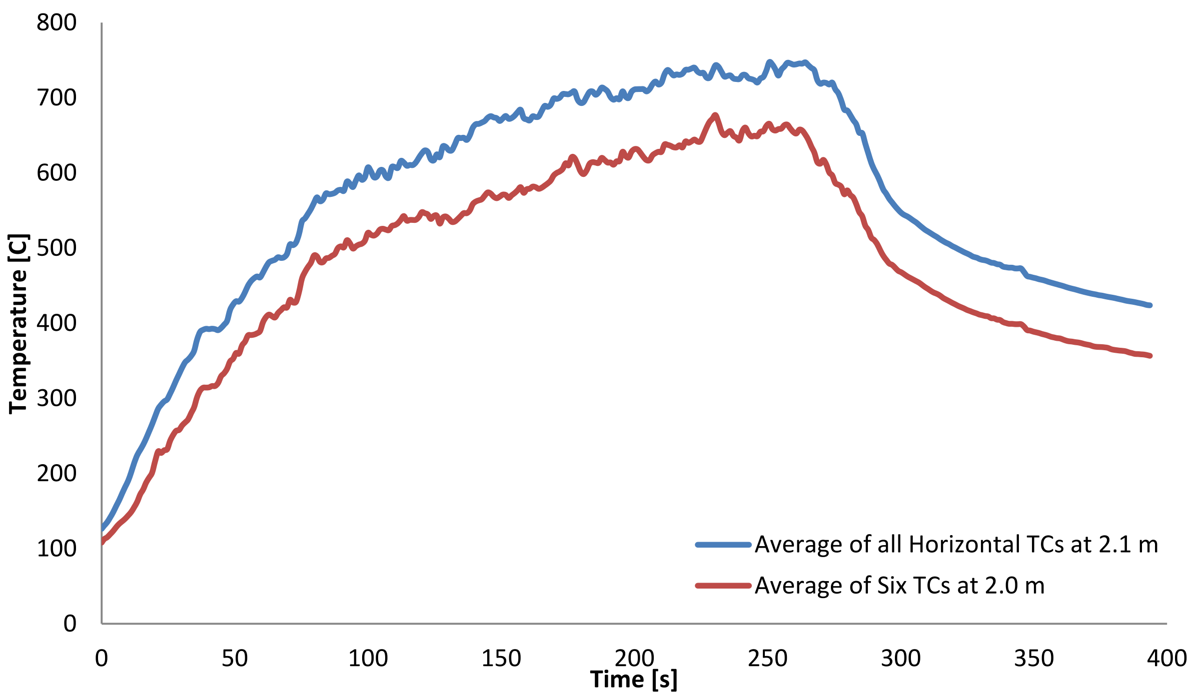


Figure 4-7. Comparison of Average Upper Gas Layer Temperatures for Open Diesel Fires, Showing the Average of six TCs at 2.0 m compared to the Average of all Upper Layer TCs at 2.1 m

4.3.1.1 *Upper Layer Temperature Repeatability*

Once the method for determination of average upper gas layer temperature had been determined, it was also important to ascertain the uniformity and repeatability of the average measured upper gas layer temperatures across multiple tests conducted under varying ambient conditions in order to accurately understand and compare suppression cooling rates amongst tests. Given that all suppression activity occurs within 3 min of diesel ignition, Figure 4-8 was developed to display the variations of the average upper gas layer temperatures, as defined above, for three separate characterization tests. Each test was conducted with the door held open at 30 cm. As shown in the figure, the average upper layer temperatures are fairly uniform across multiple tests even when initial compartment temperatures and ambient conditions vary. For example, the ambient temperature for tests 1 and 2 was 19^{o}C, whereas the ambient temperature for test 3 was 39^{o}C. Additionally, test 2 was conducted following test 1 giving an initial compartment temperature for test 2 of 76^{o}C. The average deviation in the temperature data represented in Figure 4-8 is 21^{o}C (approximately 3.5%), while the minimum and maximum deviations are 2.4^{o}C and 34^{o}C respectively. Despite this consistency, it was decided to conduct pre-burns at the start of each live fire testing day in order to raise the initial internal compartment temperature to approximately the same value and to reduce the moisture level in the compartment insulation. This was expected to further improve the uniformity of the average upper gas layer temperatures developed during suppression testing. Wind baffles were also installed at the front of the compartment to reduce any effects of ambient wind conditions on the development of the compartment fire environment or subsequent suppression activity.

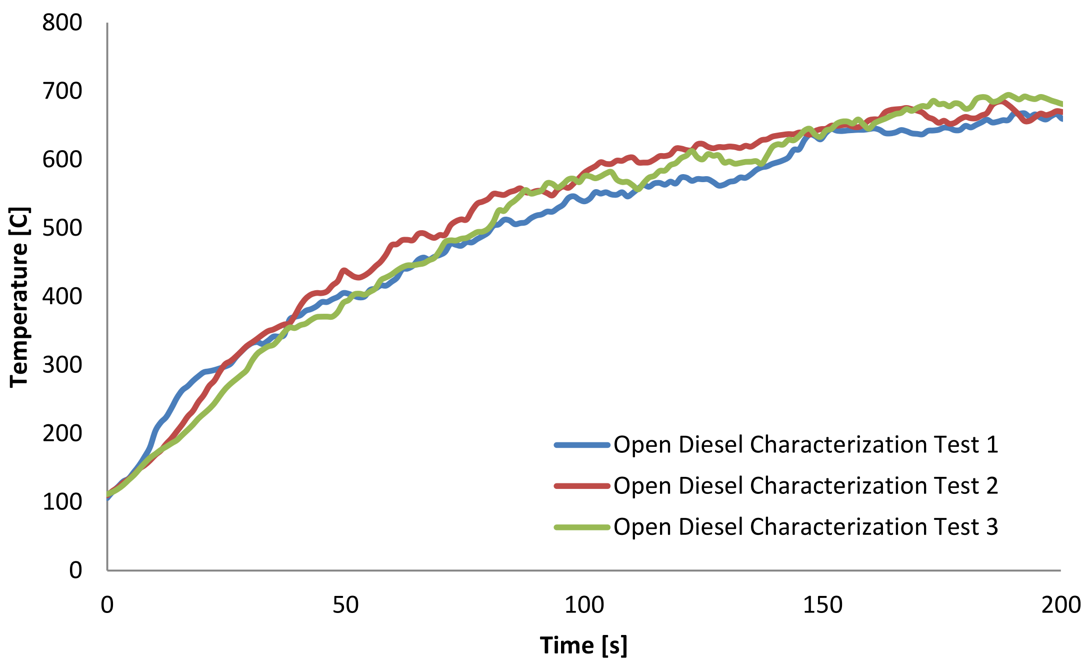


Figure 4-8. Repeatability of the Average Upper Gas Layer Temperatures Using Average of TCs at 2.0 m from ignition of an open diesel fire to 3 minutes after

4.3.2 Average Thermal Stratification

Thermal stratification within the compartment is an important indicator of the fire environment prior to suppression and can also be used for assessing the total cooling effect a suppression method has on the compartment environment. Whilst in reality the interface height is not located at a constant distance below the ceiling throughout a compartment in a real fire, fire modelling programs such as CFAST cannot resolve variations in stratification within the compartment and, instead, represent the environment using a single horizontal interface height to separate the upper hot and lower cool gas layers. In this work, it was found that, as expected in a real fire situation, the temperature, as a function of height within the compartment, varied from front to back due to the flow of gases into and out of the compartment, heat losses to walls and ceiling, and proximity of a given measurement location to the fuel load. The measurements show an interface height that was lower in the back of the compartment near the fire source and higher towards the front where the hot gases were flowing out the door. Using the temperature measurements from the same open diesel characterization fire as discussed in section 4.3.1, thermal stratification plots were developed for the rear, middle and front of the compartment to understand the longitudinal variation in interface height within the burn compartment. The rear stratification was taken by averaging the back two vertical TC rakes and plotting the temperature as a function of height for 1, 2, 3, and 4 minutes after ignition of the fire. The same process was followed to determine the stratification in the middle and front of the compartment by averaging the two middle and the two front vertical TC rakes respectively. Figure 4-9, Figure 4-10, and Figure 4-11 show the rear, middle and front stratification profiles respectively. From these three plots for the same fire, the longitudinal variation in the compartment interface height and stratification is clearly represented. At the rear of the compartment, temperatures vary almost linearly with height in the early stages of fire development, but by 4 minutes after ignition, temperatures are less stratified at the rear of the compartment, ranging from approximately 475^{o}C at the floor to 760^{o}C at the 2.0 m height since this region is very close to the fire and the hot layer has effectively dropped to the floor. The stratification reverses above the 2.0 m height with cooler temperatures being due to heat transfer through the ceiling of the compartment. The stratification profiles in the middle of the compartment, Figure 4-10, again show large vertical temperature differences from top to bottom of the compartment with a clearly marked interface between a hotter upper layer and relatively cooler lower layer temperatures. At the 4 minute mark the temperatures are more stratified than the rear of the compartment with temperatures ranging from 290^{o}C at the floor to 735^{o}C at the 2.0 m height. The greatest temperature difference from floor to ceiling is seen in the stratification profiles at the front of the compartment, Figure 4-11, which also show a clearly marked upper hot layer and cooler lower layer due to cool air feeding the fire through the lower one-third of the door. Again looking at the 4 minute mark, the temperatures at the floor were 170^{o}C, while the temperatures at the 2.0 m height were 655^{o}C. The wavy profiles in Figure 4-11 may be an indication of the effects of turbulent gas flow and its impact on the average temperatures at various heights during the fire development. This is consistent with both rear and front profiles since these TC rakes are just forward of the fuel load in the compartment.

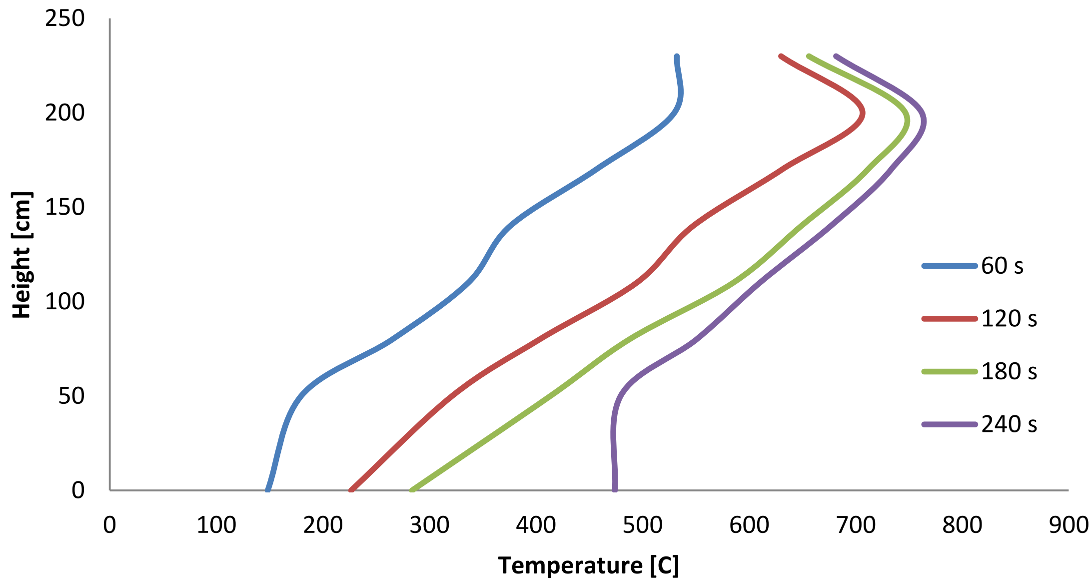


Figure 4-9. Rear Thermal Stratification of Burn Room for an Open Diesel Fire Taken from the Average of the Rear Two Vertical Thermocouple Rakes (V1 and V2) Over Four Time Intervals after Ignition

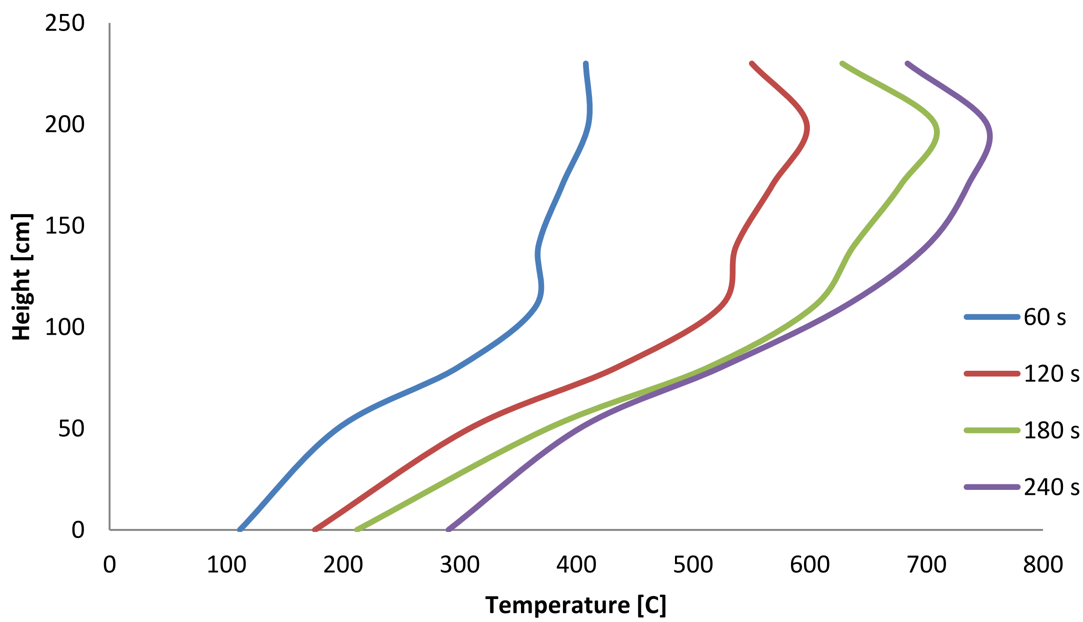


Figure 4-10. Middle Thermal Stratification of Burn Room for an Open Diesel Fire Taken from the Average of the Middle Two Vertical Thermocouple Rakes (V5 and V6) Over Four Time Intervals after Ignition

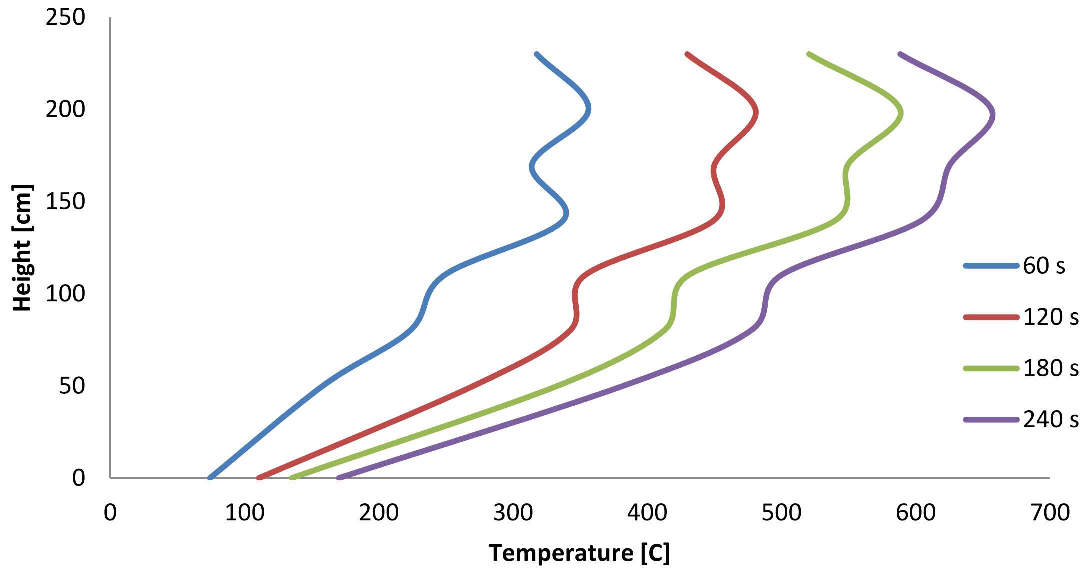


Figure 4-11. Front Thermal Stratification of Burn Room for an Open Diesel Fire Taken from the Average of the Front Two Vertical Thermocouple Rakes (V3 and V4) Over Four Time Intervals after Ignition

Given the longitudinal variation in thermal stratification within the fire compartment, it was of interest to determine if a single average profile could be used to accurately represent the global environment within the compartment for the purpose of measuring total cooling during aerosol suppression. Figure 4-12 shows averaged thermal stratification profiles across all six vertical TC rakes for the same open diesel fire for the four times given above. From this Figure, it can be seen that the averaged profile does capture many of the key elements of the previous three profiles in that the hotter temperatures at the lower rear of the compartment have tempered the lower portion of the average profile while upper layer effects from the front of the compartment can be seen in the upper portions of the averaged profile. It was therefore proposed to use this average stratification profile as a reference by which to measure the total compartment cooling during each suppression test and to distinguish the impact of aerosol suppression on thermal stratification in the fire compartment.

To confirm the validity of using the average profile for these determinations, a sensitivity analysis was conducted for three open diesel fire suppression tests. The cooling effects at the rear, middle, and front of the compartment were independently calculated and the results were compared to the cooling effect determined by using the total average thermal stratification. The method and results of the sensitivity analysis are discussed in Section 4.3.5.

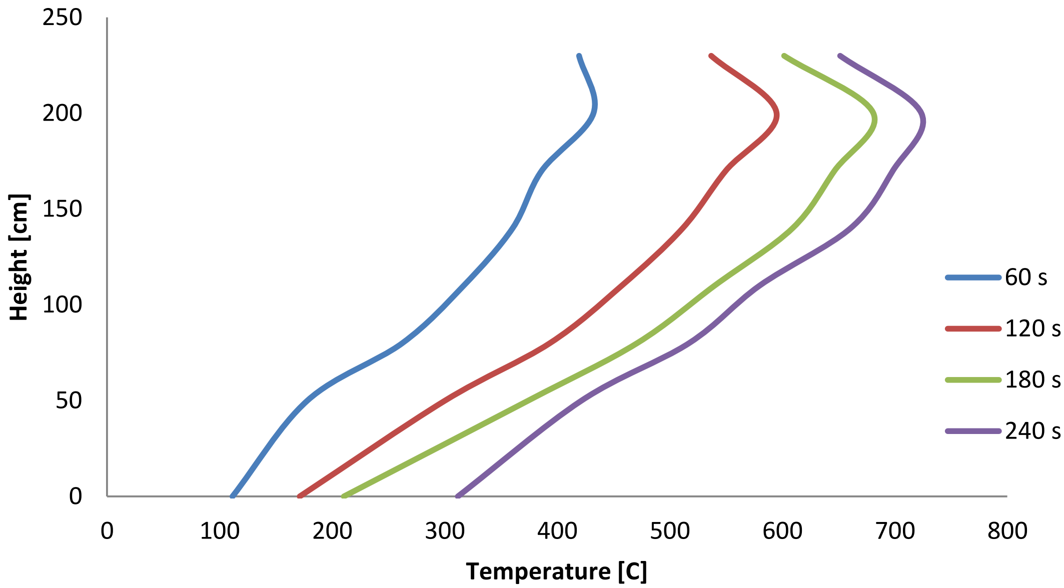


Figure 4-12. Average Thermal Stratification of Burn Room for an Open Diesel Fire Using the Average of all Six Vertical TC Rakes over Four Time Intervals after Ignition

4.3.3 Assessing Cooling Rate

Once the average upper gas layer temperature was defined, a method for consistently assessing cooling rates could be determined, allowing suppression efficacy to be measured. The cooling rate was defined as the maximum decrease seen in the average upper layer gas temperatures from the onset of suppression to 60 seconds after the onset of suppression, which is a similar method to those successfully utilized in previous testing in the UW burn room [59]. The challenge was then choosing a consistent time by which to mark the onset of suppression for comparison of the cooling effects of oxygen starvation (closing the door) alone against the cooling effects seen during use of the two variants of handheld aerosol extinguishers. Since the DSPA 5-4 had a fuse delay of approximately 6-10 seconds, and StatX FR unit had a fuse delay of approximately 3.5-5 seconds (Table 3-1 refers) using the fuse start time would not give consistent results. Furthermore, the discharge times for the two units differed, being approximately 25 seconds and 20 seconds respectively for the DSPA 5-4 and the StatX FR units. As a result, it was decided to use the peak average temperature in the entire compartment (average of all 48 vertical TCs) immediately before suppression to mark the temperatures and times corresponding to onset of suppression in all cases. Using this method, any lateral and axial variations in temperature within the compartment were accounted for. Figure 4-13 shows a plot of the average upper gas layer temperature versus time for an open diesel characterization fire with the door initially open 30 cm, but subsequently closed once a fully developed fire environment was achieved. This was the same fire test discussed in Section 4.2 and plotted in Figure 4-6. Using the method above, the peak average temperature of the compartment was determined to be 519^{o}C and occurred at 190 seconds after diesel pan ignition. The average upper gas layer temperature (2.0 m height) at 190 seconds was 688^{o}C, indicating that the fire environment did simulate that of a fully developed fire before suppression. Looking 60 seconds later, 250 seconds after ignition, the average upper gas layer temperature had cooled to 399^{o}C. Therefore, the cooling rate by oxygen starvation on the open diesel fire was calculated to be 289°C/min or 4.8°C/second. It is by this method that cooling rates for all aerosol suppression tests were determined.

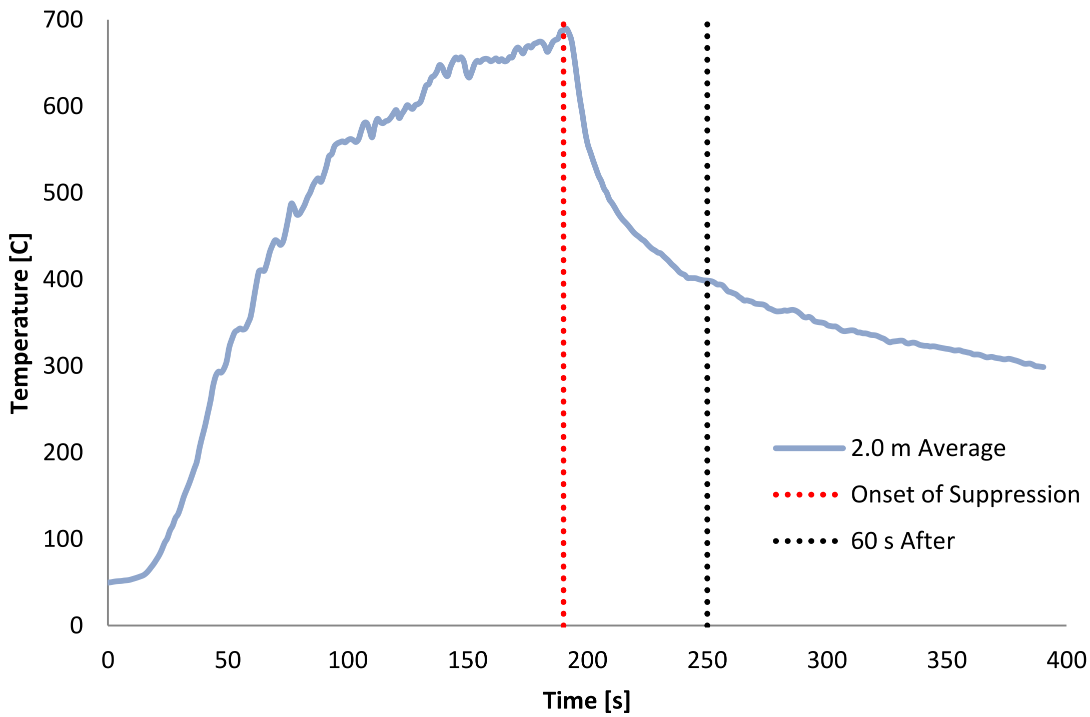


Figure 4-13. Cooling Rate of the Upper Gas Layer by Oxygen Starvation on Open Diesel Fire

4.3.4 Assessing Total Cooling Effect

Total cooling effect is a means of assessing the overall impact of a suppression method, agent or mechanism on the compartment fire environment based on differences in average compartment temperature before and after suppression as a function of vertical height. This is to say that it is a measure of the difference in thermal stratification within the compartment from the onset of suppression to a period of time following suppression. As defined in section 4.3.3, the onset of suppression is again taken as the time corresponding to the peak average temperature within the entire compartment. Figure 4-14 shows profiles of average temperature with height above the floor of the compartment, i.e. thermal stratification within the compartment, for the same fire as was discussed above, from the onset of suppression to 60 seconds after closing the door. Taking the difference between the two profiles plotted in Figure 4-14, the plot in Figure 4-15 is obtained. It represents the average compartment temperature difference as a function of height that occurs as a result of oxygen starvation of the fire (closing the compartment door). By integrating (or finding the area under) the curve in Figure 4-15, a measure of total cooling throughout the compartment is obtained in the units of centimeters·degrees. Since the temperature axis is temperature difference, the total cooling effect can be represented in either centimeters·Kelvin [cm·K] or in centimeters·degrees Celsius [cm.°C]. For the purpose of this report, the total cooling effect figures are represented in centimeters·Kelvin [cm·K] and the integrated values are divided by 1000 to give a number in meters·Kelvin [m·K]. The method of integration used for the x and y axis orientation of Figure 4-14 is the trapezoidal rule as:

$$\int_a^b f(x)dx \approx \frac{1}{2}\sum_{i=0}^{n-1}(x_{i+1} + x_i)(y_{i+1} - y_i) \qquad [16]$$

The integration of Figure 4-15. Average Compartment Temperature Difference from Oxygen Starvation of an Open Diesel Fire yields a total cooling effect of 54003 cm·K or 540.03 m·K.

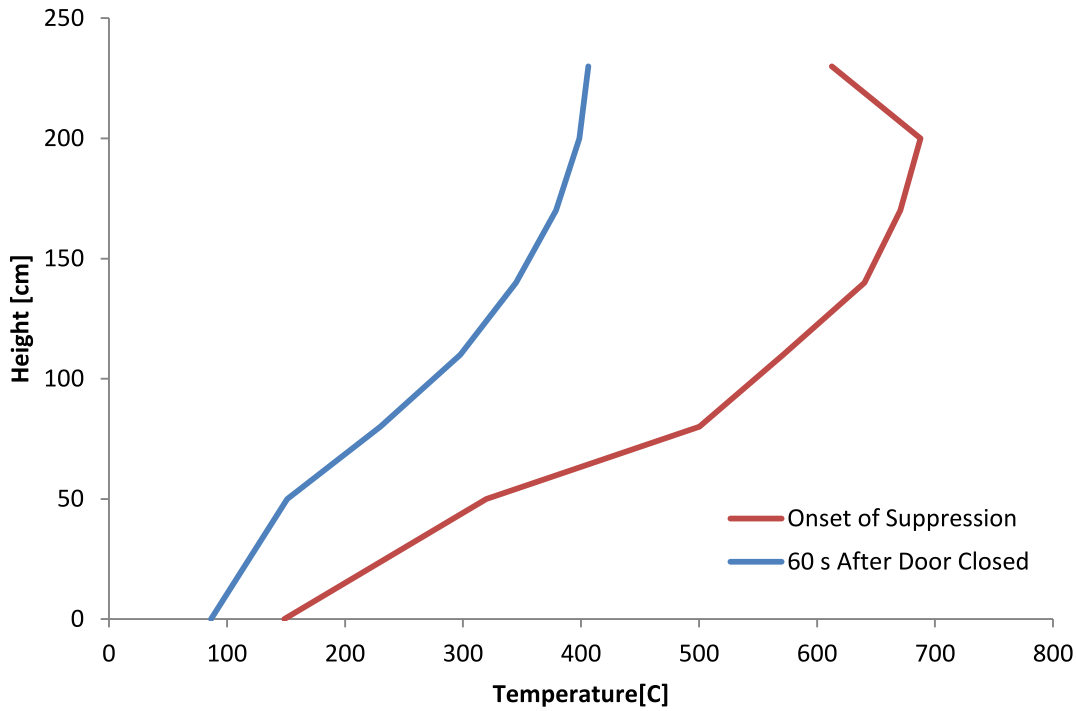


Figure 4-14. Average Effect of Oxygen Starvation on Thermal Stratification for an Open Diesel Fire

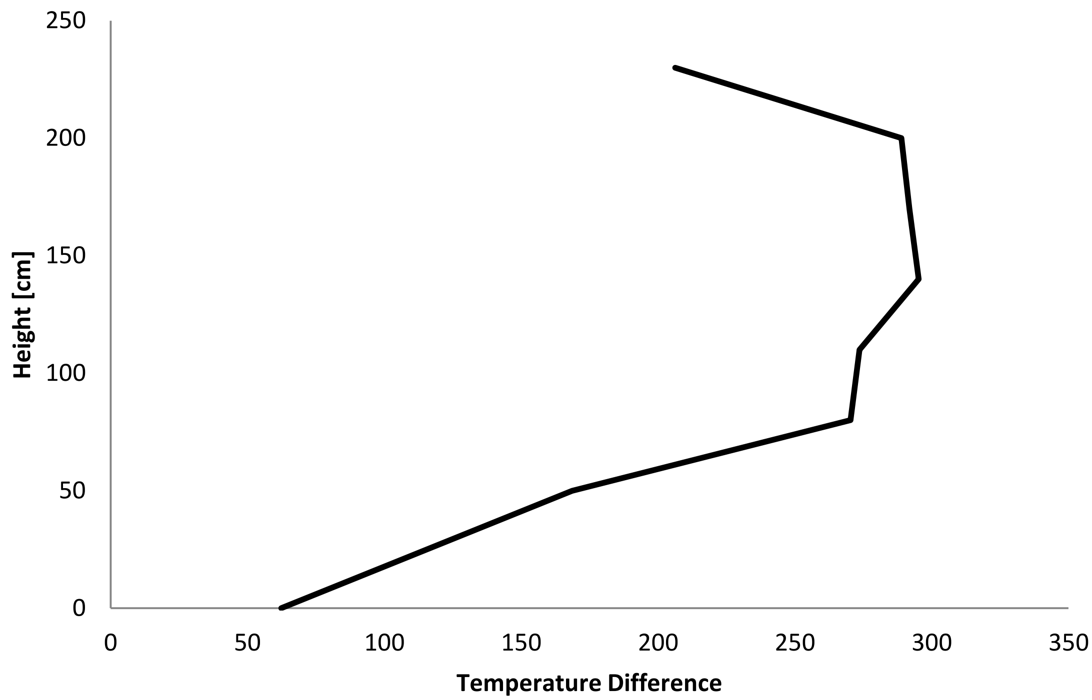


Figure 4-15. Average Compartment Temperature Difference from Oxygen Starvation of an Open Diesel Fire

4.3.5 Total Cooling Effects Sensitivity Analysis

Values of the total compartment cooling as determined above were then used as a comparative measure of suppression efficacy between the two variants of handheld aerosol extinguishers and the method of oxygen starvation alone. For this, it is important to ensure that the use of the global average compartment temperature differences outlined in Section 4.3.2 is appropriate. Therefore, to confirm the validity of using an average compartment thermal stratification, a sensitivity analysis was conducted. In this analysis, the total cooling effects were calculated as described above for the front, middle and rear of the compartment for three separate fire tests and compared to the average global cooling effects for the same tests to determine if the trends in values were similar in all cases. The three open diesel fire tests used for the sensitivity analysis were: Test 1a: StatX FR, Test 1a: DSPA 5-4 and the diesel fire characterization test where the burn room door was closed. The global, rear, middle and front temperature differences on all eight vertical heights were determined using the same process as outlined in Section 4.3.4. Results are listed in Table 4-2 for each of the three tests. To represent the sensitivity of the results to height above the compartment floor, Figure 4-16 shows the global average temperature differences from peak compartment temperature (as the onset of suppression activity) to 60 seconds after for each of the three test cases. Next, to highlight the temperature differences obtained using values of temperature measured by thermocouples on the rakes at the rear, middle and front of the shipping container burn room, Figure 4-17, Figure 4-18, and Figure 4-19 respectively are provided. These plots clearly indicate that there are variations in the magnitudes and distribution of temperature differences at various positions within the compartment during suppression activity. The key question, however, is to determine if there was any significant variation in the relative values of compartment cooling integrated using temperature differences measured at the rear, middle or front of the compartment. Further, it was of interest to see if the values from each of the above followed the same trends as those determined using the global average temperature differences for the entire compartment. Values of total compartment cooling for all four scenarios (global, rear, middle, and front temperature differences) were calculated and are listed in Table 4-2. They are also shown graphically in Figure 4-20. Analysis of the integrated cooling values for all four scenarios shows that there is certainly a variation between the individual values of total cooling. In general, however, independent of the location of temperature profiles that are used to determine the integrated value of compartment cooling, the test-to-test trends in the results are consistent. The compartment cooling observed during the Stat-X FR test was always the lowest, during the DSPA 5-4 test was always the highest and the cooling during the compartment confinement test (i.e. closing the door) fell in the middle. These results suggest that integrated values of compartment cooling based on the rear, middle or front compartment temperature differences vary in the same way as do those integrated from the global average compartment temperature differences. Based on this sensitivity analysis and interest in determining global compartment cooling during suppression, it was concluded that the global average compartment temperature differences would be used for comparative analysis of suppression efficacy throughout this work.

Table 4-2. Temperature Difference and Total Cooling Effects Location Sensitivity Comparison

	Test	Temperature Difference from Peak Compartment Temperature to 60 seconds								Total Cooling Effect [m·K]
		0.0 m	0.5 m	0.8 m	1.1 m	1.4 m	1.7 m	2.0 m	2.3 m	
Average Global Cooling Effects	1a: StatX FR	71	130	171	235	284	278	294	236	484
	1a: DSPA 5-4	86	164	233	299	322	295	310	226	558
	Closed Door	62	169	270	274	295	292	289	206	540
Rear (V1/V2) Cooling Effects	1a: StatX FR	40	76	69	116	119	194	200	168	275
	1a: DSPA 5-4	116	204	281	342	276	276	285	261	588
	Closed Door	66	137	278	268	263	275	290	251	521
Middle (V5/V6) Cooling Effects	1a: StatX FR	60	152	216	288	260	283	270	189	499
	1a: DSPA 5-4	116	193	297	429	385	394	322	219	687
	Closed Door	94	248	348	380	350	365	320	197	681
Front (V3/V4) Cooling Effects	1a: StatX FR	23	107	131	150	254	187	209	132	348
	1a: DSPA 5-4	63	152	187	207	358	239	270	185	482
	Closed Door	28	122	190	177	277	237	258	170	423

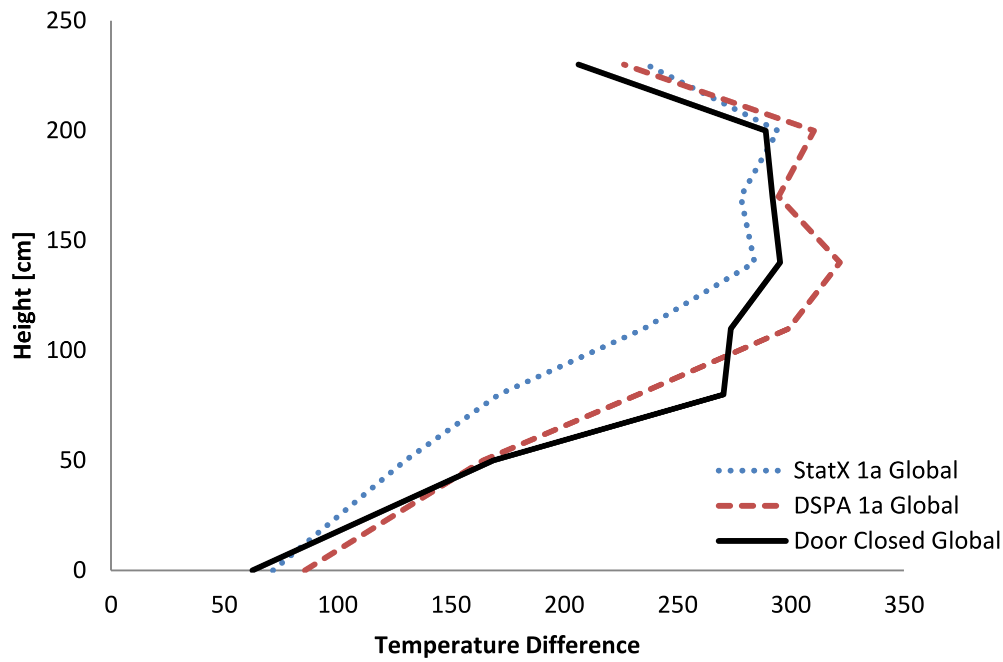


Figure 4-16. Compartment Cooling with Height for Three Open Diesel Fire Suppression Tests Using the Global Average Compartment Temperature Differences

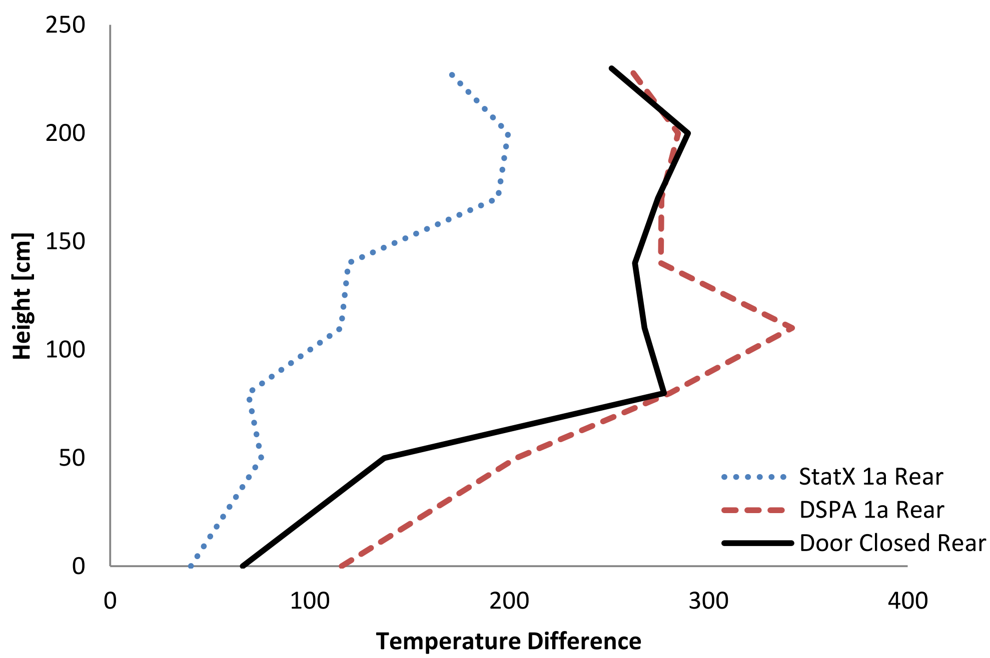


Figure 4-17. Compartment Cooling with Height for Three Open Diesel Fire Suppression Tests Using the Rear-Compartment Temperature Differences

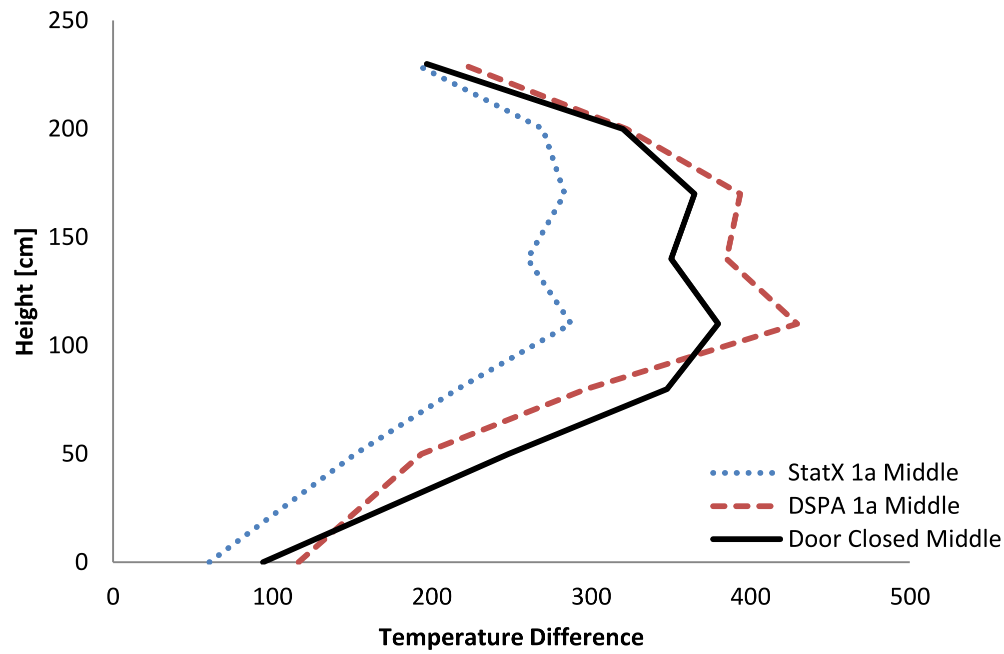


Figure 4-18. Compartment Cooling with Height for Three Open Diesel Fire Suppression Tests Using the Middle-Compartment Temperature Differences

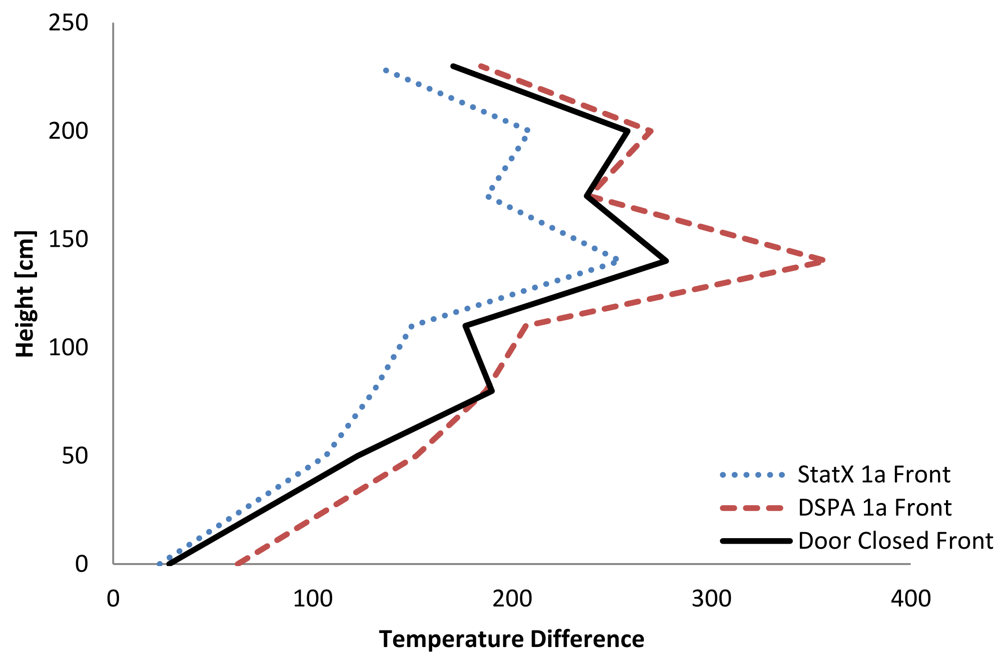
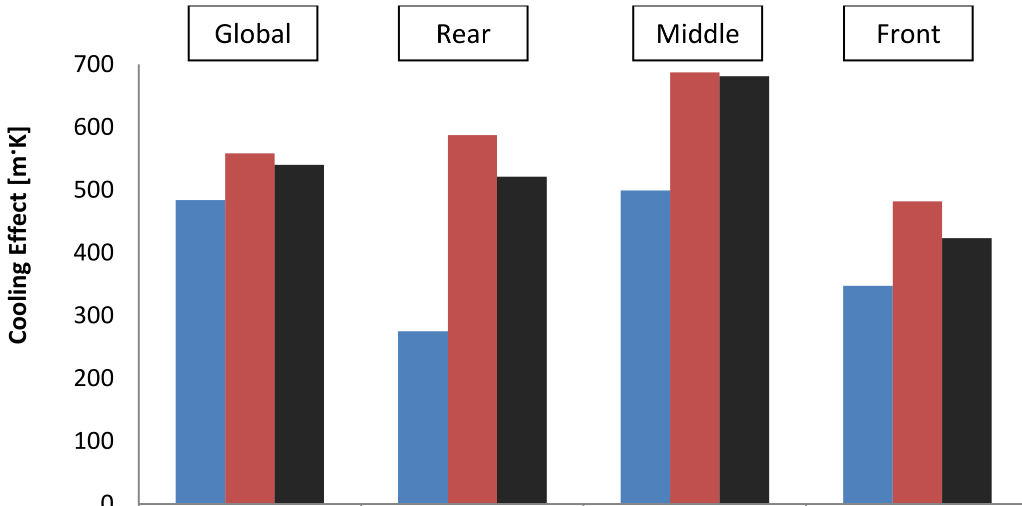


Figure 4-19. Compartment Cooling with Height for Three Open Diesel Fire Suppression Tests Using the Front-Compartment Temperature Differences



	1	2	3	4
StatX	484	275	499	348
DSPA	558	588	687	482
Closed Door	540	521	681	423

Figure 4-20. Comparison of Compartment Cooling Effects Calculated for Three Open Diesel Fire Suppression Tests Using Global (1), Rear (2), Middle (3), and Front (4) Temperature Differences

4.4 Actual Thermal Properties of the Burn Room Composite Wall Construction

Upon completion of the compartment characterization fires, it was determined that the CFAST predicted compartment temperatures were consistently higher than the measured compartment temperatures. Understanding the possible reasons for this discrepancy is important to both the analysis of aerosol suppression effects and to use of the model for experimental design for future work utilizing the UW burn room.

The higher CFAST predicted temperatures suggest that more heat is lost from the compartment during an actual fire than is assumed or calculated by model. The CFAST model references operator inputs for the effective thermal properties to represent the composite wall construction of the shipping container as outlined in the model development Section 4.1.1. The thermal properties were determined using the results of the live compartment fire tests to learn whether or not the effective thermal properties inputted into the CFAST model are accurate in reality. Based on the lower compartment temperatures experienced, the aim is to determine if the heat loss is the result of higher than predicted thermal conductivity through the compartment walls and ceiling. Looking at the global energy balance, it is known that the overall heat transfer by conduction is equal to the overall heat transfer by convection as follows [54]:

$$\dot{q}''_{conduction} = \dot{q}''_{convection} \qquad [17]$$

$$\dot{q}''_{conduction} = \frac{k}{L}(T_1 - T_2) \qquad [18]$$

$$\dot{q}''_{convection} = h(T_2 - T_\infty) \quad [19]$$

$$\frac{k}{L}(T_1 - T_2) = h(T_2 - T_\infty) \quad [20]$$

Using temperature data obtained during compartment fire characterization tests, the thermal conductivity, k, of the compartment was estimated by re-arranging the heat transfer equations to solve for k. The ambient temperature during this test was measured in real-time and is shown in Figure 4-21, while the internal and external side wall surface temperatures at a height of 170 mm (in the upper gas layer) are shown in Figure 4-22.

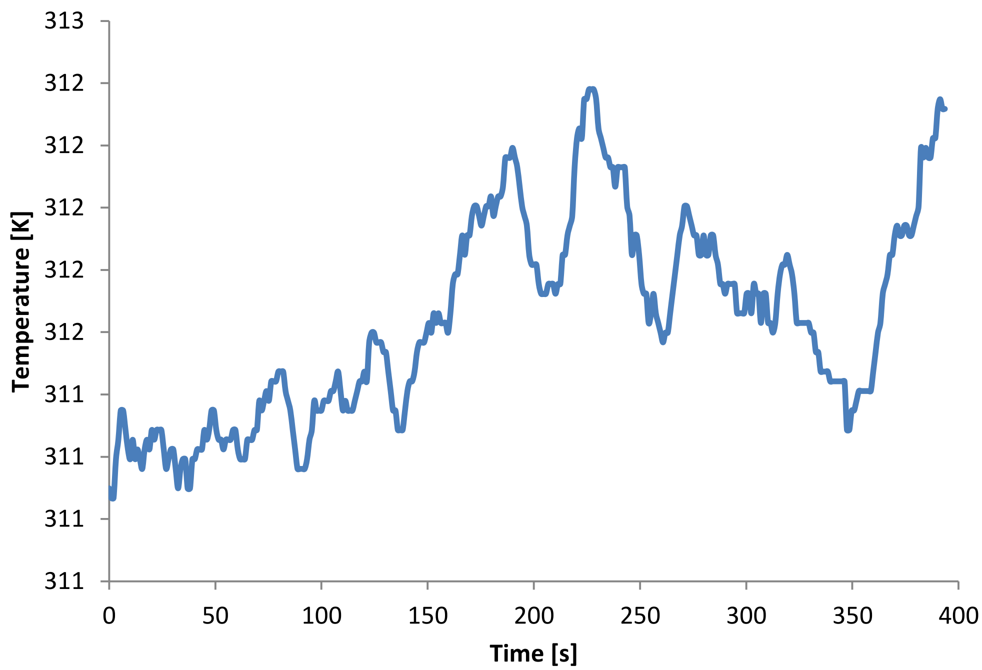


Figure 4-21. Ambient Air Temperature During Live Compartment Characterization Diesel Fire

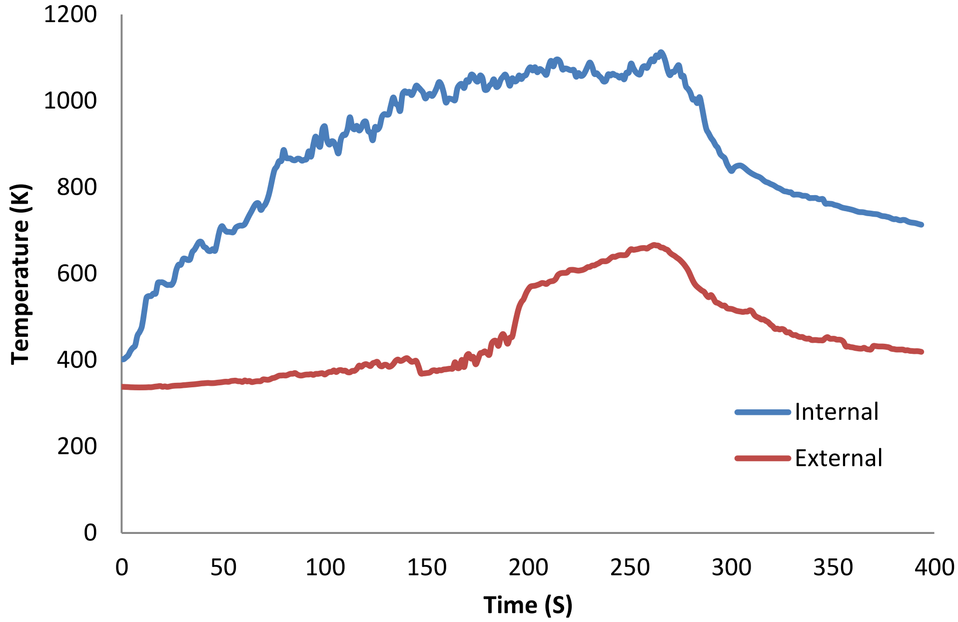


Figure 4-22. Internal and External Wall Surface Temperatures at 1.7 m from the Burn Room Floor

With the total wall thickness of 0.0545 m and assuming an average convection coefficient of 12 W/m^2K [54], the thermal conductivity of the shipping container walls may be calculated as follows:

$$k_{wall} = (0.05405m)(12W/m^2 \cdot K)\left[\frac{T_2 - T_{amb}}{T_1 - T_2}\right] \qquad [21]$$

Figure 4-23 shows the calculated results for k_{wall} throughout the live fire test using characterization fire temperature data from both Figure 4-21 and Figure 4-22.

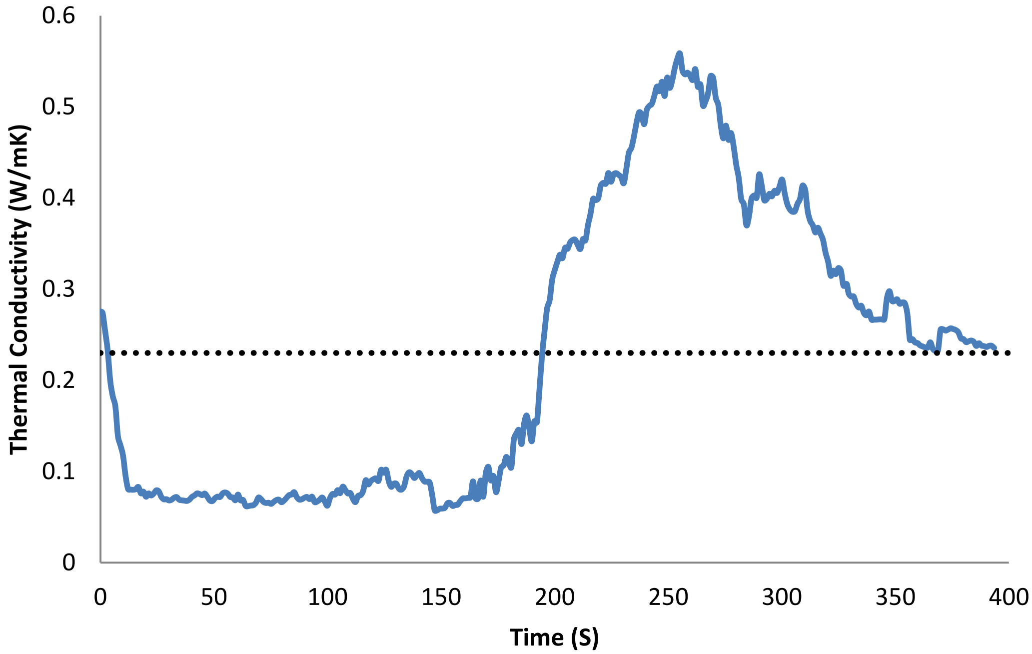


Figure 4-23. Calculated Thermal Conductivity of Burn Room Walls

CFAST cannot accommodate temperature dependent thermal properties, which is why the average effective properties were calculated and input to the model. Looking at the live compartment fires, the average coefficient of thermal conductivity was determined to be 0.23 W/mK. This is significantly higher than the effective thermal conductivity calculated and input to the CFAST model, which was a k_{eff}, of 0.0403 W/m·K. . The higher conductivity of the walls derived from the test results suggests a greater heat loss through the walls than calculated using the CFAST model which accounts, at least in part, for the higher predicted temperatures from the model. One reason is that CFAST assumes that the specific heat of the wall and ceiling materials does not vary as a function of temperature, which is not true in reality [70]. From Figure 4-23, the time to 150 sec looks like the wall is not heating significantly so that measured value would be expected to be closest to 0.04 but may be slightly higher because of moisture in the walls. Then after 150 secs the walls start to heat up and the impact of temperature variations in k become more noticeable. Another likely reason for an increase in the actual conductivity is moisture ingress saturating the ceramic fiber insulation in the burn room walls. This is supported by the observation that significant amounts of steam were observed to emanate from under the aluminum cladding during the fire tests even though no water suppression was utilised. Both of these factors would contribute to the much higher thermal conductivity, and therefore higher heat losses, apparent in the real fire situation.

4.5 Compartment Characterization Summary

This chapter has outlined results of characterization of the UW burn compartment using both computer numerical simulation methods and by live full-scale compartment characterization fires. These were used to predict and then confirm the fully developed fire environments essential to repeatable aerosol suppression testing. Optimum ventilation factor by means of compartment door opening fraction was evaluated and determined to be best set at 30 cm (33%) in order to prevent oxygen starvation while still minimising the amount of aerosol dispersal and exit from the compartment. The compartment environment was confirmed to be consistent and repeatable through several live fire tests in different ambient conditions. The effects on the test fire environment of oxygen starvation of the fire by means of closing the compartment door were also established. This allows the effects of oxygen starvation to be understood in isolation of aerosol suppression, which then allows the efficacy of aerosol suppression alone to be quantified, compared and evaluated. Next, methods of averaging the experimental data and evaluating suppression efficacy were developed and validated, allowing for upper gas layer cooling rate, impact on thermal stratification and total compartment cooling effects to be consistently determined for each suppression test. Finally, the actual thermal properties of the UW shipping container were calculated to understand the real thermal properties of the walls and ceilings as they relate to heat loss during live fire testing. Upon successful characterization, the burn room and fuel loads were ready for live fire testing, and a well characterized and repeatable fire and compartment environment were established, enabling the accurate data acquisition and analysis necessary to determine aerosol agent efficacy and to facilitate head-to-head comparison of the two variants of aerosol extinguishers.

5 Aerosol Suppression Tests

Using the experimental design, test set up and data calculation methods determined through the characterization tests, the aerosol suppression tests were conducted. In the first series, the aerosol units were evaluated against three fire scenarios that are representative of the challenging marine machinery space fires and one general on-board fire scenario of interest to the RCN. The first scenario was a 0.905 m x 0.910 m (0.82 m^2) open diesel pool fire in the UW Burn Room test compartment. The second was an obstructed diesel pool fire in the same compartment where a 1.4 m x 1.3 m x 0.46 m steel structure was suspended 0.40 m above the floor and 0.21 m above the surface of the diesel pool fire to simulate an engine enclosure fire. The third scenario involved the same obstructed fire in the compartment; however, in this scenario, the extinguisher was activated and placed into the pan of water 0.3 m deep located under the burning diesel fuel to simulate an aerosol suppression unit falling into a watery bilge during suppression of the fire. The final scenario was a wood crib fire in the same compartment designed to simulate a general Class A fire in a shipboard compartment.

A series of tests designed to investigate key characteristics of the aerosol agent alone (agent only tests) were also developed and conducted in the UW shipping container. In these tests, the aerosol unit was discharged into a compartment without a fire and aerosol dispersion, particle suspension and settling and the consequent obscuration of vision were observed throughout the compartment, while temperature and gas concentration data were collected to assess any heat and toxic gases that might be generated during discharge of the unit. Functioning electronic devices were placed within the compartment for several of the agent only tests to assess the possibility of aerosol powder residue build-up on the electronics and what impact that might have on the subsequent operation of the devices. Finally, a fully outfitted firefighter with SCBA was situated in the closed compartment during agent only tests to evaluate powder residue on the breathing apparatus (BA) and personal protective ensemble (PPE) and to conduct a series of fuel re-ignition tests using a butane lighter.

In the following sections, the fire suppression test programme details are first outlined and then results of the tests for each fire scenario are presented and discussed in Sections 5.3 through 5.7. The agent only tests and the corresponding results are then outlined separately in Chapter 6.

5.1 Suppression Test fires and Programme

The tests undertaken in this study used four different basic fire configurations with configuration, fuel and fire sizes as described in Table 5-1 below. These included Fire A which is the basic diesel fire used in the open and obstructed diesel fuel fire tests, as well as Fire B which is the basic wood crib fire used in the Class A fire scenarios. Fire C is a small methanol fire that was used to ignite the softwood crib fires, while Fire D is a butane torch fire used in the investigation of possible re-ignition after suppression using an aerosol unit.

The various fire configurations are used to fuel the five different fire scenarios as outlined in Table 5-2. Each test listed in the Table was conducted for both aerosol units, with some repeat tests, for a total of 16 suppression tests.

Table 5-1. Parameters of Suppression Test Fires

Fire	Type	Fuel	Fire Size, MW
A	0.82 m^2 with 10 ℓ of Diesel over a 105 ℓ water base	Diesel	0.9
B	Softwood crib	Spruce	0.12
C	0.1 m^2 tray with 0.2 ℓ methanol	Methanol	0.03
D	Butane Lighter	Butane	0.0005

Table 5-2. Aerosol Suppression Test Programme

Test No.	Fire Suppression Test Scenarios
1A	Fire A: 0.82 m^2 tray as unobstructed diesel pool fire
1B	Fire A: 0.82 m^2 tray as unobstructed diesel pool fire (repeat)
2A	Fire A: 0.82 m^2 tray as obstructed diesel pool fire under engine enclosure mock-up
2B	Fire A: 0.82 m^2 tray as obstructed diesel pool fire under engine enclosure mock-up (repeat)
3A	Fire A: 0.82 m^2 tray as obstructed diesel pool fire under engine enclosure mock-up; activate extinguisher and slid into fuel pan to simulate units falling into a watery bilge
3B	Fire A: 0.82 m^2 tray as obstructed diesel pool fire under engine enclosure mock-up; activate extinguisher and slid into fuel pan to simulate units falling into a watery bilge (repeat)
4	Fire B: 4 softwood cribs near back wall of test room as unobstructed Class B fire with Fire C: As an ignition source – 1 methanol ignition fire
5	Fire D: Activate unit in burn room and continually attempt spark-ignition of butane in the aerosol environment. Also expose electronic devices to aerosol and assess noise and obscurity.

5.2 General Test Procedure

For each test, the compartment was first preheated with a 2-3 minute pre-burn diesel fire. Following this, the main test fire was burned until steady state, fully developed fire conditions were established in the burn compartment. The aerosol extinguisher was then activated and placed on the floor just inside the door of the test compartment, positioned to allow the discharged aerosol particles to be drawn to the fire along the path of cool ambient air entering the compartment and feeding the fire. Since preliminary testing of handheld aerosol systems at UW had determined that placement of the aerosol units was critical to ensure integrity of agent distribution from different aerosol unit designs, consistent placement of the extinguishers was done to facilitate test to test repeatability so that comparative data could be collected to determine the impacts of different aerosol units on the compartment fire environment. Pre-set location of the units for each test also allowed better analysis of aerosol suppression efficacy as no changes in test fire characteristics arose due to changes in compartment ventilation and, as such, a consistent scenario was developed for evaluation of the units. Through the discussion, results obtained in this research using pre-set aerosol locations are combined with existing UW information on possible influences of location and movement of aerosol units during fire suppression activity to better identify issues associated with integrity of agent distribution during knock down operations that might be undertaken by RRTs and RATs in fighting fires on board ship.

Pertinent details of the methods used, as well as results from the fire suppression tests are presented and discussed in the following several sections. The body of each section contains representative graphs that summarise the tests and convey the important results. All raw data, video and thermal imaging files are available for research purposes on request.

5.3 Aerosol Suppression Tests Results and Discussion

The results from all suppression tests are presented and discussed in this section. The body of this section contains sufficient graphs to summarise the tests and convey the results in a concise manner as they pertain to particular discussion points.

5.4 Discussion of Tests 1a and 1b: Open Diesel Fire Suppression

5.4.1 Fire Suppression Techniques for Tests 1a and 1b

Test 1a and 1b were two identical open diesel fire suppression tests conducted for both the StatX FR and the DSPA 5-4 handheld extinguishers (for a total of four experiments). The compartment setup for this test is shown in Figure 5-1. The results are utilized to evaluate the three key elements discussed above in terms of suppression efficacy: cooling rate of the upper gas layer, total cooling effect on the compartment, and average effect on thermal stratification. Measured concentrations of oxygen and carbon dioxide are also presented since these are also directly proportional to fire growth and decay. As such, they serve as additional indicators that further outline some of the effects of aerosol suppression on the open diesel fires discussed here.

For each open diesel fire suppression test, a 3 ℓ diesel pre-burn was conducted to heat the compartment and to drive as much moisture as possible from the ceramic fibre insulation in the compartment walls. Upon completion of the pre-burn, 10 ℓ of diesel fuel was added to the 105 ℓ water substrate in the fuel pan and the freeboard height was adjusted to 1 cm by adding or removing water. Thermocouple and gas analysis data acquisition was started and the video recordings commenced for internal colour and low wavelength cameras, internal IR camera and external colour video camera. Ambient conditions were recorded and the 10 ℓ diesel fuel load was ignited via propane torch on an extension handle. The compartment door was fixed at 30 cm for an initial burn period of approximately 2 min or until the average upper gas layer reached approximately 550^{o}C, whichever came first. At this point, the aerosol unit under test was activated and placed precisely on the floor inside the door frame without changing the opening fraction of the door itself, thereby minimising test to test variability that might be caused due to changes in ventilation and/or location of the aerosol units. The activation time and discharge duration of the units were recorded and visual observations were made throughout the suppression tests. Temperature, gas concentration, and video data were analysed after the test to determine the suppression efficacy of aerosol agent in each test.

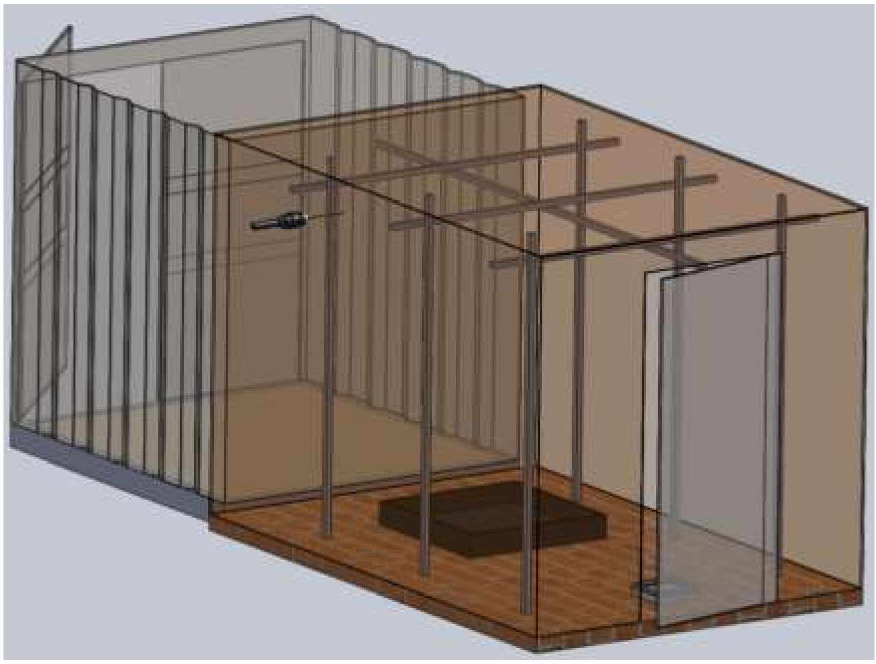


Figure 5-1. UW Shipping Container Burn Room Setup for Test 1a and 1b, Open Diesel Fire Suppression

5.4.2 Suppression Results for Test 1a: StatX FR Open Diesel Fire

The StatX FR unit in Test 1a successfully suppressed and then extinguished the open diesel fire. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-2. From the Figure, the cooling rate in the compartment from the onset of suppression to 60 seconds after suppression was determined to be 296^{o}C/min or 4.9^{o}C/second. The effects of aerosol suppression on compartment thermal stratification are represented in 10 s intervals in Figure 5-3, and the average temperature difference vertically in the compartment is shown in Figure 5-4. Integrating the curve in Figure 5-4 indicates a global cooling effect in the compartment of 484 m·K. Oxygen and carbon dioxide concentrations throughout the suppression test are plotted in Figure 5-5, showing the decrease in oxygen concentration and the increase in carbon dioxide concentration as the fire grows, up to the onset of suppression. During suppression oxygen concentration increases and production of carbon dioxide decreases. After the end of the test, both concentrations return to atmospheric values representative of a fully extinguished fire.

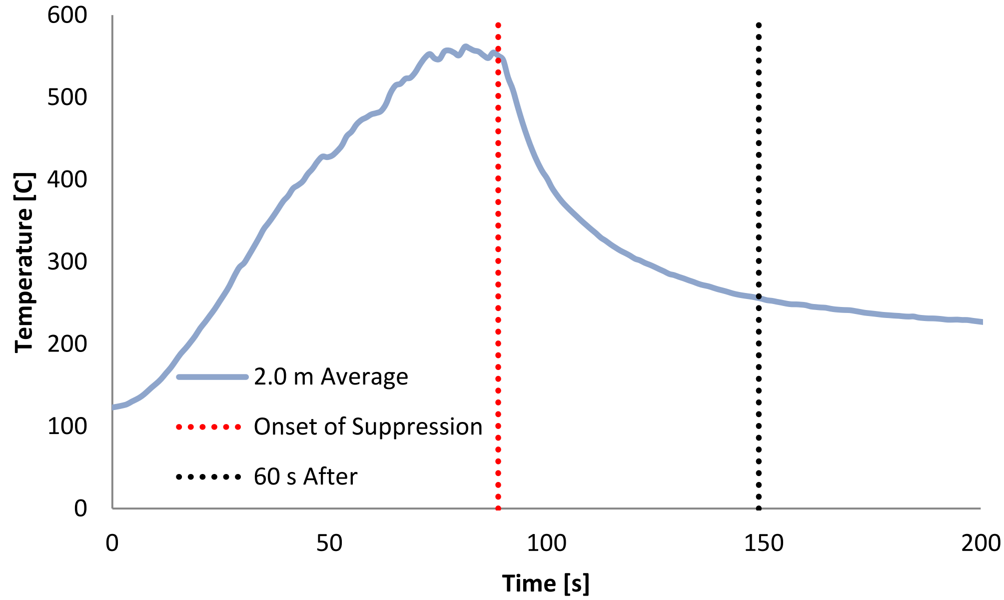


Figure 5-2. Test 1a: StatX FR Open Diesel Fire Upper Layer Temperature Cooling Rate after Aerosol Released with the door kept open at 30 cm throughout

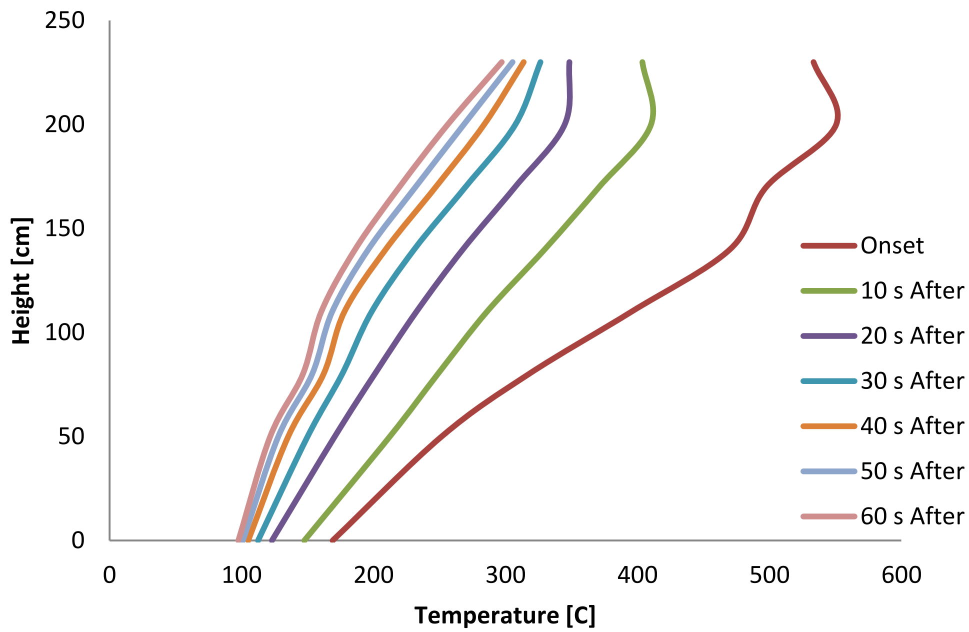


Figure 5-3. Test 1a: StatX FR Suppression Effect on Average Thermal Stratification after Aerosol Released with the door kept open at 30 cm throughout

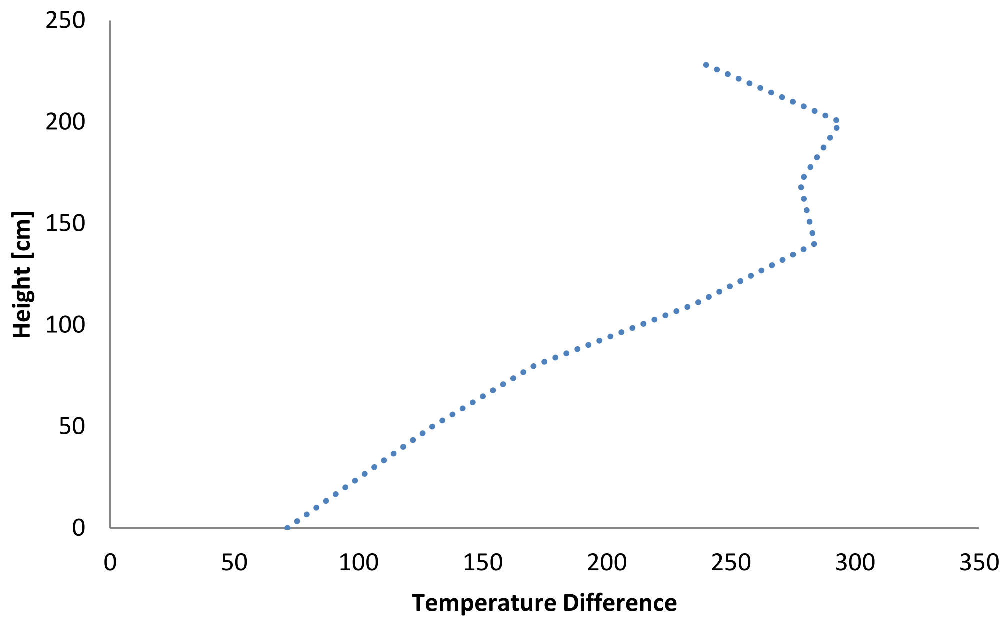


Figure 5-4. Test 1a: StatX FR Average Temperature Difference Due to Aerosol Agent from the onset of suppression to 60 seconds after

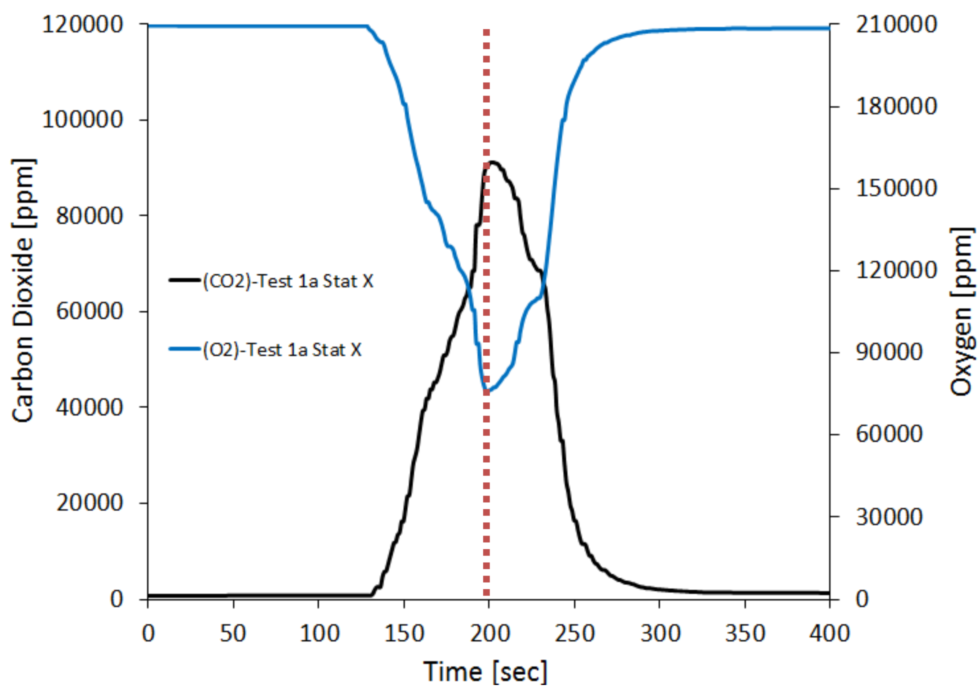


Figure 5-5. Test 1a: Stat X's Carbon Dioxide and Oxygen concentrations as a result of aerosol suppression

5.4.3 Suppression Results for Test 1b: StatX FR Open Diesel Fire

The StatX FR unit in Test 1b successfully suppressed and then extinguished the open diesel fire. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-6. From the Figure, the cooling rate was determined to be 318^{o}C/min or 5.4^{o}C/second from the onset of suppression to 60 seconds after suppression. The change in compartment thermal stratification during suppression are shown in 10 s intervals in Figure 5-7, and the average temperature difference vertically in the compartment is shown in Figure 5-8. Integrating the curve of Figure 5-8 gives a global cooling effect throughout the compartment of 518 m·K. Oxygen and carbon dioxide concentrations are plotted in Figure 5-9, again showing the decrease in oxygen concentration and the increase in carbon dioxide concentration as the fire grows up to the onset of suppression. After suppression oxygen concentrations again increase and production of carbon dioxide decreases with both concentrations returning to atmospheric values once the fire is extinguished.

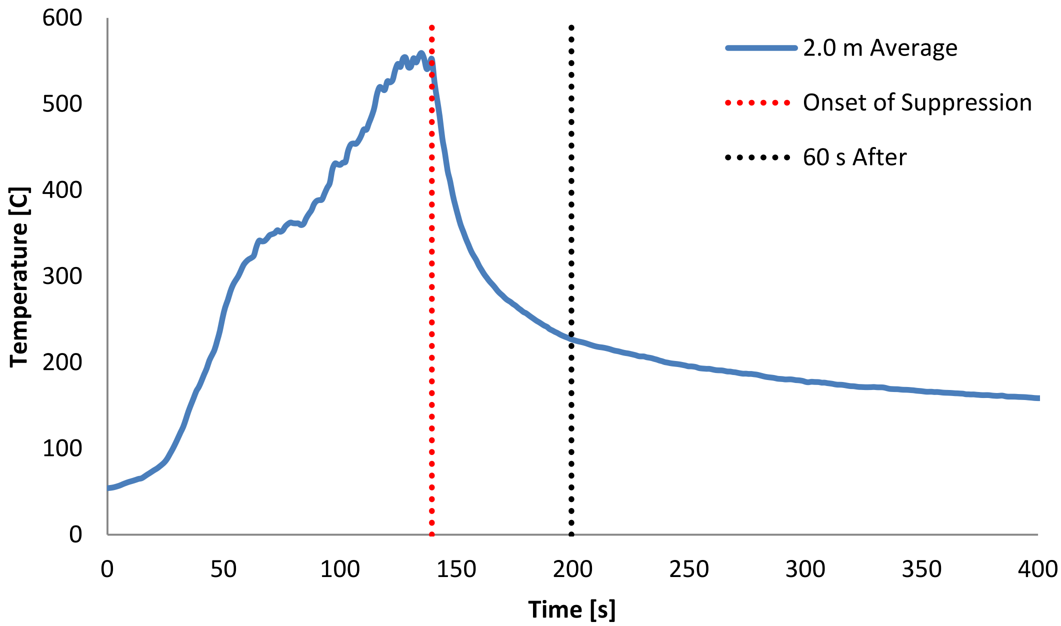


Figure 5-6. Test 1b: StatX FR Open Diesel Fire Upper Layer Temperature Cooling Rate after Aerosol Released with the door kept open at 30 cm throughout

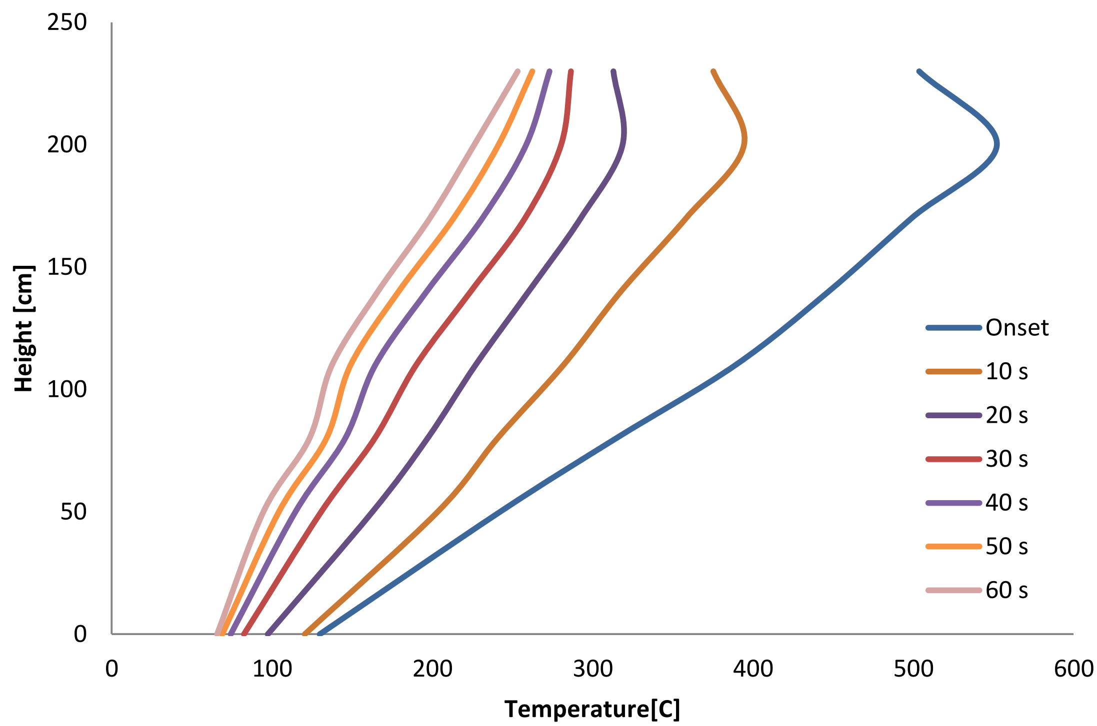


Figure 5-7. Test 1b: StatX FR Suppression Effect on Average Thermal Stratification after Aerosol Released with the door kept open at 30 cm throughout

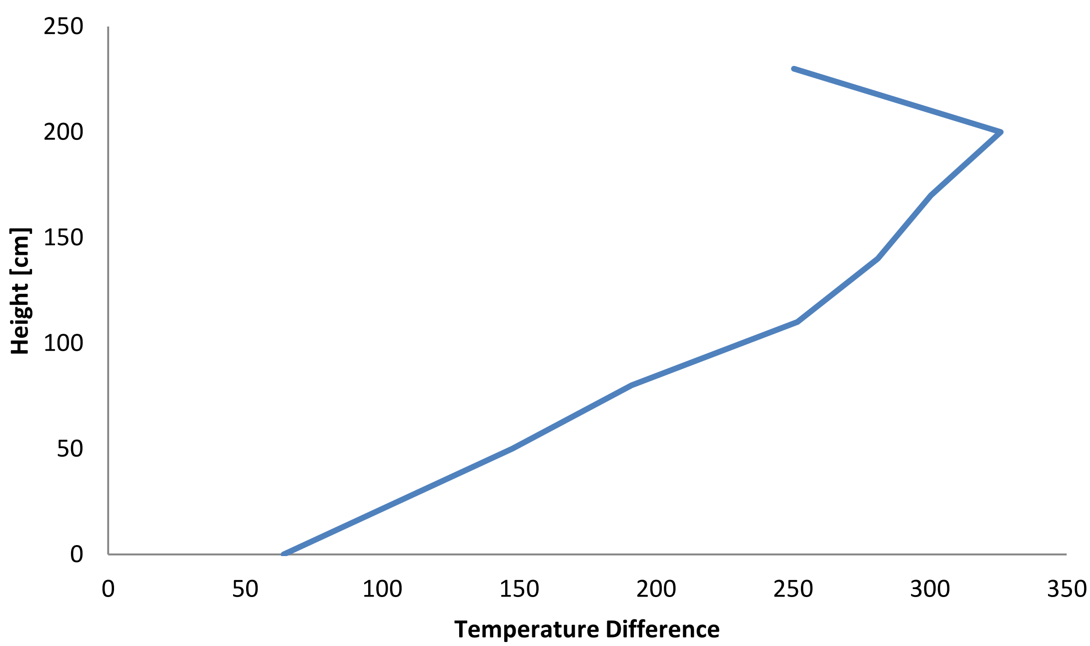


Figure 5-8. Test 1b: StatX FR Average Temperature Difference Due to Aerosol Agent from the onset of suppression to 60 seconds after

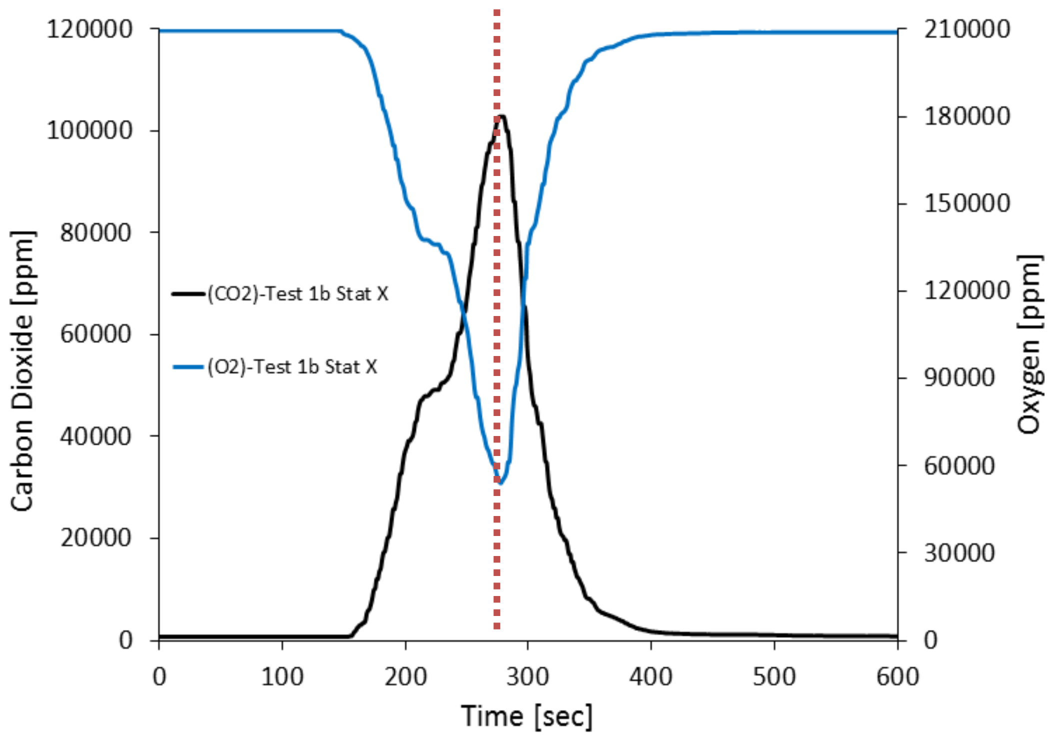


Figure 5-9-Test 1b: Stat X's Carbon Dioxide and Oxygen concentrations as a result of aerosol suppression

5.4.4 Suppression Results for Test 1a: DSPA 5-4 Open Diesel Fire

The DSPA 5-4 unit in Test 1a successfully suppressed and then extinguished the open diesel fire. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-10. From the Figure, the cooling rate from the onset of suppression to 60 seconds after suppression was determined to be 292^{o}C/min or 5.2^{o}C/second. Effects on thermal stratification in the compartment are shown for 10 s intervals in Figure 5-11, and the average temperature difference vertically in the compartment is shown in Figure 5-12. Integrating the curve in Figure 5-12 indicates a global cooling effect of 558 m·K throughout the compartment. Oxygen and carbon dioxide concentrations throughout the suppression test are plotted in Figure 5-13, showing the same trends as in the previous tests.

Due to a communication error in this test, the fire was allowed to grow past an average upper gas temperature of 550^{o}C before suppression was initiated. At the two minute point, the average upper gas layer temperature was 686^{o}C. The higher threshold for "onset of suppression" yielded a higher relative cooling rate and total estimated cooling effect obtained in this test in comparison to those from the other tests where suppression commenced at upper gas temperatures closer to 550^{o}C. In addition, the longer burn time produced more carbon dioxide than seen in other tests, causing the respective gas analyser cell to plateau for a few seconds at its maximum measurable level in parts per million (ppm) of 100,000 or 10%. This can be seen in Figure 5-13 at approximately 200 seconds, around the time of fire suppression.

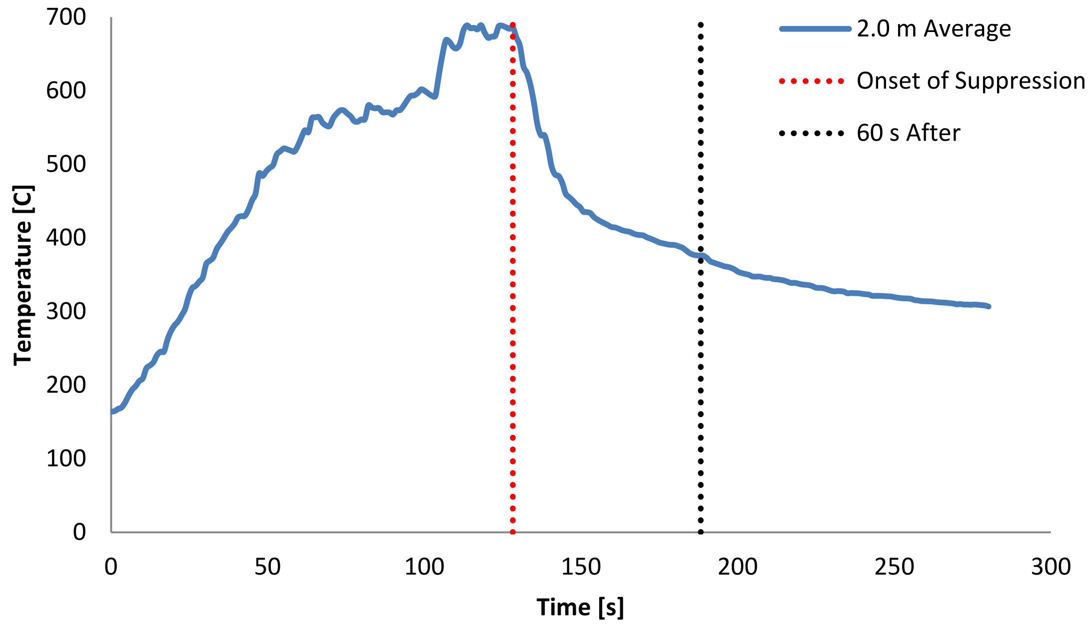


Figure 5-10. Test 1a: DSPA Open Diesel Fire Upper Layer Temperature Cooling Rate after Aerosol Released with the door kept open at 30 cm throughout

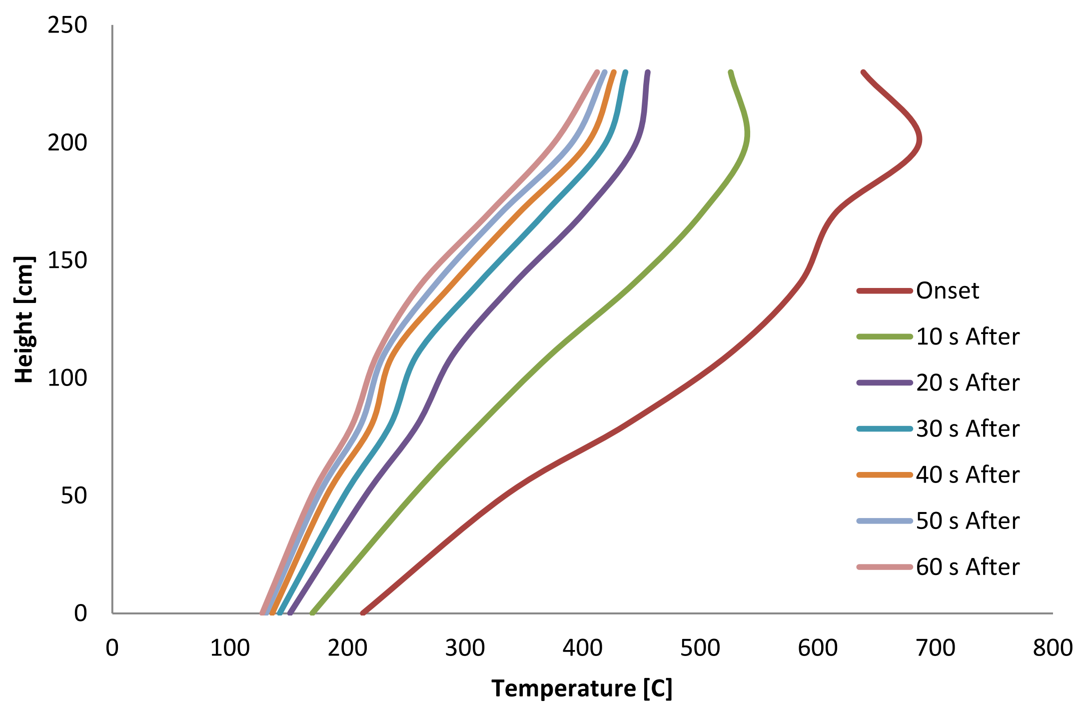


Figure 5-11. Test 1a: DSPA 5-4 Suppression Effect on Average Thermal Stratification after Aerosol Released with the door kept open at 30 cm throughout

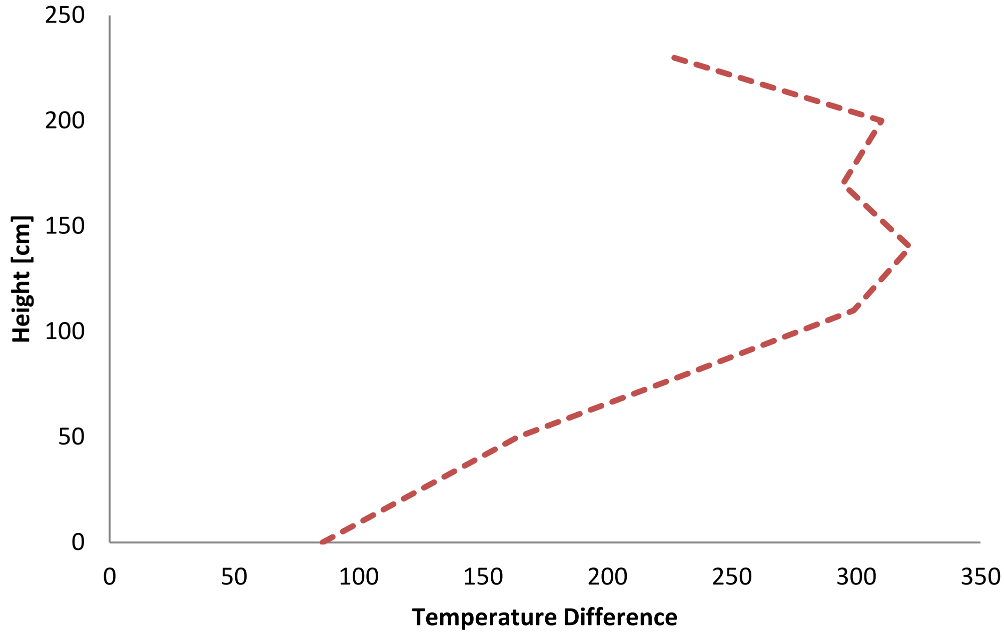


Figure 5-12. Test 1a: DSPA 5-4 Average Temperature Difference Due to Aerosol Agent from the onset of suppression to 60 seconds after

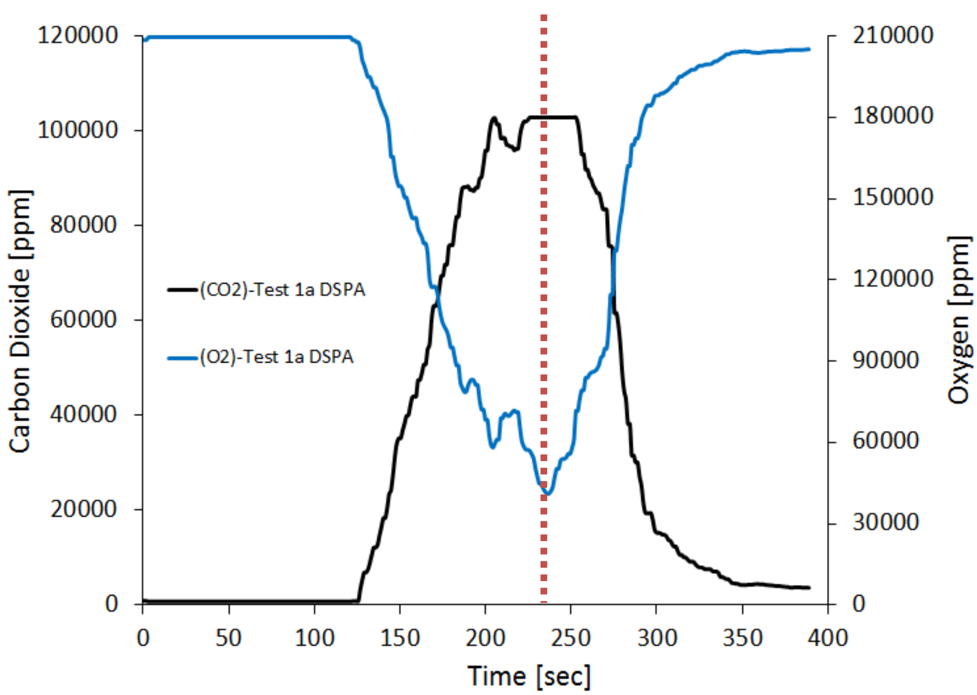


Figure 5-13. Test 1a: DSPA's Carbon Dioxide and Oxygen concentrations as a result of aerosol suppression

5.4.5 Suppression Results for Test 1b: DSPA 5-4 Open Diesel Fire

The DSPA 5-4 unit in Test 1b suppressed but did not fully extinguish the open diesel fire in sharp contrast to the previous three tests. Therefore, in this test, an assessment of the level of suppression was obtained by focusing on the period of time between the peak average compartment temperature and the lowest average compartment temperature before the fire began to grow again which occurred at about 9 seconds after the beginning of suppression. From Figure 5-14, the cooling rate from the onset of suppression to 9 seconds after suppression was determined to be 144°C/min or 16°C/second. The effects of aerosol agent on the thermal stratification in the compartment are represented in 1.125 s intervals over this 9 second period in Figure 5-15, and the average temperature difference vertically in the compartment is shown in Figure 5-16. Integrating the curve in Figure 5-16 gives a global cooling effect of 218 m·K. Oxygen and carbon dioxide concentrations throughout the suppression test are plotted in Figure 5-17, and show the same trends before suppression as in all other tests. Fire suppression is then marked by increased oxygen concentration and decreased production of carbon dioxide; however, since the fire was not extinguished in these tests, the oxygen concentration begins to drop and carbon dioxide increase again as the fire began to grow. The gas concentration results seen in this test clearly provide a secondary indication of how the aerosol agent has interacted with the compartment fire environment in those situations where the fire is not completely extinguished.

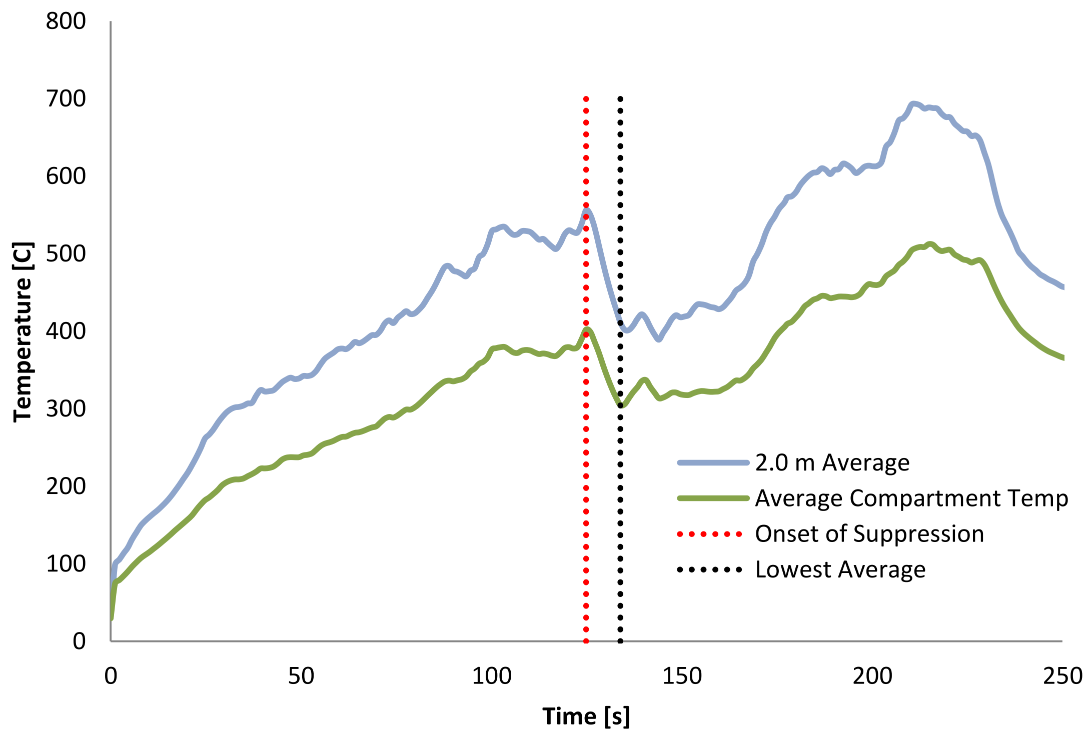


Figure 5-14. Test 1b: DSPA Open Diesel Fire Upper Layer Temperature Cooling Rate after Aerosol Released with the door kept open at 30 cm throughout

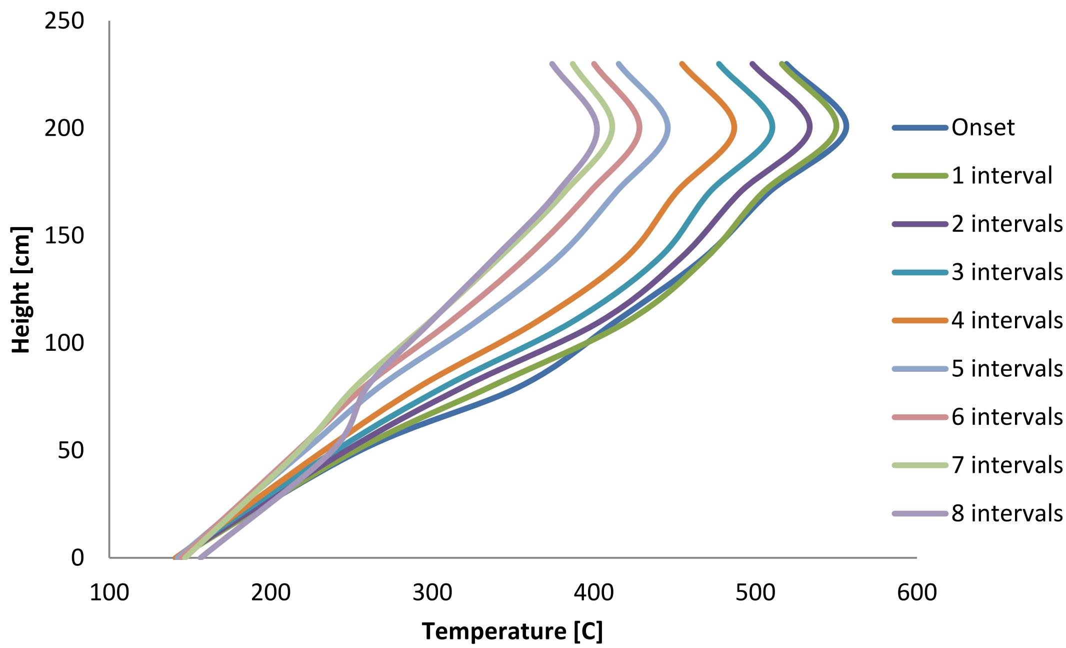


Figure 5-15. Test 1b: DSPA 5-4 Suppression Effect on Average Thermal Stratification after Aerosol Released with the door kept open at 30 cm throughout

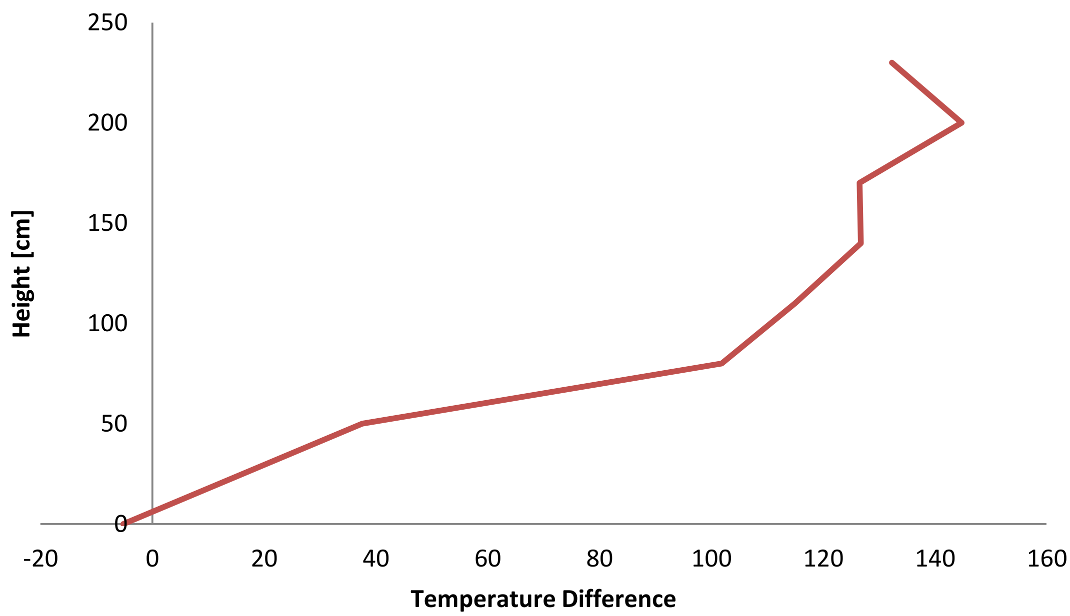


Figure 5-16. Test 1b: DSPA 5-4 Average Temperature Difference Due to Aerosol Agent from the onset of suppression to the lowest average compartment temperature

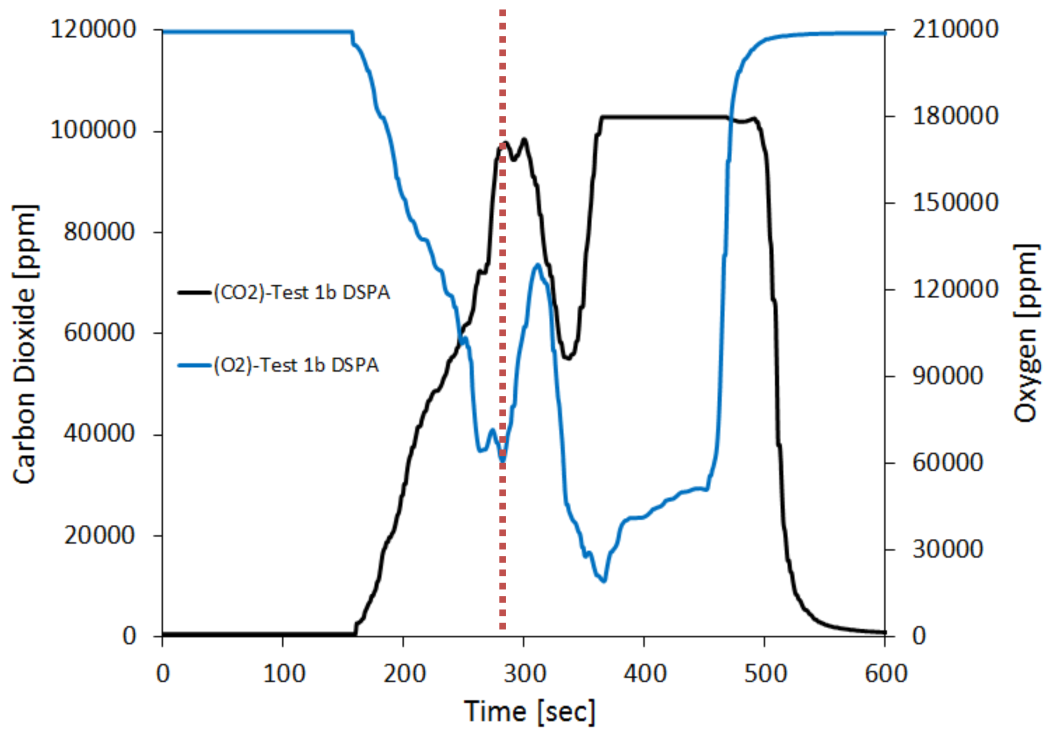


Figure 5-17. Test 1b: DSPA 5-4 Carbon Dioxide and Oxygen concentrations due to Aerosol Suppression

5.4.6 Summary and Discussion of Test 1a and 1b: Open Diesel Fire Results

The summary of results contained in Table 5-3 and Figure 5-18 shows that the suppression efficacy of both aerosol units was similar. Comparison with results outlined in Section 4.2 for the characterization fire in which the door was closed and the fire starved of oxygen, further indicates that both sets of aerosol suppression results mimic the effects of fire room confinement and oxygen starvation of an open diesel fire. From the Table, it can be seen that cooling rates across the tests range from 4.8 – 5.4°C/s, with the average cooling rate for the DSPA 5-4 being 5.3°C /s in comparison to 4.9°C /s for the Stat-X, both slightly higher than the value of 4.8°C /s for fire confinement alone. The average total cooling index for the DSPA 5-4, however, was very close to that for fire confinement with no aerosol, around 540 m-K, while that for the Stat-X unit was lower at 484 m-K. With the exception of DSPA Test 1b, the fires were suppressed and then extinguished, resulting in rapid temperature drops throughout the compartment.

It is important to note that for both sets of tests (1a and 1b) the compartment door was held open at 30 cm throughout the experiment, meaning that a large percentage of aerosol agent may have escaped without interacting effectively with the compartment fire environment. As such, the fact that the aerosol agent demonstrated similar suppression and cooling effects on the fire as did closing the door (oxygen starvation) is a positive note for their efficacy. In contrast, as seen via the negative result for the DSPA 5-4 unit in Test 1b, ventilation conditions within the fire compartment can have a marked effect on aerosol action. Although the aerosols did suppress the fire for three of the four test scenarios studied here, in other tests conducted with the compartment door held open at 30 cm, it was found that the fire was not extinguished when the aerosol units were activated right beside the diesel fuel pan. From the combined results, it appears that the aerosol generation pathways must be aligned such that the cool air entering the fire compartment can effectively pick up the aerosol particles and thus carry the agent to the seat of the fire. Otherwise, in a fully developed fire environment when the compartment ventilation cannot be fully confined, the buoyant forces generated by the hot fire plume gases appear to overcome the ability of the aerosol to fill the compartment, resulting in a large fraction of the agent being dispersed and expelled from the compartment along with the hot fire gases before it has had a chance to interact both thermally and chemically to suppress the fire. From preliminary research at UW, it is clear that the location of aerosol activation is critical to the success of fire extinguishment in unconfined or, from the perspective of naval fire scenarios, breached compartments.

Table 5-3. Summary of Test 1a and 1b: Open Diesel Fire Results

Test	Ambient Temp [^{o}C]	Ambient RH [%]	Ambient Wind Speed [m/s]*	Ambient Wind Direction	Peak Average Temp [^{o}C]	Cooling Rate (^{o}C/Sec)**	Total Cooling Effect [m·K]
1a: StatX FR	39	75	2.0-5.0	W	401	4.9	484
1b: StatX FR	19.4	72	0.5	SW	385	5.4	518
1a: DSPA 5-	39	76	2.0-5.0	W	504	5.2	558
1b: DSPA 5-	20.6	58	0.8-0.9	S-SW	402	16***	218
Closed Door	19	33	0.0-0.8	W	519	4.8	540

*Note 1: Ambient wind speed taken at door of compartment between wind blocks to assess air flow at the door during suppression testing.

**Note 2: Cooling rates assessed from onset of suppression to 60 seconds after peak average temperature.

***Note 3: Cooling rate is only for 9 seconds between peak average and lowest average temperature since the fire was not extinguished in this test.

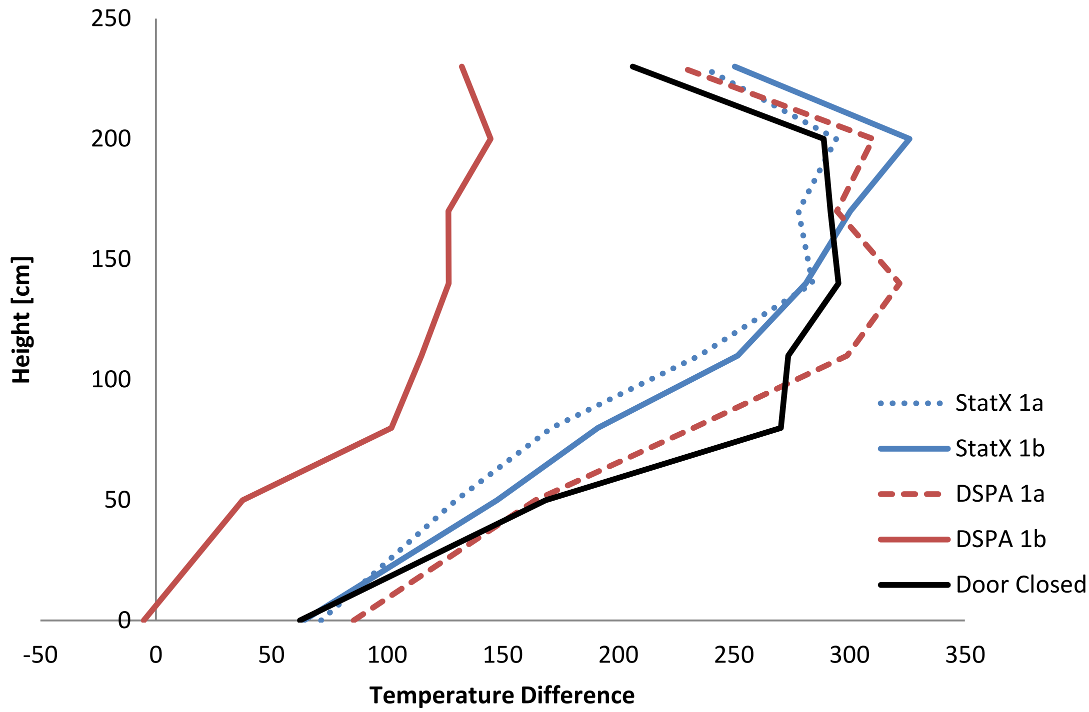


Figure 5-18. Summary of Average Compartment Temperature Difference Caused by Aerosol Agent Suppression from a Fixed Location while the Compartment Door was held open at 30 cm

5.5 Discussion of Test 2a, 2b and 2c: Obstructed Diesel Fire Suppression

5.5.1 Fire Suppression Techniques for Test 2a and 2b: Obstructed Diesel Fire

Test 2 was designed to investigate fire suppression of an obstructed diesel fire using both the StatX FR and the DSPA 5-4 handheld extinguishers. The compartment layout for obstructed diesel fire suppression tests is shown in Figure 5-19. The obstruction measured 1.4 m x 1.3 m x 0.46 m (width x length x height) and was suspended 40 cm above the fire brick floor of the burn room as described in Section 3.6 and shown in Figure 3-4. It was designed and built to simulate an engine enclosure, such as an emergency generator, that might cause an obstruction over a diesel pool fire. The distance between the top of the fuel surface and the underside of the engine enclosure was 21 cm.

To be consistent with Test 1, the door was held open at 30 cm in Test 2a and 2b to maintain the same ventilation for all cases of aerosol suppression. Therefore, the only change between Tests 1 and 2 was the fire obstruction, which was the mock-engine enclosure. In the initial test results shown below, however, the StatX FR and the DSPA 5-4 units used in Test 2a and 2b had very little effect on the obstructed fire, and did not suppress it, suggesting that having the door held 30 cm open was too challenging. Therefore, Test 2c was added to the test program. In this case, the compartment door was closed after aerosol activation, allowing suppression efficacy to be measured relative to the effects of oxygen starvation alone.

Prior to testing, an obstructed diesel pan fire test was conducted to characterize the compartment environment without aerosol suppression. This test involved assessing the effects of ventilation control (closing the compartment door) on a fully developed obstructed diesel fire, confirming the pre-burn time, and heating the compartment to remove moisture from the ceramic fibre insulation in the compartment walls. Upon completion of the pre-burn, 10 ℓ of diesel fuel was added to the fuel pan and the freeboard height was adjusted to 1 cm by adding or removing water base. Thermocouple and gas analysis data acquisition was started and the video recordings commenced for internal colour and low wavelength cameras, internal IR camera and external colour video camera. Ambient conditions were recorded and the diesel was ignited by a propane torch on an extension handle.

The compartment door was fixed at 30 cm for the initial burn period of approximately 2 minutes in all tests. At this point, for Tests 2a and 2b, the aerosol unit under test was activated and placed precisely on the floor inside the door frame without changing the opening fraction of the door, thereby minimising test to test variability that might be caused by changes in ventilation and/or location of the aerosol units. The activation time and discharge duration of the units were recorded and visual observations were made throughout the suppression tests. For Test 2c, the aerosol units were activated and placed inside the door frame and the compartment door was immediately closed and the same parameters recorded. Temperature, gas concentration, and video data were analysed after all tests to determine the suppression efficacy of aerosol agent in each test.

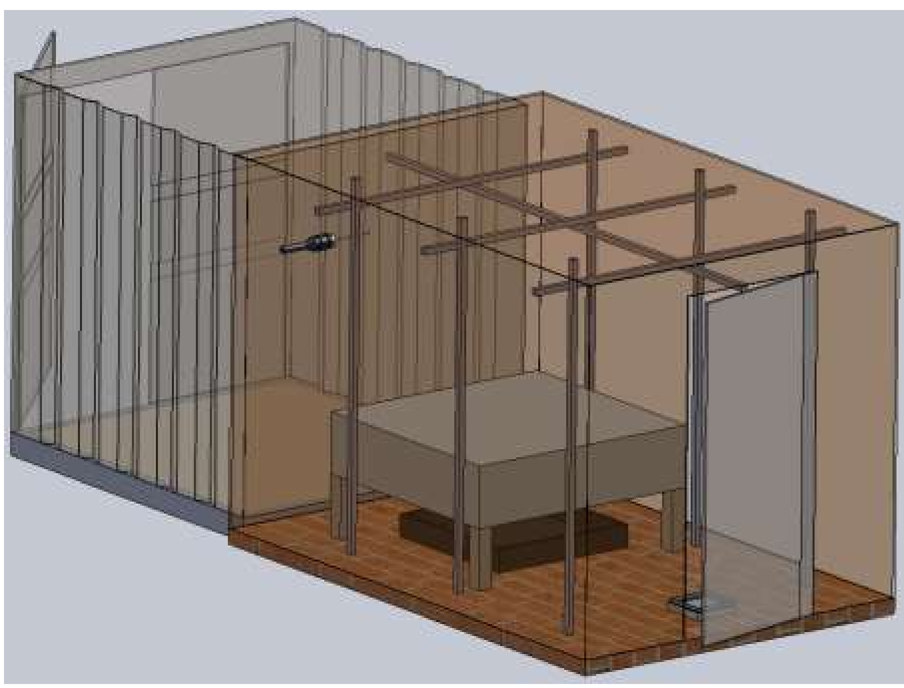


Figure 5-19. UW Shipping Container Burn Room Setup for Test 2a, 2b and 2c: Obstructed Diesel Fire Suppression

5.5.2 Suppression Results for Test 2a: StatX FR Obstructed Diesel Fire

In Test 2a, aerosol suppressant generated from the StatX FR unit had only a small effect on the fully developed obstructed diesel fire and consequently a minor effect on the respective compartment environment. There was so little effect seen that measuring the impact of the aerosol in terms of cooling of the compartment was not practical for this fire scenario. Therefore, these results are presented differently than those for Test 1a and 1b in order to highlight the minimal impact on the fire that did occur. Instead of plotting the average upper layer temperature profile at 2.0 m, the average temperature profiles on all eight horizontal planes within the compartment are plotted versus time in Figure 5-20. This plot shows that the impact of the aerosol generated from the StatX FR unit was greatest in regions below 0.5 m above the floor. To highlight this further, average temperatures measured on the plane 0.5 m above the floor are re-plotted in Figure 5-21. On average, the effect of the StatX FR aerosols on the fire and compartment resulted in a cooling of these lower regions by 46^{o}C over the 26 seconds from the onset of suppression to the lowest average temperature. In contrast, Figure 5-22 shows the overall average compartment temperature with time, and indicates an overall compartment cooling of just 9.3^{o}C in 18 seconds between the onset of suppression and the lowest average temperature. Oxygen and carbon dioxide concentrations throughout the test are plotted in Figure 5-23 and, as expected, show a decrease in oxygen concentration and increase in carbon dioxide concentration as the fire grows and up to the onset of suppression, followed by decreasing carbon dioxide and increasing oxygen concentrations during suppression of the fire. Figure 5-23 shows a 22 second period of time from the onset of suppression when oxygen concentration is increasing before dropping steeply once again as the fire grows again. On re-growth of the fire, the carbon dioxide concentration increases to levels which saturate the cell of the gas analyser, suggesting that there was more than 100,000 ppm carbon dioxide in the hot gases of the upper layer. All observations confirm the minimal impact that the aerosols had on the fire in this test scenario.

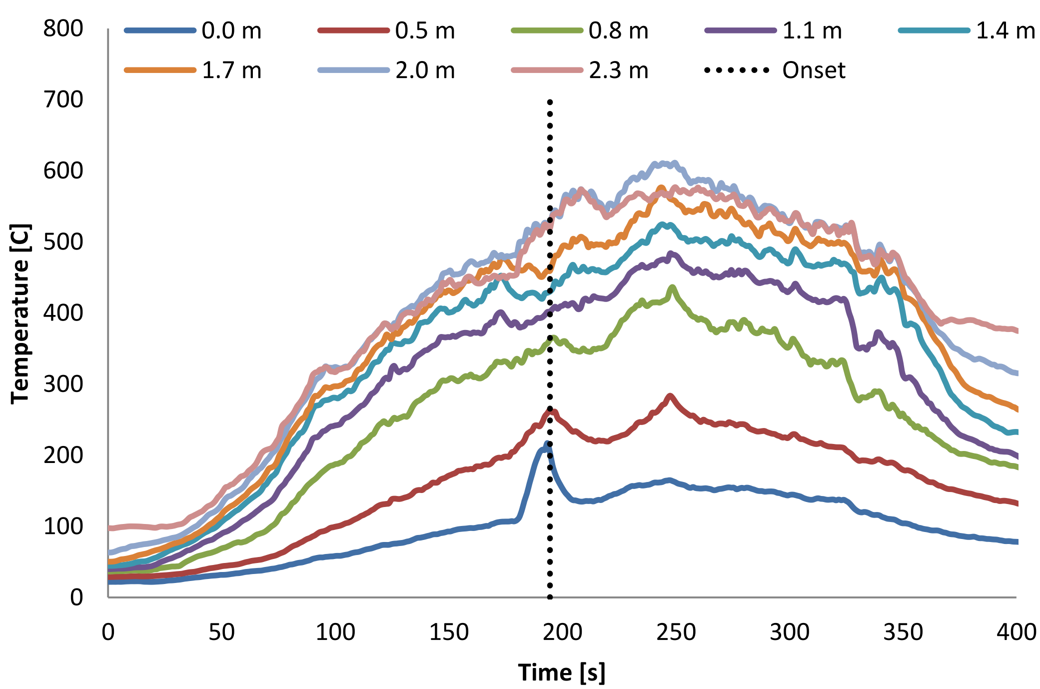


Figure 5-20. Test 2a, Obstructed Diesel Fire: StatX FR Suppression Effect on Horizontal Planes

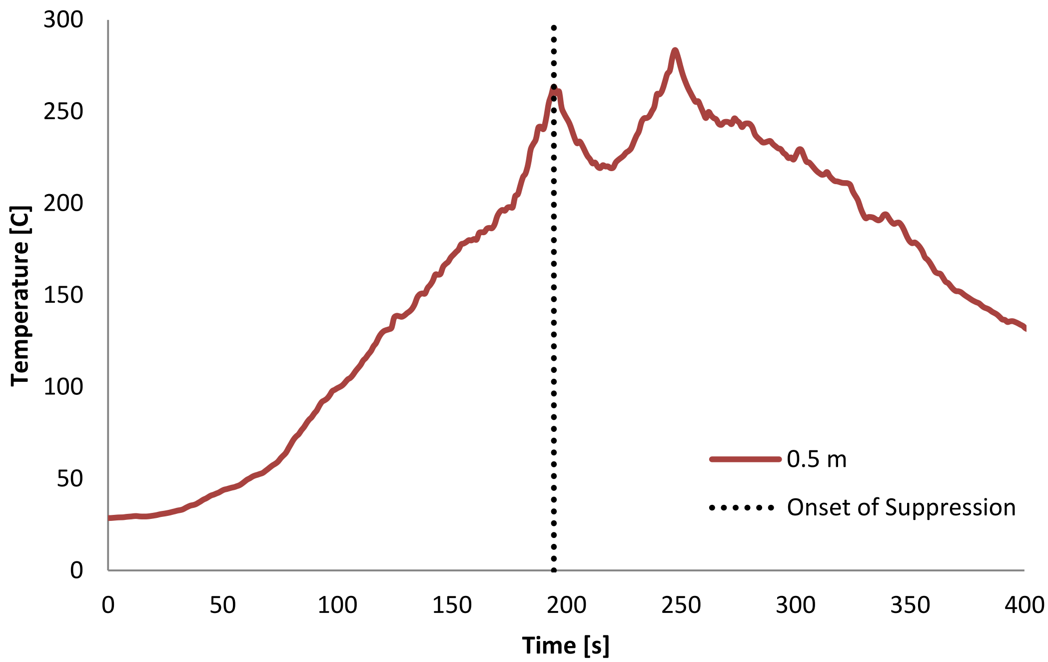


Figure 5-21. Test 2a, Obstructed Diesel Fire: StatX FR Suppression Effect on the 0.5 m Horizontal Plane

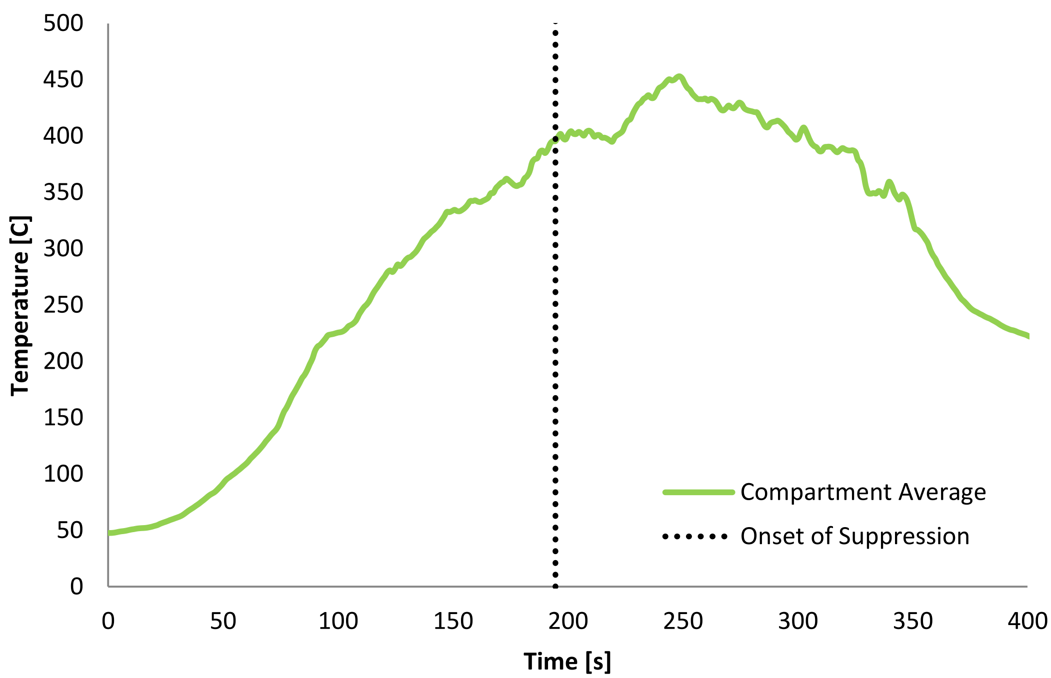


Figure 5-22. Test 2a, Obstructed Diesel Fire: StatX FR Suppression Effect on the Compartment Average

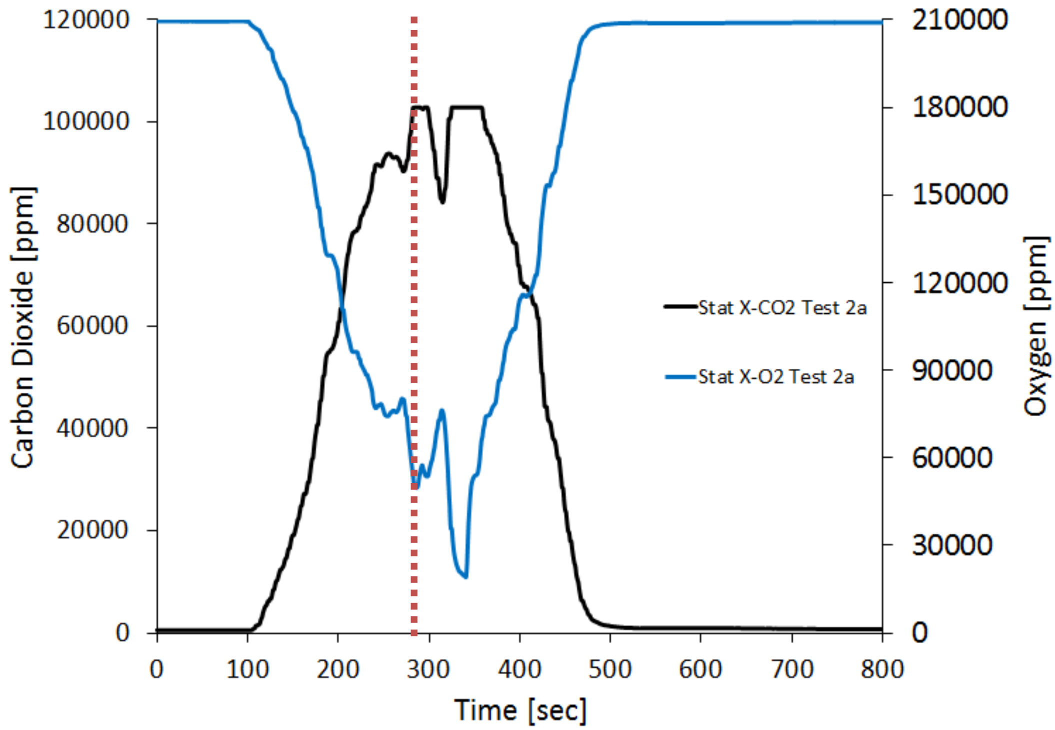


Figure 5-23. Test 2a, Obstructed Diesel Fire: Stat X's Carbon Dioxide and Oxygen concentrations

5.5.3 Suppression Results for Test 2a: DSPA 5-4 Obstructed Diesel Fire

Aerosols generated from the DSPA 5-4 unit also had only a minor impact on the fully developed obstructed diesel fire and the respective compartment environment. The effect was so minor that measuring cooling rate and cooling effect was not practical. Therefore, the results are presented in a similar fashion to those for the StatX FR results above in order to highlight the small impact that did occur. The average temperature profiles on all eight horizontal planes within the compartment are plotted versus time in Figure 5-24. From this plot, it can again be seen that the aerosols generated by the DSPA 5-4 unit had their greatest impact in regions below 0.5 m above the floor. To highlight this, average temperatures measured on the plane 0.5 m above the floor are re-plotted in Figure 5-25. On average, the effect of the DSPA 5-4 aerosols on the fire and compartment resulted in a cooling of the lower regions by 26^{o}C over the 27 seconds from the onset of suppression to the lowest average temperature. In contrast, Figure 5-26 shows the overall average compartment temperature plotted against time and indicates an overall compartment cooling of 47^{o}C in the 27 seconds between the onset of suppression and the lowest average temperature. Oxygen and carbon dioxide concentrations throughout the test are plotted in Figure 5-27, again showing the decrease in oxygen concentration and increase in carbon dioxide concentration expected as the fire grows up to the onset of suppression. After the aerosol enters the compartment, there is a 23 second period of time over which the oxygen concentration increases and carbon dioxide decreases, suggesting that the fire was partially suppressed. Following this the oxygen concentration drops steeply once again as the fire re-establishes itself and grows. This clearly indicates that while the aerosol did have a small impact on the fire, it was clearly not enough to have a large effect on temperatures in the compartment or to fully extinguish the fire in this scenario.

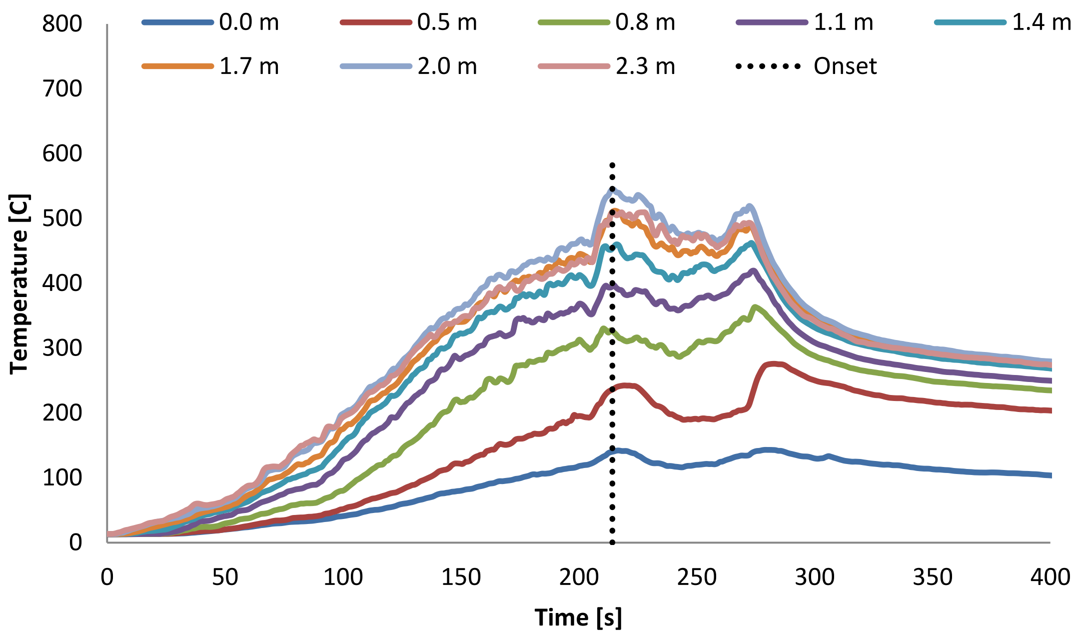


Figure 5-24. Test 2a, Obstructed Diesel Fire: DSPA 5-4 Suppression Effect on Horizontal Planes

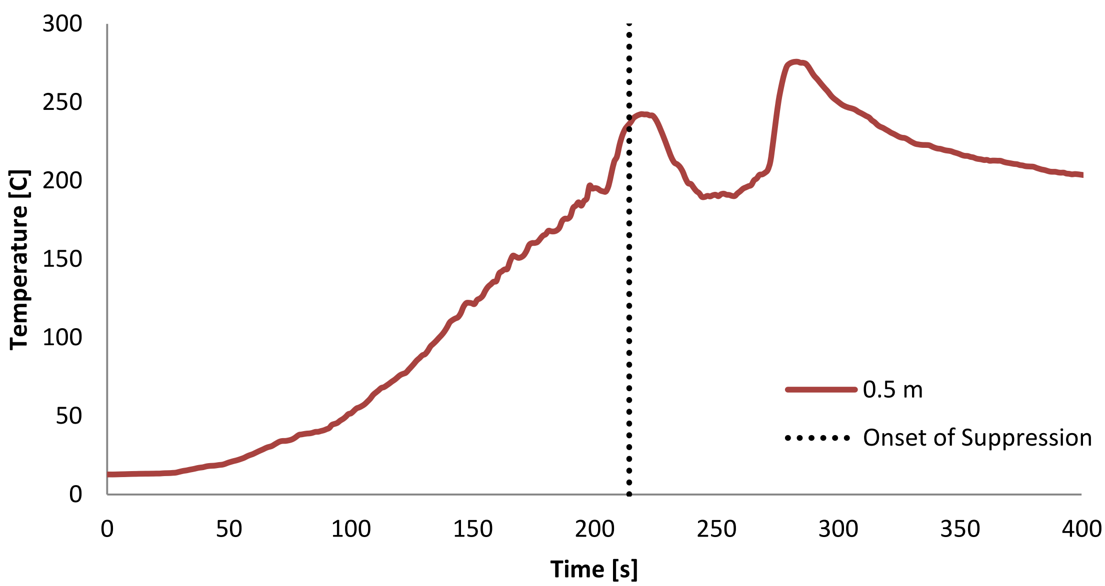


Figure 5-25. Test 2a, Obstructed Diesel Fire: DSPA 5-4 Suppression Effect on the 0.5 m Horizontal Plane

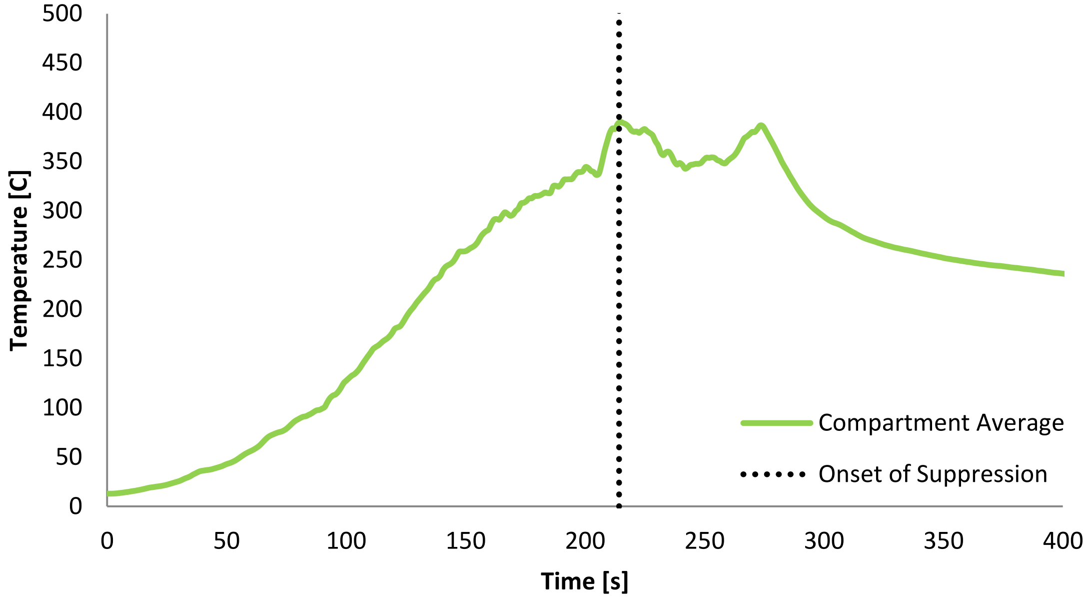


Figure 5-26. Test 2a, Obstructed Diesel Fire: DSPA 5-4 Suppression Effect on the Compartment Average Temperature

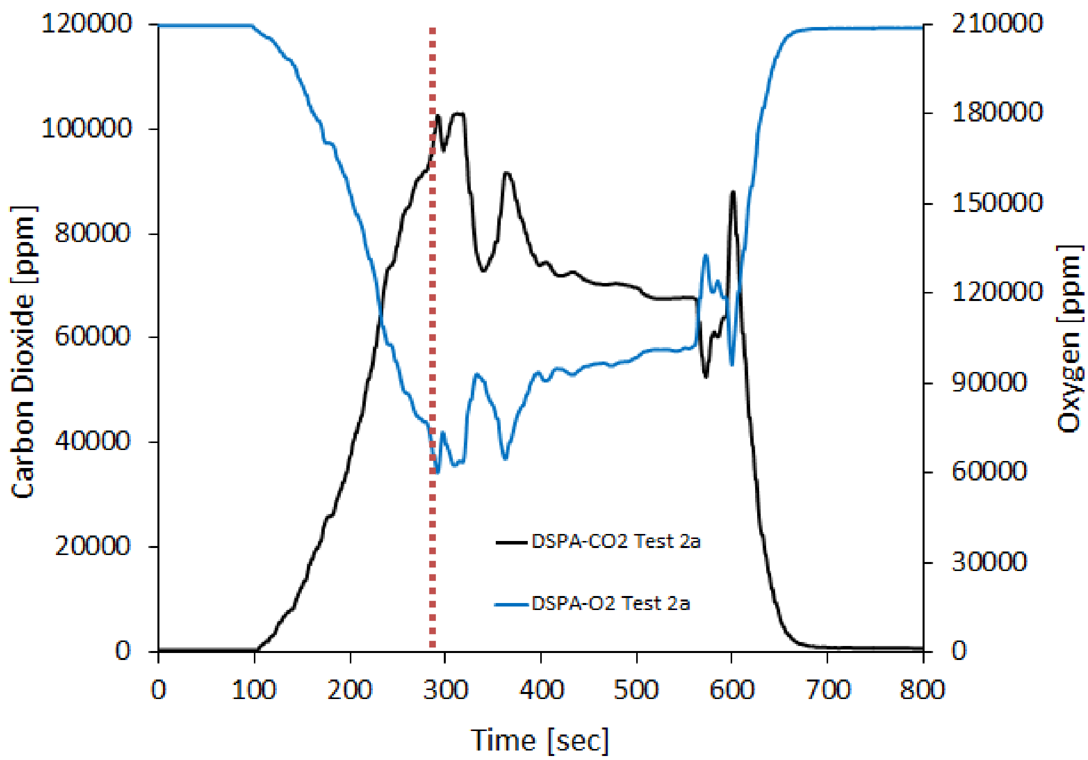


Figure 5-27. Test 2a, Obstructed Diesel Fire: DSPA's Carbon Dioxide and Oxygen concentrations

5.5.4 Suppression Results for Test 2b: StatX FR Obstructed Diesel Fire

The aerosols generated by the StatX FR unit used for fire suppression in Test 2b again had only a minor effect on the fully developed obstructed diesel fire and therefore on the environment in the fire compartment. Once again, measuring a cooling rate and cooling effect were not practical so these results are presented in the same fashion as for the previous sections. Average temperature profiles on all eight horizontal planes within the compartment are plotted versus time in Figure 5-28. It can be seen that the greatest effects of the aerosols from the StatX FR unit were felt in regions below 0.5 m above the floor. Average temperatures from the 0.5 m horizontal plane are plotted against time in Figure 5-29. On average, the effect of the StatX FR aerosols on the fire and compartment resulted in a cooling of the lower regions by 41^{o}C over the 23 seconds from the onset of suppression to the lowest average temperature. In contrast, Figure 5-30 shows the average compartment temperature profile plotted against time and indicates an overall cooling rate of 13^{o}C in 7 seconds between the onset of suppression and the lowest average temperature. Oxygen and carbon dioxide concentrations throughout the suppression test are plotted in Figure 5-31 and show the expected decrease in oxygen concentration and increase in carbon dioxide concentration as the fire grows up to the onset of suppression. As the aerosol enters the compartment, Figure 5-31 shows a 28 second period of time when the oxygen concentration increases and carbon dioxide decreases, suggesting that the fire is being suppressed. Following this, the oxygen concentration drops steeply once again as the fire re-establishes itself and grows. The carbon dioxide concentration also grows again, increasing to a level that saturates the cell of the gas analyser. This suggests that the fire had fully re-established itself since there was more than 100,000 ppm carbon dioxide in the hot gases of the upper layer. This clearly indicates that while the aerosol did have a small impact on the fire, it was not enough to fully extinguish the fire in this scenario. [It should be noted from this plot that the impact of fire suppression on carbon dioxide concentration is well illustrated by the steep drop in concentration that is seen at about 400 seconds. This is due to the compartment door being closed, halting any further combustion from occurring.]

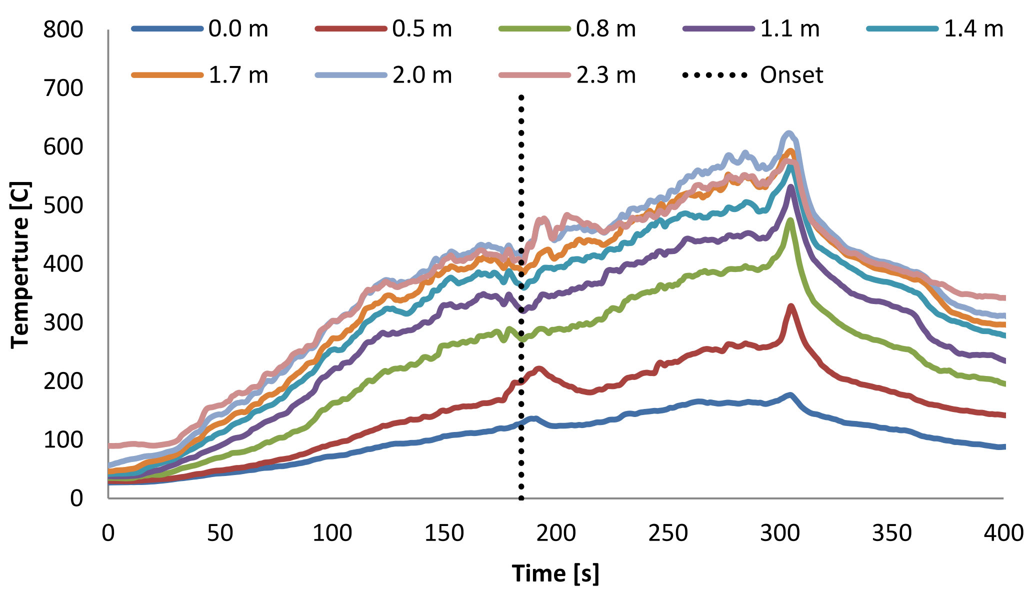


Figure 5-28. Test 2b, Obstructed Diesel Fire: StatX FR Suppression Effect on Horizontal Planes

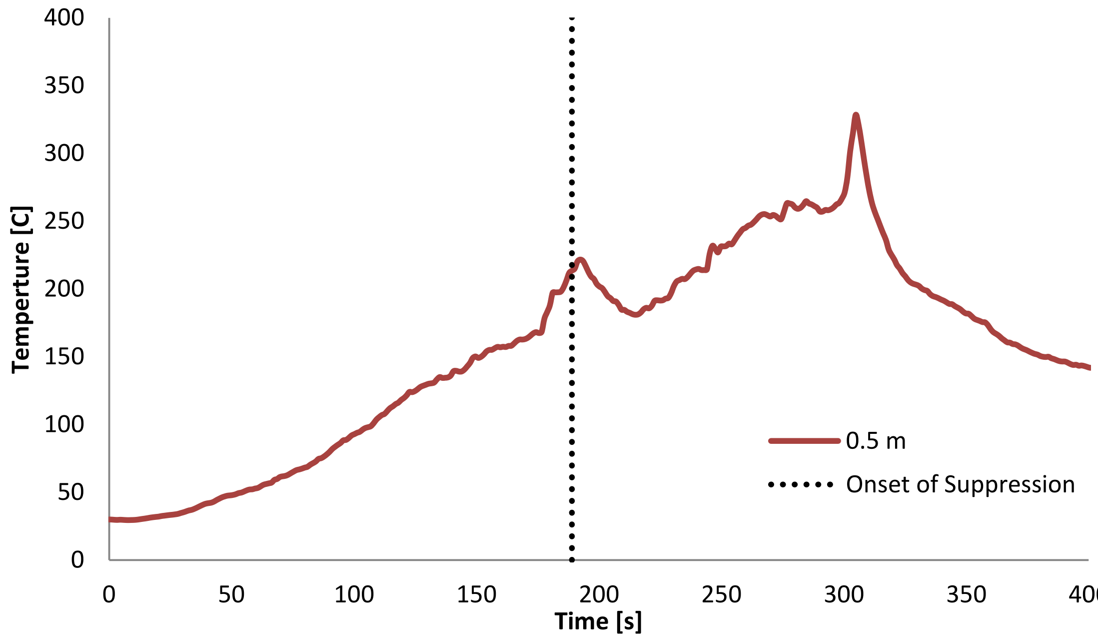


Figure 5-29. Test 2b, Obstructed Diesel Fire: StatX FR Suppression Effect on the 0.5 m Horizontal Plane

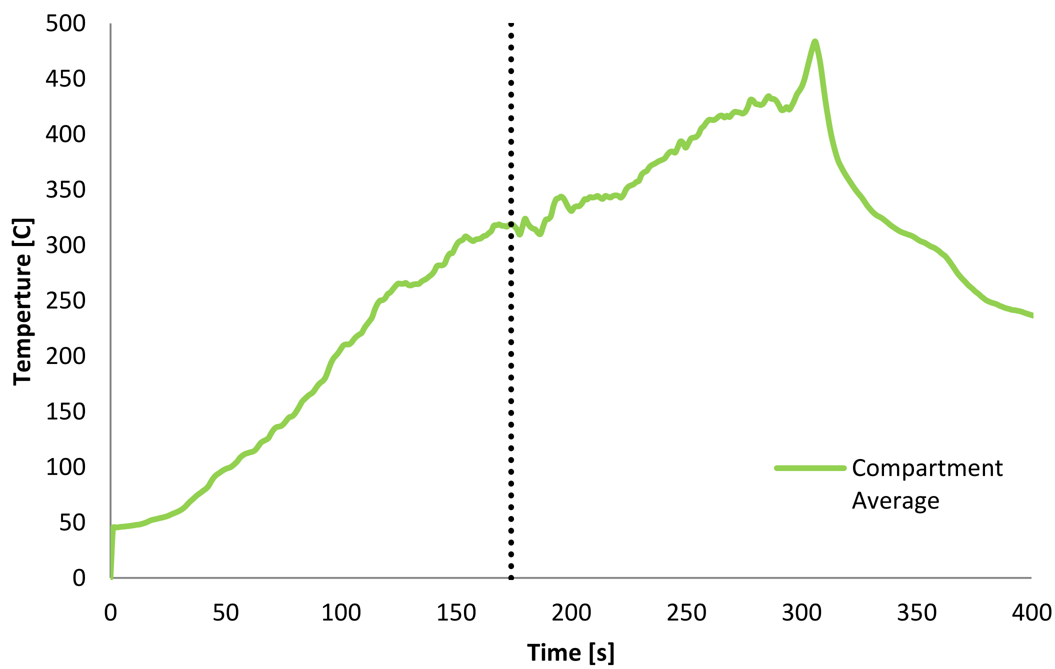


Figure 5-30. Test 2b, Obstructed Diesel Fire: StatX FR Suppression Effect on the Compartment Average Temperature

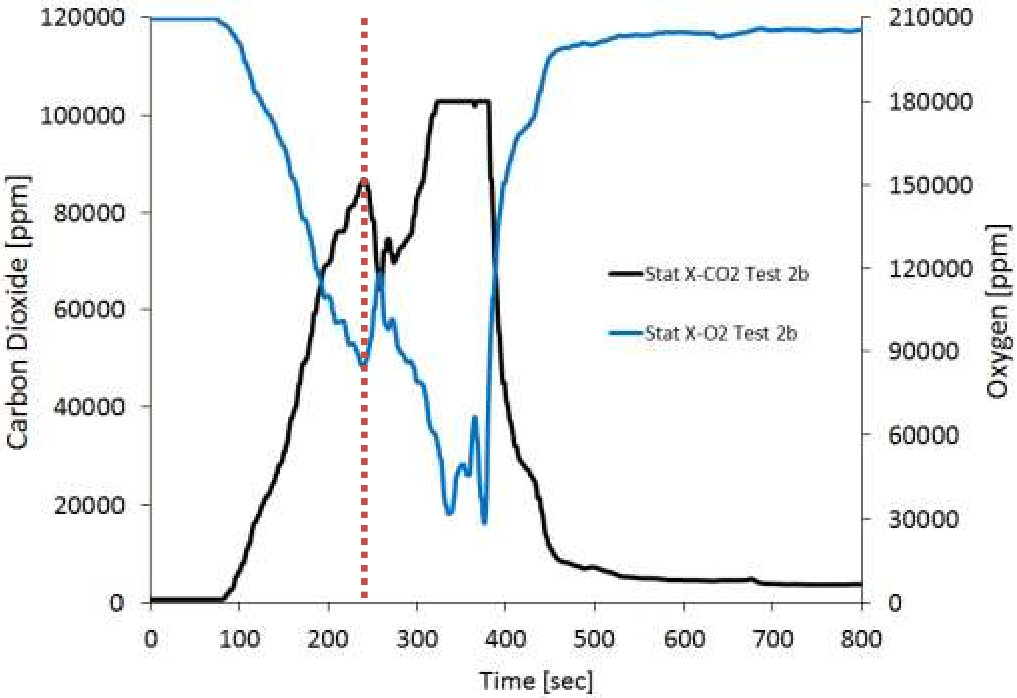


Figure 5-31. Test 2b, Obstructed Diesel Fire: Stat X's Carbon Dioxide and Oxygen concentrations

5.5.5 Suppression Results for Test 2b: DSPA 5-4 Obstructed Diesel Fire

The aerosols generated by the DSPA 5-4 unit used for fire suppression in Test 2b again had only a minor effect on the fully developed obstructed diesel fire and therefore on the environment in the fire compartment. Once again, measuring a cooling rate and overall cooling effect were not practical so these results are presented in the same fashion as for the previous sections. Average temperature profiles on all eight horizontal planes within the compartment are plotted versus time in Figure 5-32. From this plot, it can be seen that the greatest effects of the aerosols from the DSPA 5-4 unit were felt in regions below 0.5m above the floor. Average temperatures from the 0.5 m horizontal plane are plotted against time in Figure 5-33. On average, the effect of the DSPA 5-4 aerosols on the fire and its surroundings resulted in a cooling of the lower regions of the compartment by 91^{o}C over the 30 seconds from the onset of suppression to the lowest average temperature.

In contrast, Figure 5-34 shows the average compartment temperature profile plotted against time and indicates an overall cooling rate of 11.4^{o}C in the 6 seconds between the onset of suppression and the lowest average temperature. Oxygen and carbon dioxide concentrations throughout the suppression test are plotted in Figure 5-35, showing the decrease in oxygen concentration and increase in carbon dioxide concentration expected as the fire grows up to the onset of suppression. As the aerosol enters the compartment, Figure 5-35 shows a 27 second period of time when oxygen concentration increases and carbon dioxide concentration decreases suggesting some suppression of the fire. Following this, the oxygen concentration drops steeply once again as the fire re-establishes itself and grows. The carbon dioxide concentration also grows again, increasing to a level that saturates the cell of the gas analyser. This suggests that the fire had re-established itself since there was more than 100,000 ppm carbon dioxide in the hot gases of the upper layer. This clearly indicates that while the aerosol did have a small impact on the fire, it was not enough to fully extinguish the fire in this scenario. The steep decrease in carbon dioxide at about 320 seconds was again indicative of suppression of the fire as the compartment door was closed at the end of the test.

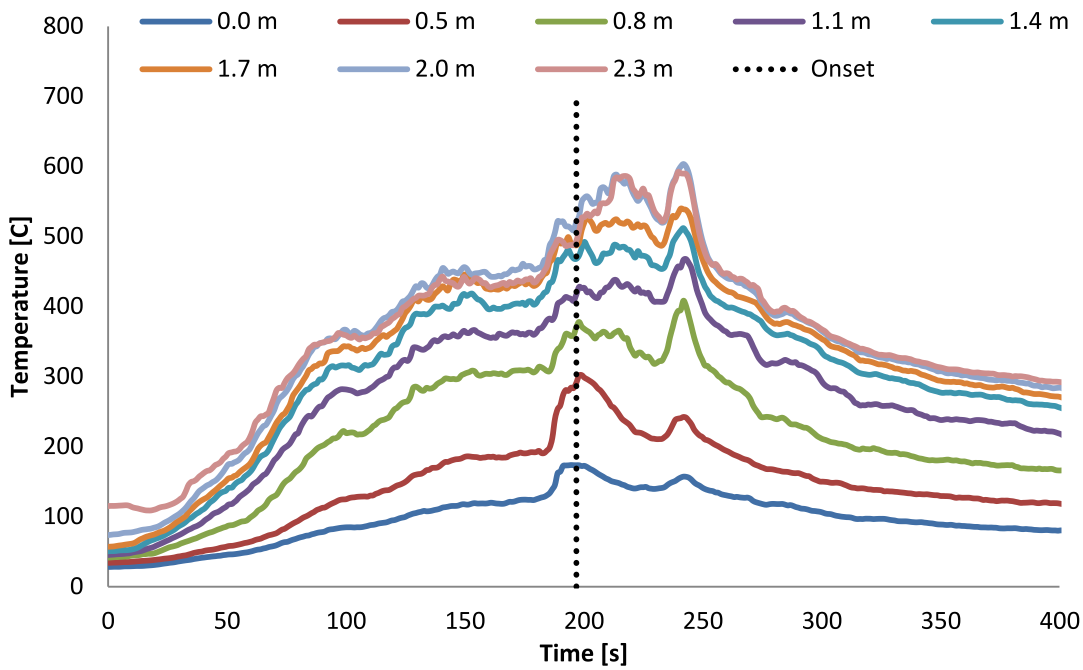


Figure 5-32. Test 2b, Obstructed Diesel Fire: DSPA 5-4 Suppression Effect on Horizontal Planes

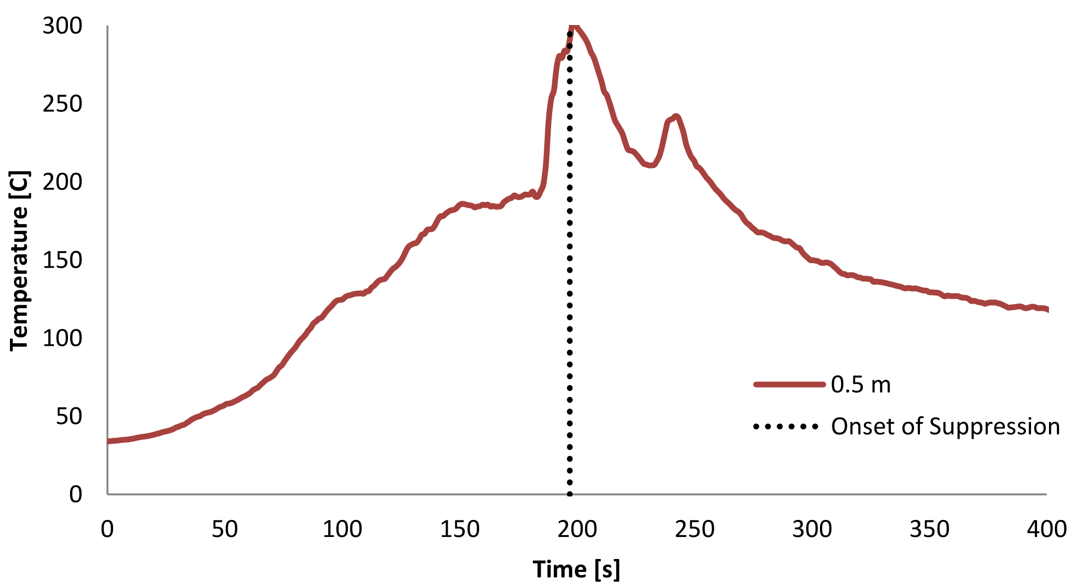


Figure 5-33. Test 2b, Obstructed Diesel Fire: DSPA 5-4 Suppression Effect on the 0.5 m Horizontal Plane

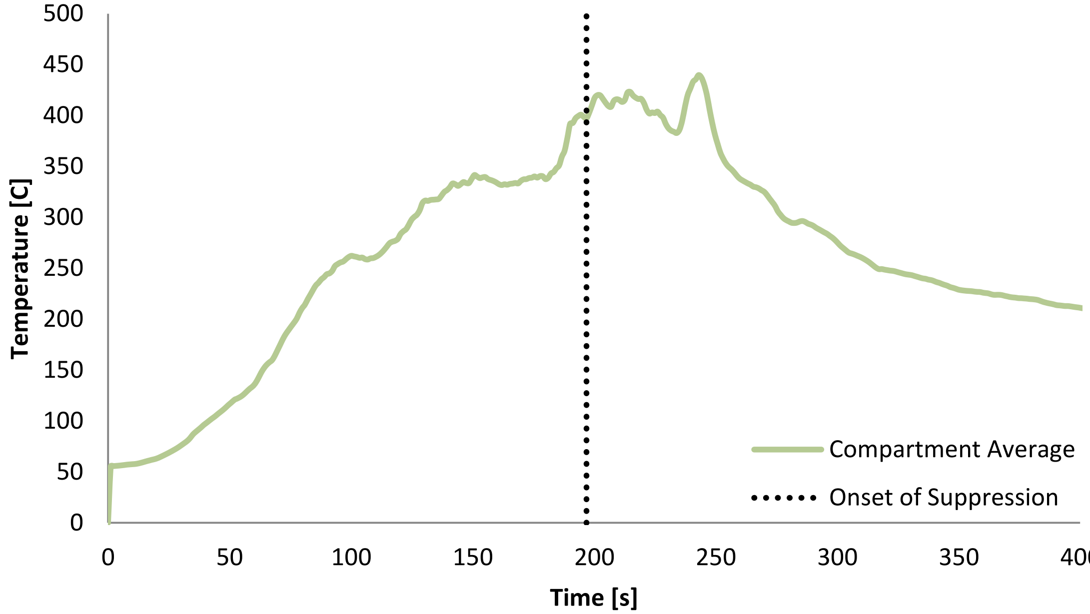


Figure 5-34.Test 2b, Obstructed Diesel Fire: DSPA 5-4 Suppression Effect on the Compartment Average Temperature

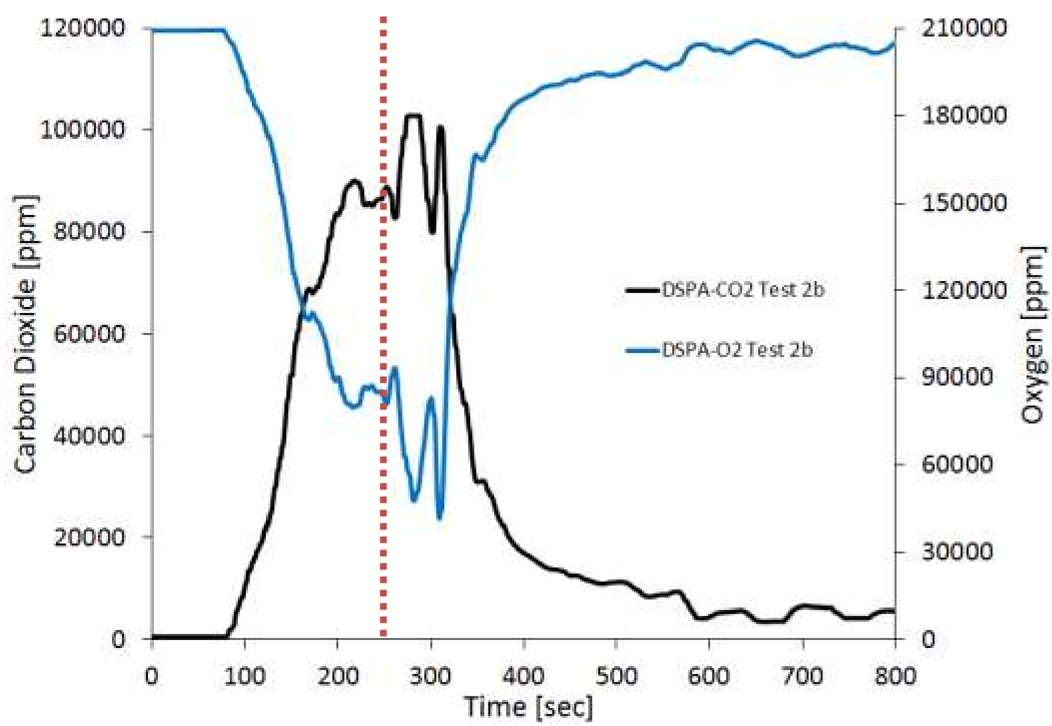


Figure 5-35. Test 2b, Obstructed Diesel Fire: DSPA 5-4 Carbon Dioxide and Oxygen concentrations

5.5.6 Suppression Results for Test 2c, Door Closed: StatX FR Obstructed Diesel Fire

Because of the limited impact that the aerosols generated by the StatX FR unit had on the fire, and therefore the compartment environment, during the obstructed diesel fire tests when the compartment door was held open at 30 cm (Tests 2a and 2b), it was decided to conduct an additional test, Test 2c, in which the compartment door was closed after aerosol unit activation. The intent was to provide a comparative measure of the impact of aerosols on open pool fires versus obstructed pool fires, as well as provide a comparison between the impact of using an aerosol agent versus that of oxygen starvation of the fire alone.

Aerosols generated by the StatX FR unit in Test 2c successfully suppressed and then extinguished the obstructed diesel fire so results in this section are presented in the same fashion as those from Test 1. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-36. From the Figure, the cooling rate was determined to be 136°C/min or 2.3°C/second from the onset of suppression to 60 seconds. The effect of fire suppression by the aerosols on thermal stratification in the compartment are represented in 10 s intervals in Figure 5-37, and the average temperature difference with height above the floor of the compartment is shown in Figure 5-38. Integrating the curve in Figure 5-38 using the same methods as previously described indicates a global cooling effect of 235 m·K throughout the compartment.

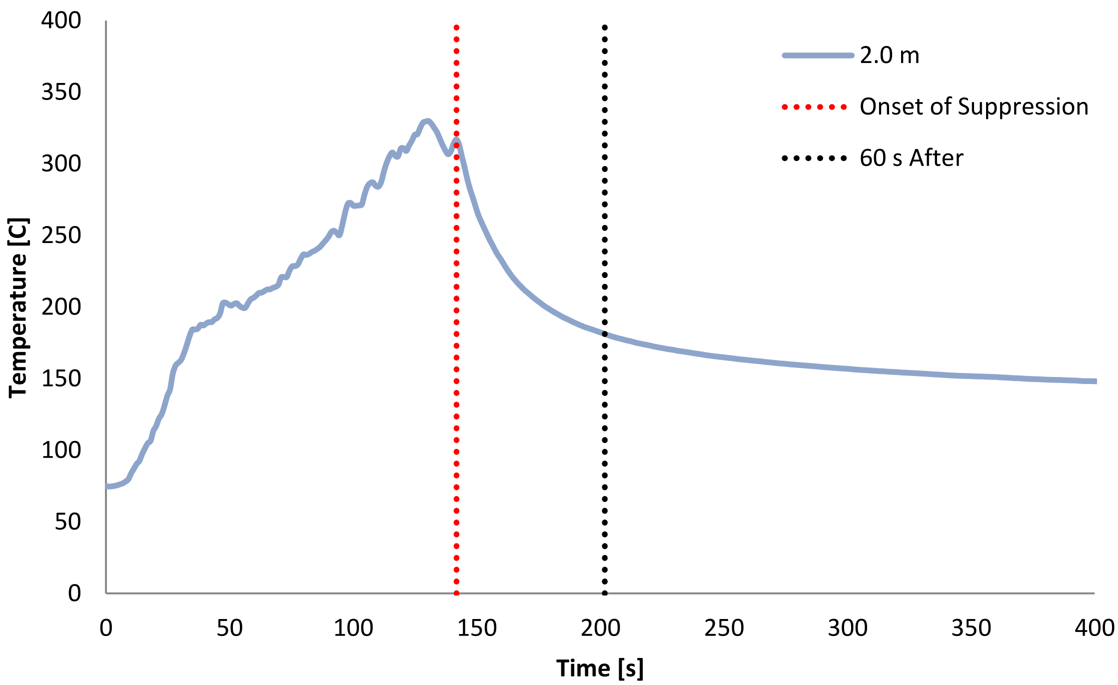


Figure 5-36. Test 2c: StatX FR Obstructed Diesel Fire Upper Layer Temperature Cooling Rate after Aerosol Released and the compartment door was closed

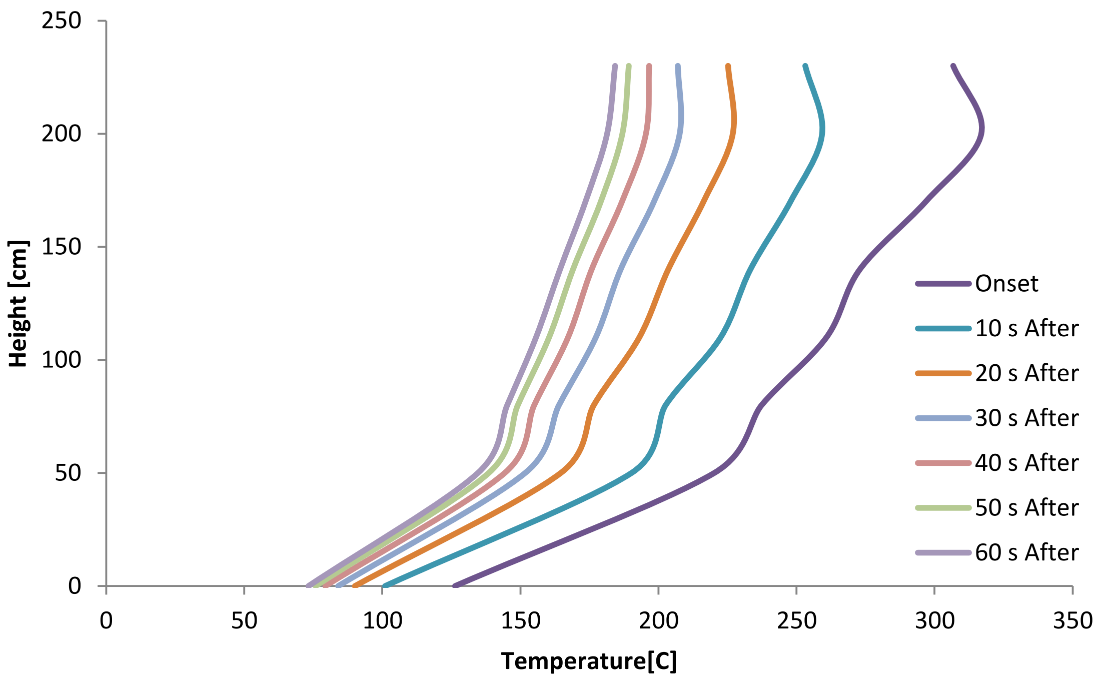


Figure 5-37. Test 2c: StatX FR Suppression Effect on Average Thermal Stratification after Aerosol Released and the compartment door was closed

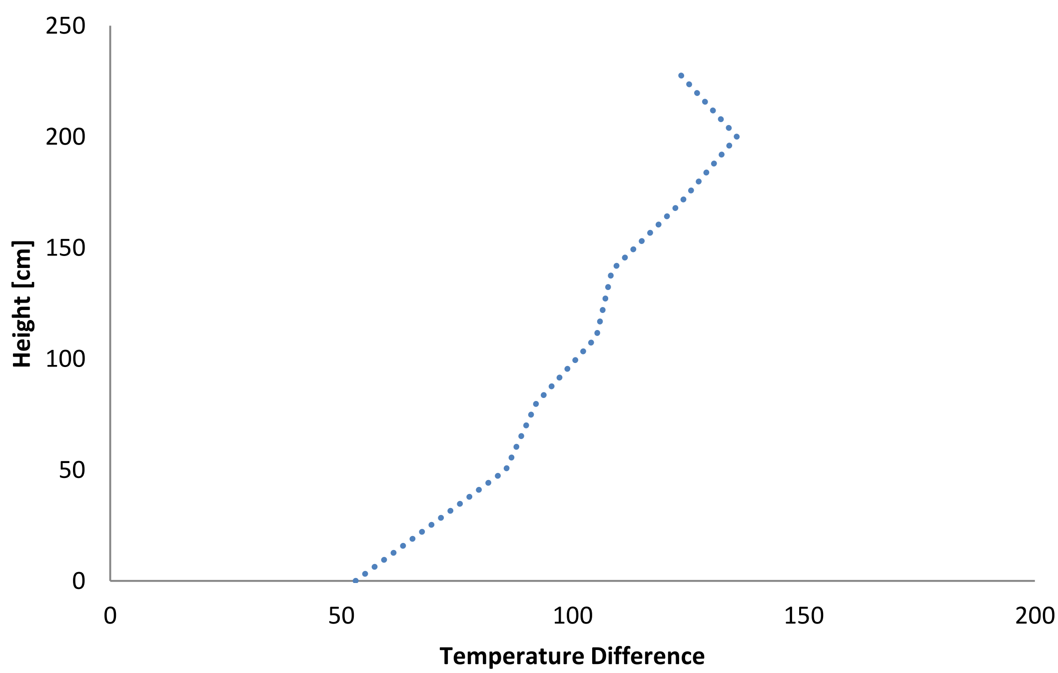


Figure 5-38. Test 2c: StatX FR Average Temperature Difference Due to Aerosol Agent from the onset of suppression to 60 seconds after

5.5.7 Suppression Results for Test 2c, Door Closed: DSPA 5-4 Obstructed Diesel Fire

Because of the limited impact that the aerosols generated by the DSPA 5-4 unit had on the fire, and therefore the compartment environment, during the obstructed diesel fire tests when the compartment door was held open at 30 cm (Tests 2a and 2b), it was decided to conduct an additional test, Test 2c, in which the compartment door was closed after aerosol unit activation. The intent was to provide a comparative measure of the impact of aerosols on open pool fires versus obstructed pool fires, as well as provide a comparison between the impact of using an aerosol agent versus that of oxygen starvation of the fire alone.

Aerosols generated by the DSPA 5-4 unit in Test 2c successfully suppressed and then extinguished the obstructed diesel fire results in this section are presented in the same fashion as those from Test 1. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-39. From the Figure, the cooling rate was determined to be 250°C/min or 4.2°C/second from the onset of suppression to 60 seconds. The effects of fire suppression by the aerosols on thermal stratification in the compartment are represented in 10 s intervals in Figure 5-40, and the average temperature difference with height above the floor of the compartment is shown in Figure 5-41. Integrating the curve in Figure 5-41 indicates a global cooling effect in the compartment of 337 m·K.

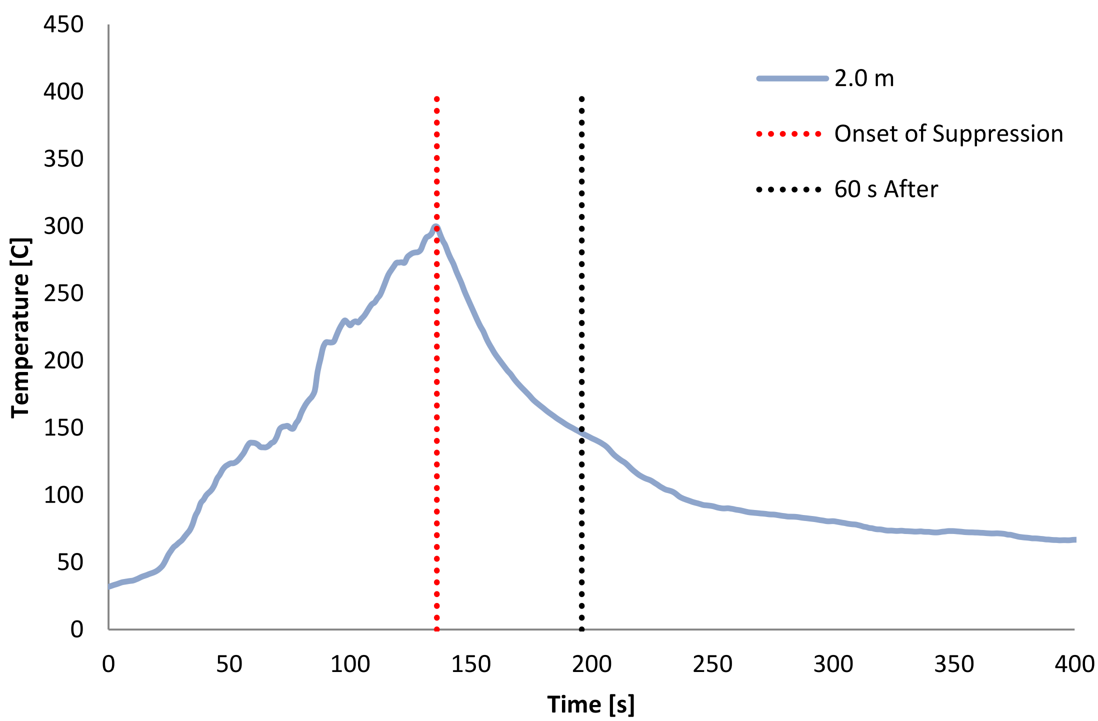


Figure 5-39. Test 2c: DSPA Obstructed Diesel Fire Upper Layer Temperature Cooling Rate after Aerosol Released and the compartment door was closed

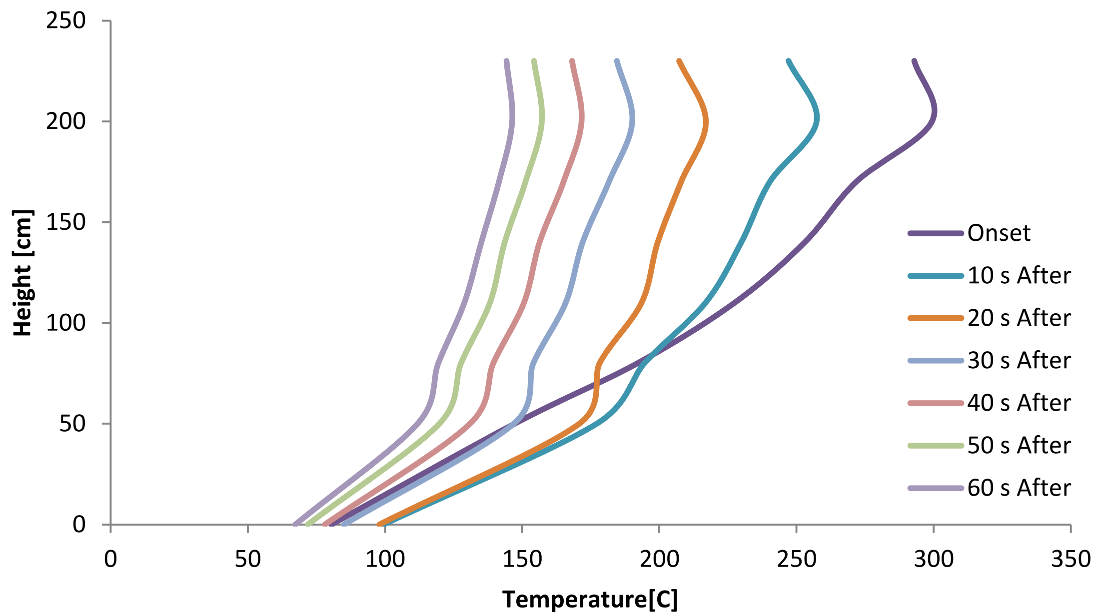


Figure 5-40. Test 2c: DSPA 5-4 Suppression Effect on Average Thermal Stratification after Aerosol Released and the compartment door was closed

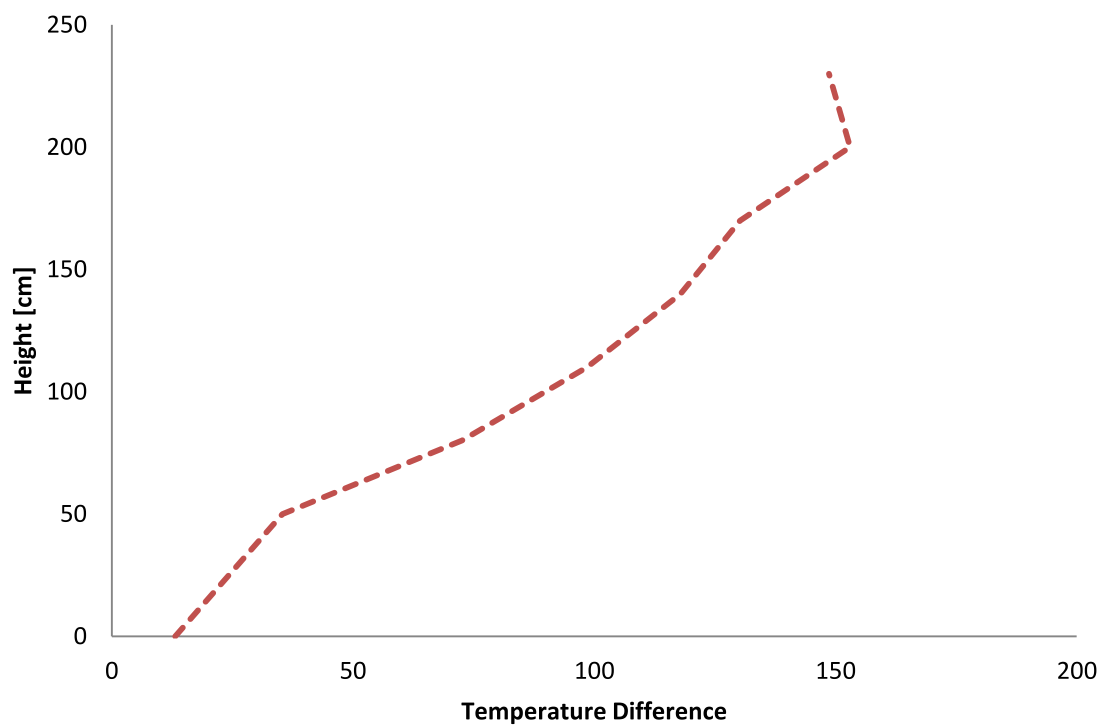


Figure 5-41. Test 2c: DSPA 5-4 Average Temperature Difference Due to Aerosol Agent from the onset of suppression to 60 seconds after

5.5.8 Summary and Discussion of Test 2a, 2b and 2c: Obstructed Diesel Fire Results

The suppression of obstructed diesel fires with the door held open at 30 cm proved to be a very challenging fire scenario for both designs of aerosol extinguisher tested here. Although the units were placed precisely inside the door and care was taken to ensure that the aerosol agent was carried to the seat of the fire on the cool air being drawn into the compartment by the fire, not enough agent got to the flames under the mock engine enclosure to have a large impact on the chemistry of reaction. Additionally, the heat flux radiating downward from the hot steel obstruction to the unburned diesel fuel, which was only 21 cm below the obstruction, helped to sustain the diesel fire during the period of aerosol suppression since the aerosol particles do not absorb large amounts of heat from the environment. In each of the four tests conducted on an obstructed diesel fire with the door held open at 30 cm, the aerosol agent made only very minor impacts on the fire and surrounding environment. The largest cooling effect was observed for positions low in the compartment, in regions below 0.5 m above the compartment floor. The results of Test 2a and 2b are combined in Table 5-4 to show the cooling rates measured via thermocouples positioned at 0.5 m above the floor of the compartment as well as the cooling rate determined based on the average compartment temperatures for each test. For comparison, the total degrees of cooling measured in Tests 2a and 2b for the StatX FR and for the DSPA 5-4, respectively, were summed together and divided by the total number of seconds in each of their cooling periods, i.e. time from onset of suppression to when compartment temperatures began to rise again. The combined results are:

- ***StatX FR Overall Cooling Rate on Obstructed Diesel Fires, Door Open**:* For StatX FR Tests 2a and 2b, the total degrees of cooling based on measurements at 0.5 m above the floor and on the average compartment temperature was 109.3^{o}C in a total of 74 seconds, which gives a cooling rate of 1.48^{o}/s.
- ***DSPA 5-4 Overall Cooling Rate on Obstructed Diesel Fires, Door Open**:* For DSPA Tests 2a and 2b, the total degrees of cooling o based on measurements at 0.5 m above the floor and on the average compartment temperature was 175.4^{o}C in a total of 90 seconds, which gives a cooling rate of 1.95^{o}/s.

Based on the comparison above and results in Table 5-4, the DSPA 5-4 appeared to have a slightly greater effect than the StatX FR against the challenging obstructed diesel fire scenario with the door open. However, neither unit came close controlling or extinguishing the fire. These results suggest that neither aerosol extinguisher should be expected to have an appreciable impact on an obstructed Class B fire if the compartment cannot be confined and/or if the compartment is larger than the rated volume of approximately 20 m^3.

Table 5-4. Summary of Test 2a and 2b, Door Open: Obstructed Diesel Fire Results

Test	Ambient Temp [^{o}C]	Ambient RH [%]	Ambient Wind Speed [m/s]*	Ambient Wind Direction	Cooling Rate of 0.5 m Plane	Cooling Rate of Average Compartment Temp
2a: StatX FR	18	33	0.5	W	46 in 26 s	9.3 in 18 s
2a: DSPA 5-4	18	33	0.5	W	26 in 27 s	47 in 27 s
2b: StatX FR	18	33	0.5	W	41 in 23 s	13 in 7 s
2b: DSPA 5-4	18	33	0.5	W	91 in 30 s	11.4 in 6 s

*Note 1: Ambient wind speed taken at door of compartment between wind blocks to assess air flow at the door during suppression testing.

Because of the minor suppression effects that the StatX FR and DSPA 5-4 units had on the obstructed diesel fire with the door open at 30 cm, Test 2c was conducted with the door closed. This test sought to compare the suppression efficacy and cooling effect of oxygen starvation plus aerosol agent against those seen for oxygen starvation alone. Table 5-5 contains a summary of the results of Test 2c, together with results based on oxygen starvation (just closing the door with no suppression agent) for the same fire scenario. Figure 5-42 displays plots of the average temperature differences measured at various heights above the compartment floor for aerosol suppression and as a result of just closing the door. From these results, it is noted that the StatX FR and the DSPA 5-4 performed in a similar fashion with cooling rates of 2.3 and 2.5^{o}C/s and total cooling effects of 235 and 211 m-K respectively. The addition of aerosol from either unit resulted in a higher rate of cooling and higher total cooling than seen when the door was closed and no aerosol was added. The key findings are:

- *StatX FR increased the cooling rate by 21% and the total cooling effect by 43% over those for oxygen starvation alone.*
- *DSPA 5-4 increased the cooling rate by 32% and the total cooling effect by 29% over those for oxygen starvation alone.*

The increases in cooling rate and total cooling observed for Test 2c when aerosols are combined with oxygen starvation of the fire speak to the benefits of employing aerosol agents during suppression of a fire, even when that fire can be confined and starved of oxygen. A 30-40% higher rate of cooling of the compartment in the same 60 seconds can significantly reduce the production of flammable vapour from unburned fuel, which in turn reduces the risk of migration of fuel vapour to other areas should hot gases later escape the compartment and of the occurrence of more dangerous rapid fire growth phenomena should oxygen be re-introduced to the compartment. It also reduces heat transfer to other fuels within the compartment and to boundaries adjoining adjacent compartments, lowering the probability and speed with which the original fire could spread past the room of origin.

Table 5-5. Summary of Test 2c, Door Closed: Obstructed Diesel Fire Results

Test	**Ambient Temp [°C]**	**Ambient RH [%]**	**Ambient Wind Speed [m/s]***	**Ambient Wind Direction**	**Peak Average Temp [°C]**	**Cooling Rate (°C/Sec)****	**Total Cooling Effect [m·K]**
2c: StatX FR	20	33	0.7	W	255	2.3	235
2c: DSPA 5-4	17	50	1.1	SW	221	2.5	211
Closed Door	18	33	0.5	W	220	1.9	164

*Note 1: Ambient wind speed taken at door of compartment between wind blocks to assess air flow at the door during suppression testing.
**Note 2: Cooling rates assessed from 60 seconds after peak average temperature.

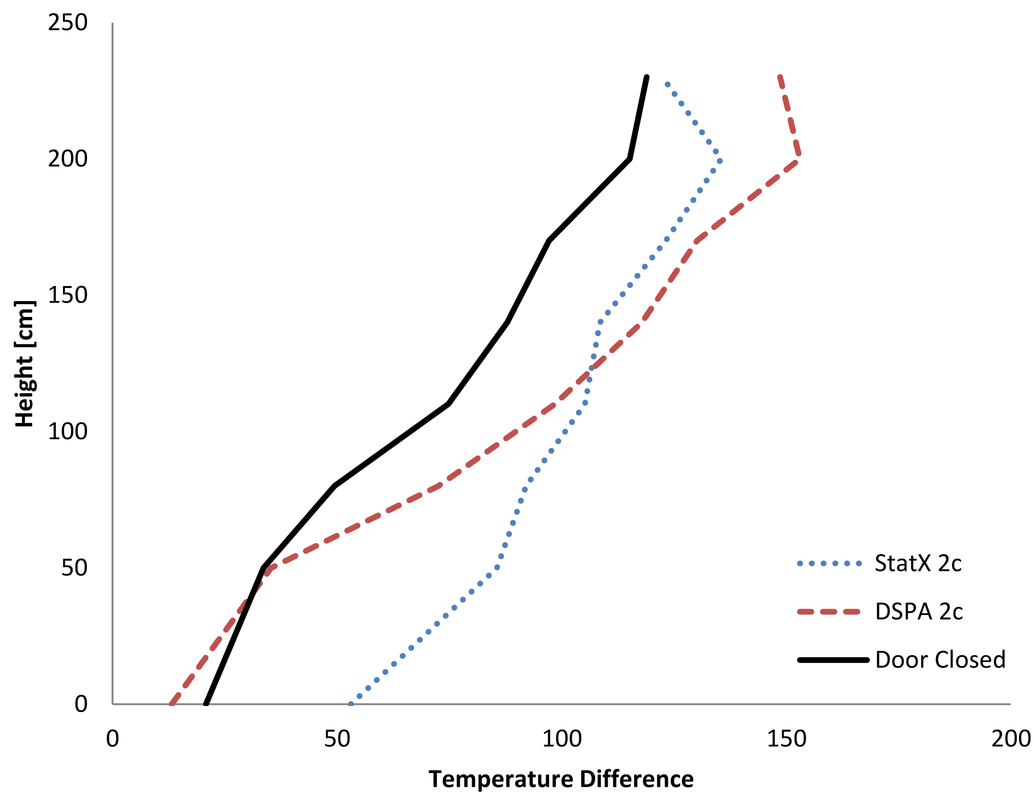


Figure 5-42. Summary of Average Compartment Temperature Difference Caused by Suppression

5.6 Discussion of Test 3a and 3b: Obstructed Bilge Fire Suppression

5.6.1 Fire Suppression Techniques for Test 3a and 3b: Obstructed Bilge Fire

Test 3 was designed to investigate suppression of an obstructed bilge fire using both the StatX and the DSPA handheld extinguishers. The compartment layout for this test is shown in Figure 5-43. The setup is essentially the same as that used in Test 2 except that after the aerosol units were activated, they were positioned such that they were fully submerged in water beneath the diesel fire prior to generation of the suppression agent. After placement of the aerosol unit, the compartment door was closed for Test 3a due to concerns that after unit activation, the rapidly expanding aerosol agent and gases would splash and spray burning diesel out of the relatively shallow pan. Based on IR camera footage inside the compartment, minimal splashing of burning diesel was observed. Therefore, Test 3b was run with the door fully open to allow better observation of the test. For all tests, the cooling rate of the upper gas layer, total cooling effect on the compartment, and average effect on thermal stratification were again investigated. Concentrations of oxygen and carbon dioxide, which vary in proportion to the fire growth and decay, serve as additional indicators of the effects of aerosol agent on the compartment environment.

Prior to aerosol testing, an obstructed diesel pan and bilge fire characterization test was conducted to characterize the compartment environment without aerosol suppression, determine the effects of ventilation control (closing the compartment door) on the fully developed diesel fire, confirm the pre-burn time, heat the compartment and remove moisture from the ceramic fibre insulation in the compartment walls. Upon completion of the pre-burn, 10 ℓ of diesel fuel was added to the fuel pan and the freeboard height adjusted to 1 cm by adding or removing base water. Thermocouple and gas analysis data acquisition was started and the video recordings commenced for internal colour and low wavelength cameras, internal IR camera and external colour video camera. Ambient conditions were recorded and the diesel was ignited by propane torch on an extension handle. The compartment door was fixed at 30 cm for the pre-burn period of approximately 2 minutes. At this point, the aerosol unit under test was activated and slid into the diesel pan such that it was completely submerged in water under the burning diesel prior to generation of the aerosol agent. The activation time and discharge duration of the units were recorded and visual observations were made throughout the suppression tests. Temperature, gas concentration, and video data were analysed after the test to determine the suppression efficacy of aerosol agents in each test.

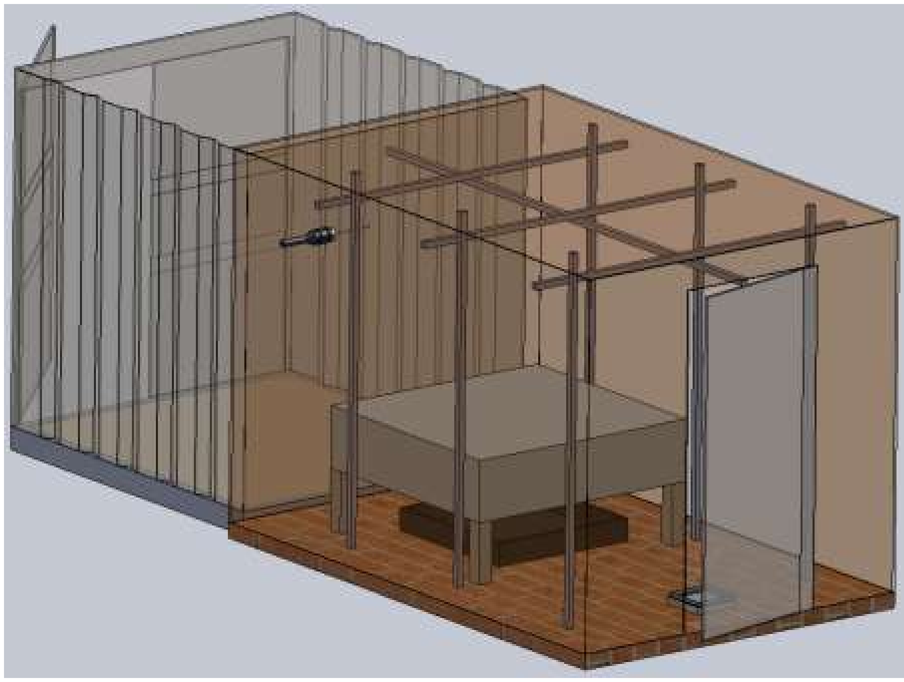


Figure 5-43. UW Shipping Container Burn Room Setup for Test 3a and 3b: Obstructed Diesel Bilge Fire Suppression

5.6.2 Suppression Results for Test 3a: StatX FR

Aerosols generated from the StatX FR unit successfully suppressed and then extinguished the obstructed diesel bilge fire in Test 3a. Although the StatX FR unit was totally submerged under water, the aerosol agent was generated successfully and distributed evenly with minimal splashing, even despite the relatively shallow water base of the diesel pan. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-44. From the Figure, the cooling rate was determined to be 250^{o}C/min or 4.2^{o}C/second from the onset of suppression to 60 seconds after suppression. The change in compartment thermal stratification during suppression are shown in 10 s intervals in Figure 5-45, and the average temperature difference from top to bottom of the compartment is shown in Figure 5-46. Integrating the curve in Figure 5-46 gives a global cooling effect throughout the compartment of 337 m·K. Oxygen and carbon dioxide concentrations throughout the suppression test are plotted in Figure 5-47, showing the expected decrease in oxygen concentration and increase in carbon dioxide concentration as the fire grows up to the onset of suppression. After suppression, oxygen concentrations increase again and the production of carbon dioxide decreases. The rise in oxygen concentration occurs more slowly in this test when compared to Test 1 because the compartment door is closed. At about 320 seconds into the test, the door is opened and the oxygen and carbon dioxide concentrations quickly return to atmospheric levels.

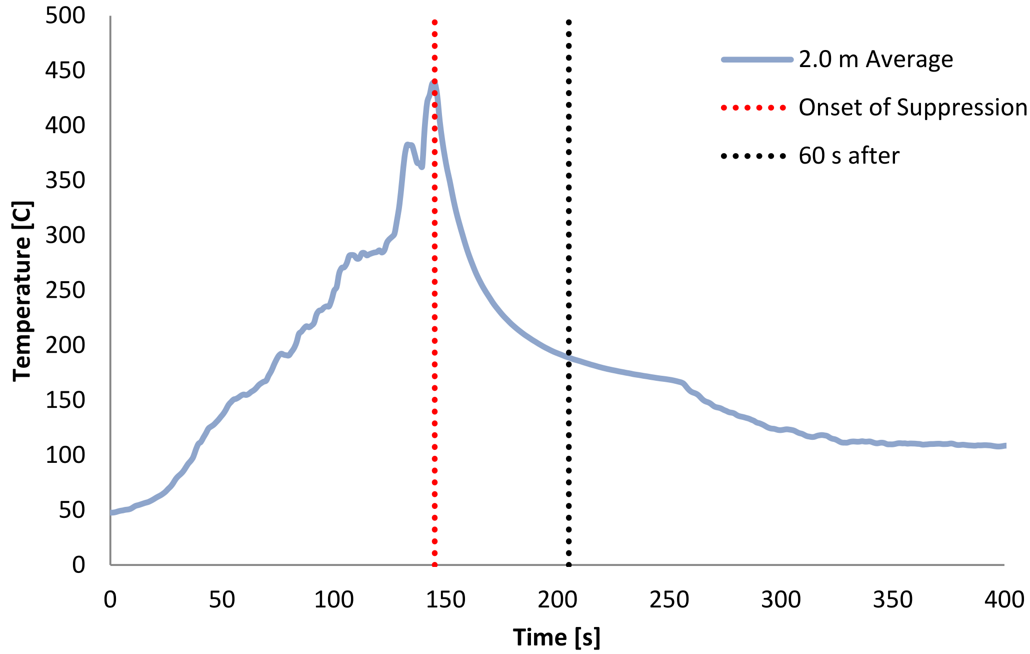


Figure 5-44. Test 3a: StatX Obstructed Bilge Fire Upper Layer Cooling Rate

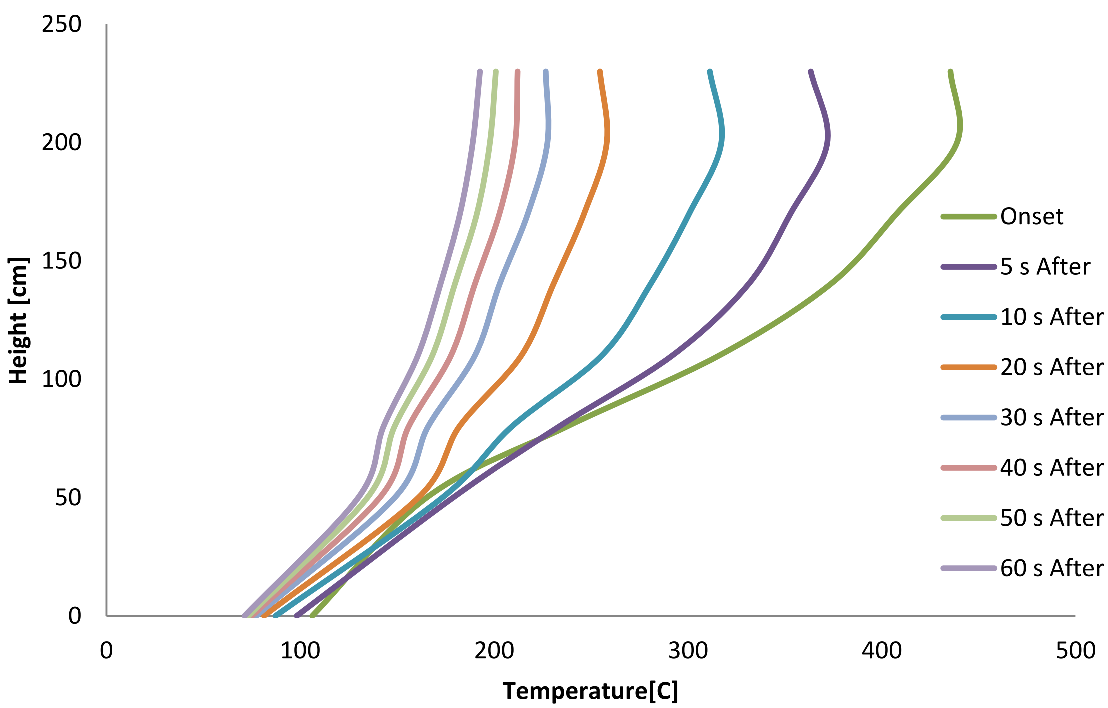


Figure 5-45. Test 3a: StatX Suppression Effect on Thermal Stratification

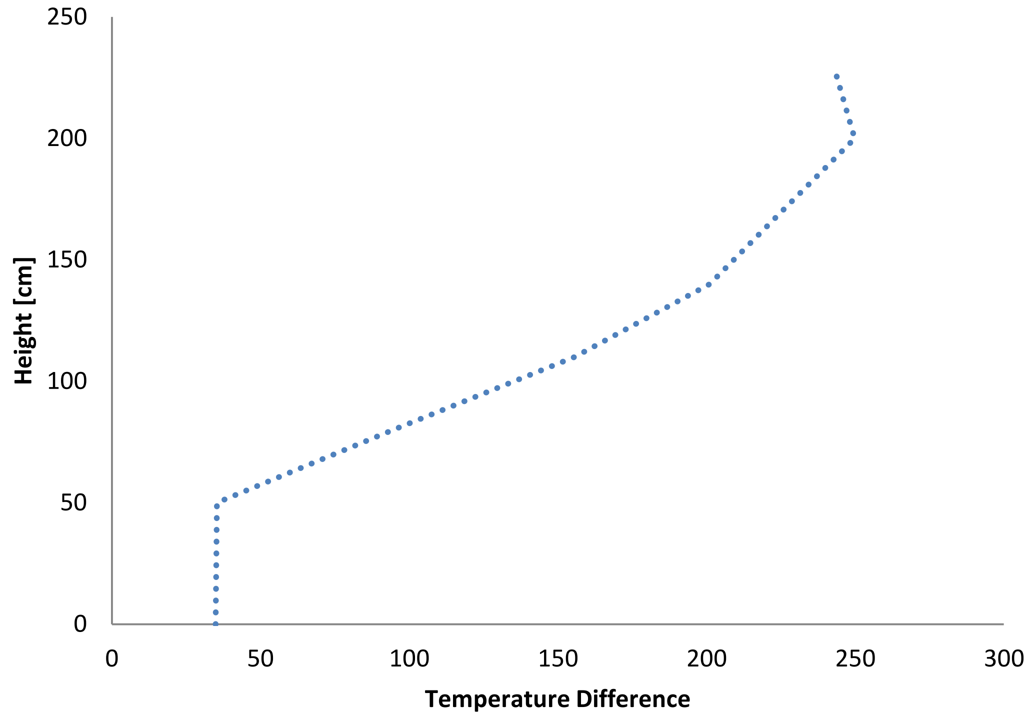


Figure 5-46. Test 3a: StatX Average Temperature Difference due to Suppression

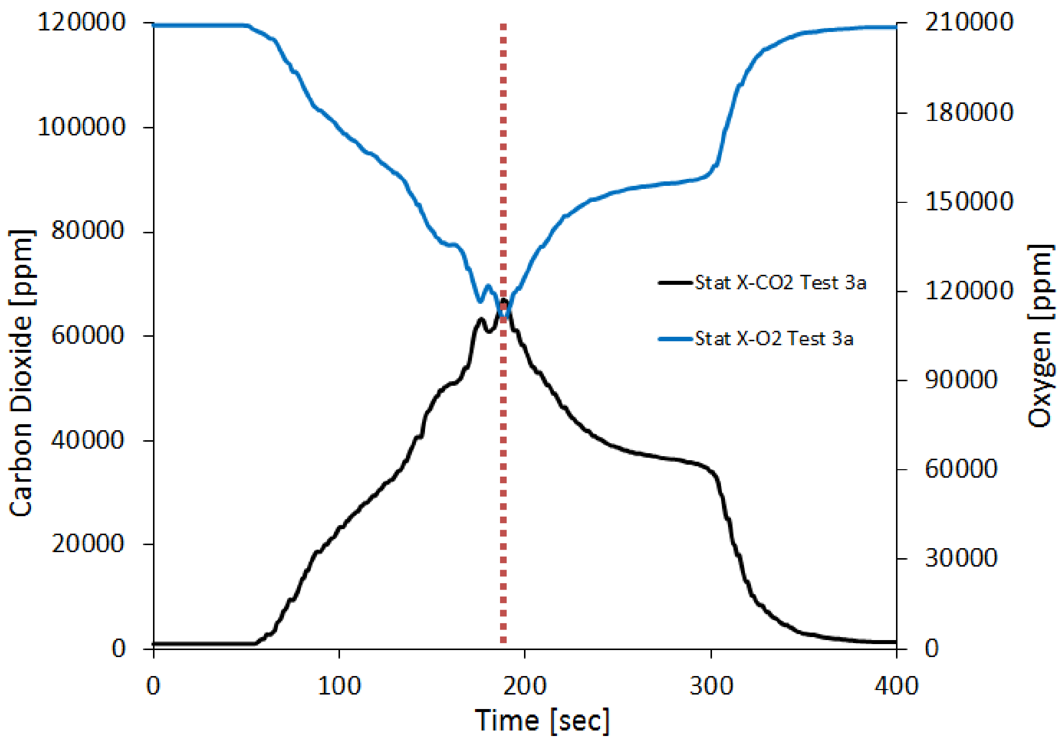


Figure 5-47. Test 3a, Bilge Fire Test: Stat X's Carbon Dioxide and Oxygen concentrations

5.6.3 Suppression Results for Test 3a: DSPA 5-4

Aerosols generated from the DSPA 5-4 unit successfully suppressed and then extinguished the obstructed diesel bilge fire in Test 3a. Although the DSPA 5-4 unit was totally submerged under water, the aerosol agent was generated successfully and distributed evenly with minimal splashing, even despite the relatively shallow water base of the diesel pan. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-48. From the Figure, the cooling rate was determined to be 193°C/min or 3.2°C/second from the onset to 60 seconds after suppression. The change in compartment thermal stratification during suppression are shown in 10 s intervals in Figure 5-49, and the average temperature difference from top to bottom of the compartment is shown in Figure 5-50. Integrating the curve in Figure 5-50 gives a global cooling effect throughout the compartment of 235 m·K. Oxygen and carbon dioxide concentrations throughout the suppression test are plotted in Figure 5-51, showing the expected decrease in oxygen concentration and increase in carbon dioxide concentration as the fire grows up to the onset of suppression. After suppression, oxygen concentrations increase again and the production of carbon dioxide decreases. The rise in oxygen concentration occurs more slowly in this test when compared to Test 1 because the compartment door is closed. At about 320 seconds into the test, the door is opened and the oxygen and carbon dioxide concentrations quickly return to atmospheric levels.

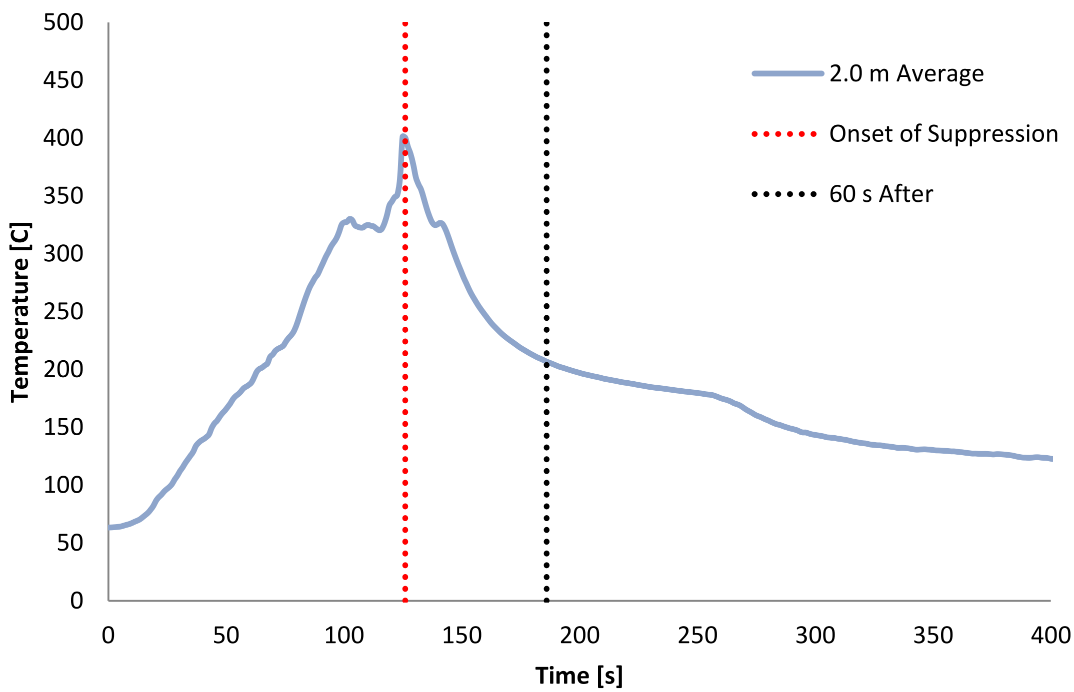


Figure 5-48. Test 3a: DSPA 5-4 Obstructed Bilge Fire Average Upper Layer Cooling Rate

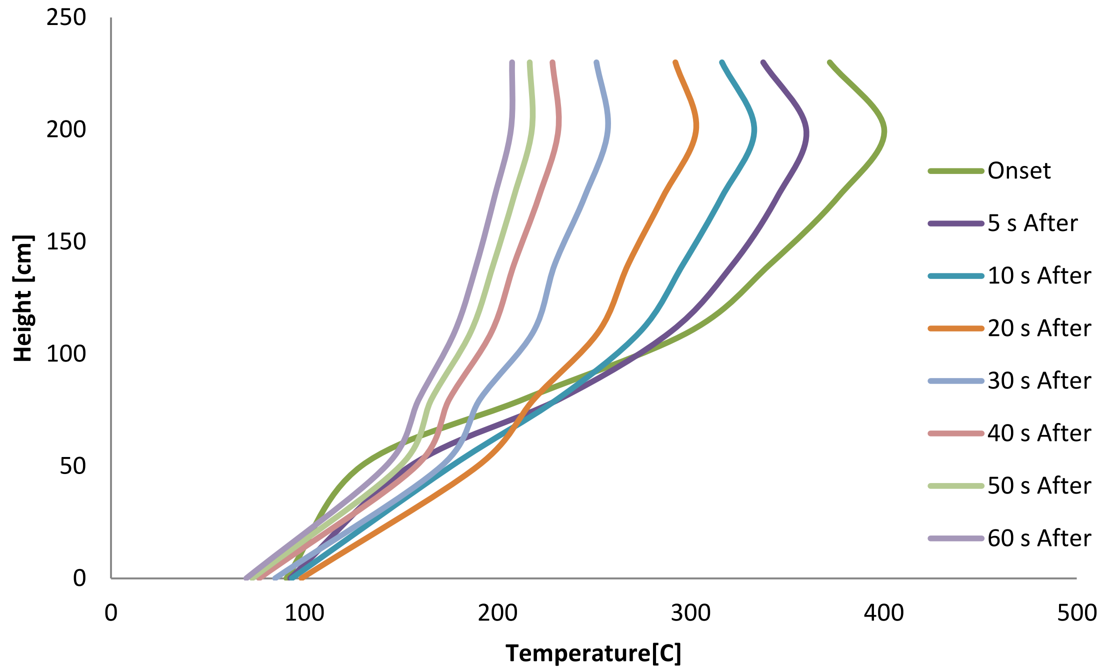


Figure 5-49. Test 3a: DSPA 5-4 Suppression Effect on Average Thermal Stratification

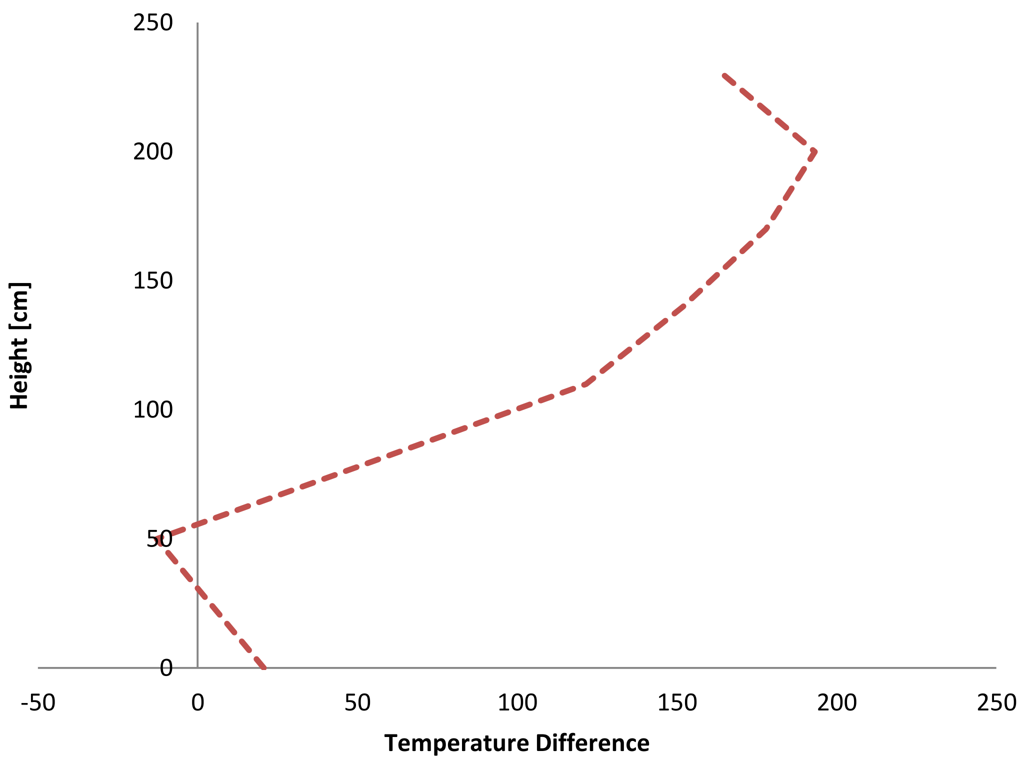


Figure 5-50. Test 3a: DSPA 5-4 Average Temperature Difference due to Suppression

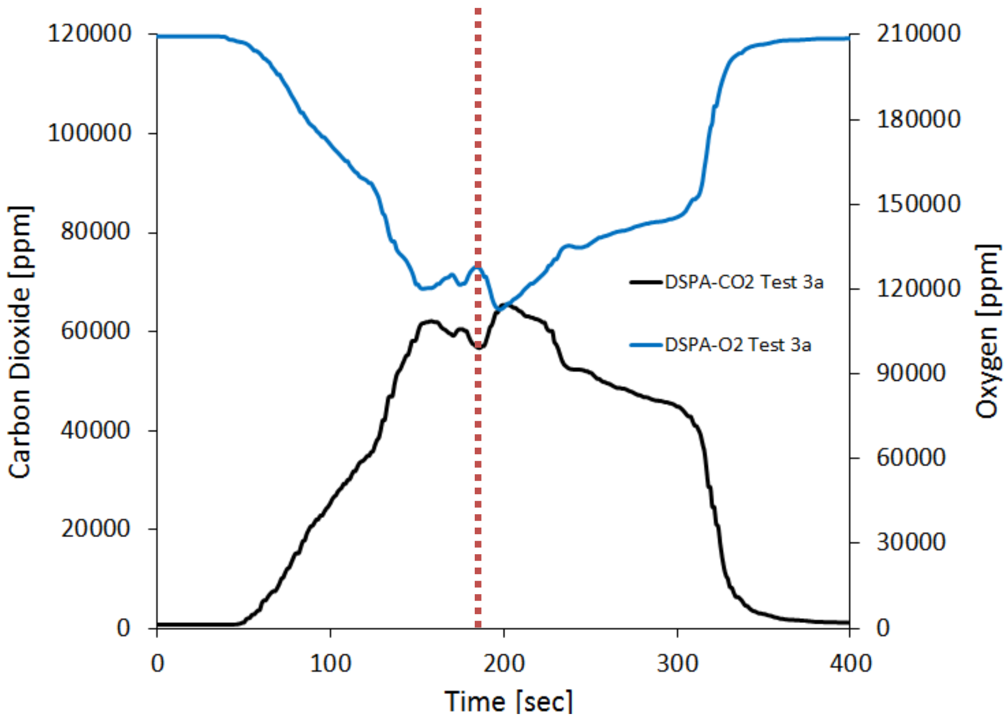


Figure 5-51. Test 3a, Bilge Fire Test: DSPA's Carbon Dioxide and Oxygen concentrations

5.6.4 Suppression Results for Test 3b: StatX FR

The Stat X unit in Test 3b successfully knocked down but did not extinguish the obstructed diesel bilge fire when the compartment door was left open. The aerosol agent was generated and distributed evenly with minimal splashing despite the relatively shallow water base of the diesel pan. Since the fire was not extinguished, the cooling rate and overall cooling of the compartment were calculated over the 27 second period from the peak average compartment temperature to the lowest average compartment temperature. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-52. From the Figure, the cooling rate was determined to be $5^{o}C$/second. The effects of fire suppression by the aerosols on thermal stratification within the compartment are represented in 5 second intervals Figure 5-53, and the average temperature difference with height in the compartment is shown in Figure 5-54. Integrating the curve in Figure 5-54 using the same methods as described previously indicates a global cooling effect of 431 m·K throughout the compartment. Oxygen and carbon dioxide concentrations through the suppression test are plotted in Figure 5-55, showing the anticipated decrease in oxygen concentration and increase in carbon dioxide concentration as the fire grows up to the onset of suppression. From the onset of suppression to 25 seconds afterwards, the oxygen concentration begins to rise and carbon dioxide concentration decrease as the fire is suppressed. However, since the fire was not extinguished, the oxygen concentration later dropped again and carbon dioxide production increased as the fire re-established itself and grew again until the door was closed at about 235 seconds into the test.

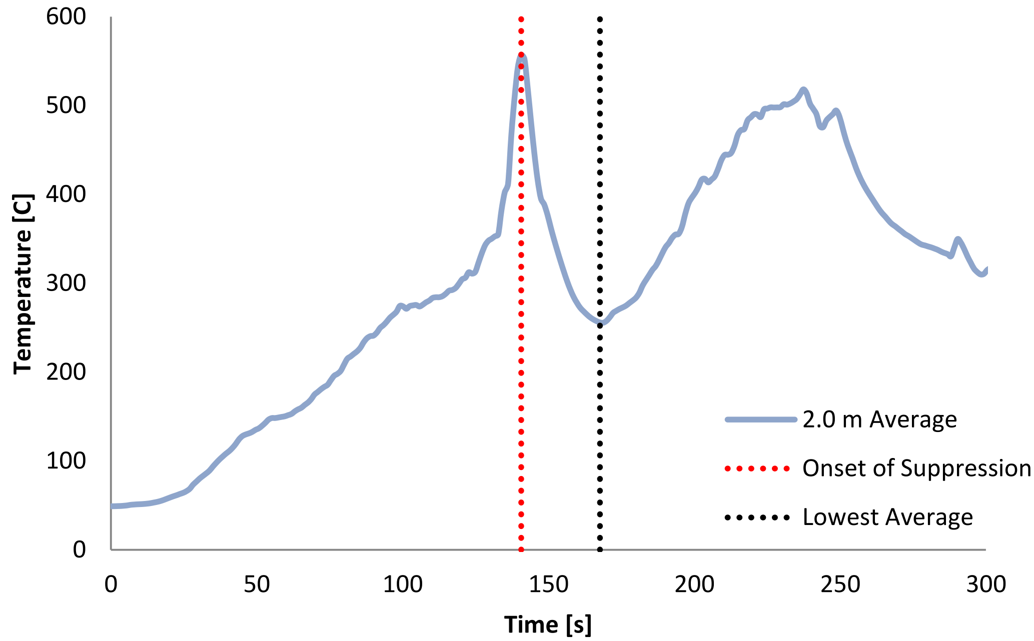


Figure 5-52. Test 3b, Door Open: StatX FR Obstructed Bilge Fire Upper Layer Cooling Rate

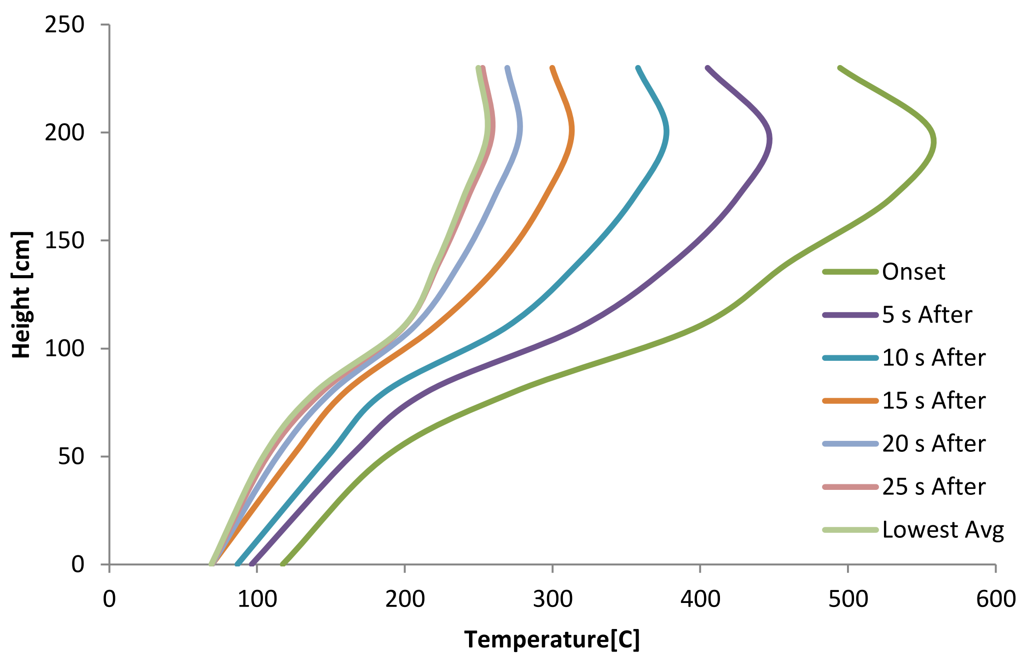


Figure 5-53. Test 3b, Door Open: StatX FR Suppression Effect on Average Thermal Stratification

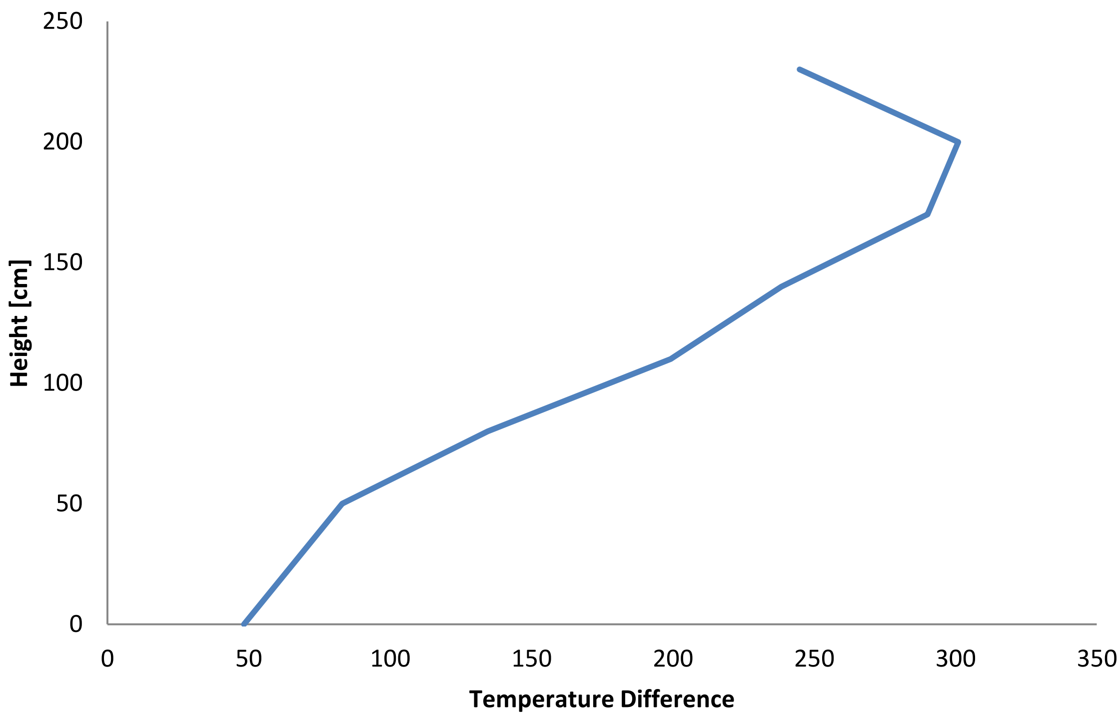


Figure 5-54. Test 3b, Door Open: StatX FR Average Temperature Difference due to Suppression

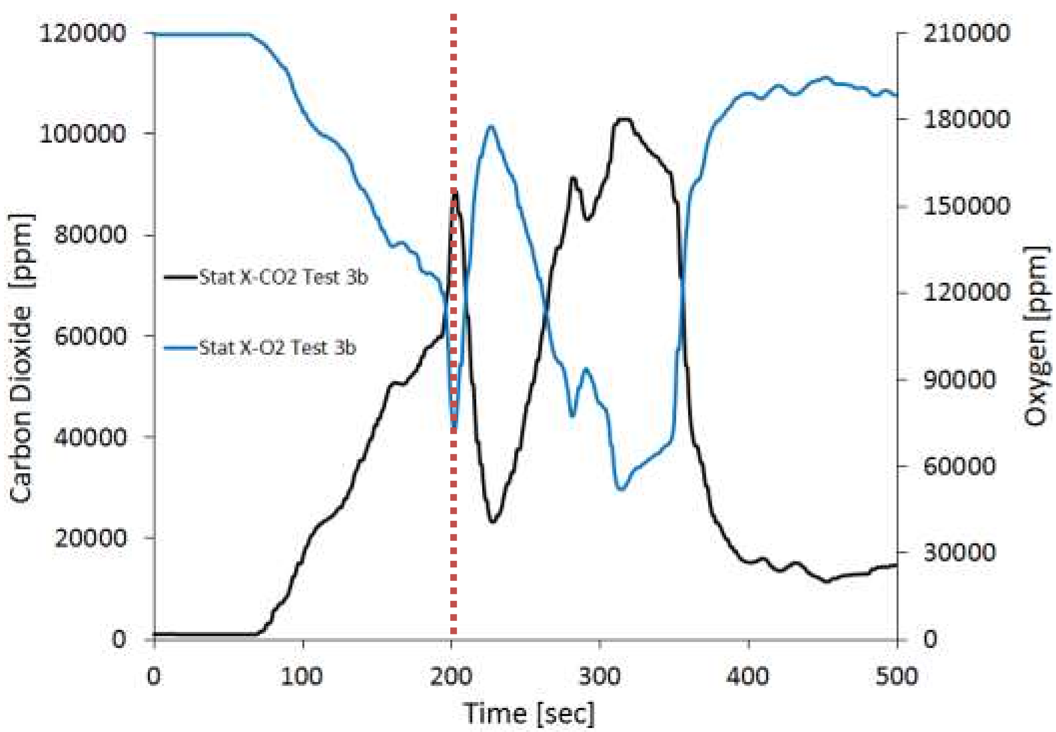


Figure 5-55. Test 3b, Bilge Fire Test: Stat X's Carbon Dioxide and Oxygen concentrations

5.6.5 Suppression Results for Test 3b: DSPA 5-4

The DSPA 5-4 unit in Test 3b successfully suppressed and then extinguished the obstructed diesel bilge fire. The aerosol agent was generated and distributed evenly with minimal splashing despite the relatively shallow water base of the diesel pan. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-56. From the plot, the cooling rate was determined to be 253°C/min or 4.2°C/second from the onset of suppression to 60 seconds after suppression. The effects of fire suppression by the aerosols on thermal stratification within the compartment are represented in 10 s intervals in Figure 5-57, and the average temperature difference with height in the compartment is shown in Figure 5-58. Integrating the curve at Figure 5-58 gives a global cooling effect in the compartment of 370 m·K. Oxygen and carbon dioxide concentrations are plotted against time in Figure 5-59, and again show a decrease in oxygen concentration and increase in carbon dioxide concentration as the fire grows up to the onset of suppression. After suppression, oxygen concentrations again increase and production of carbon dioxide decreases with both concentrations returning to atmospheric values as the fire is extinguished.

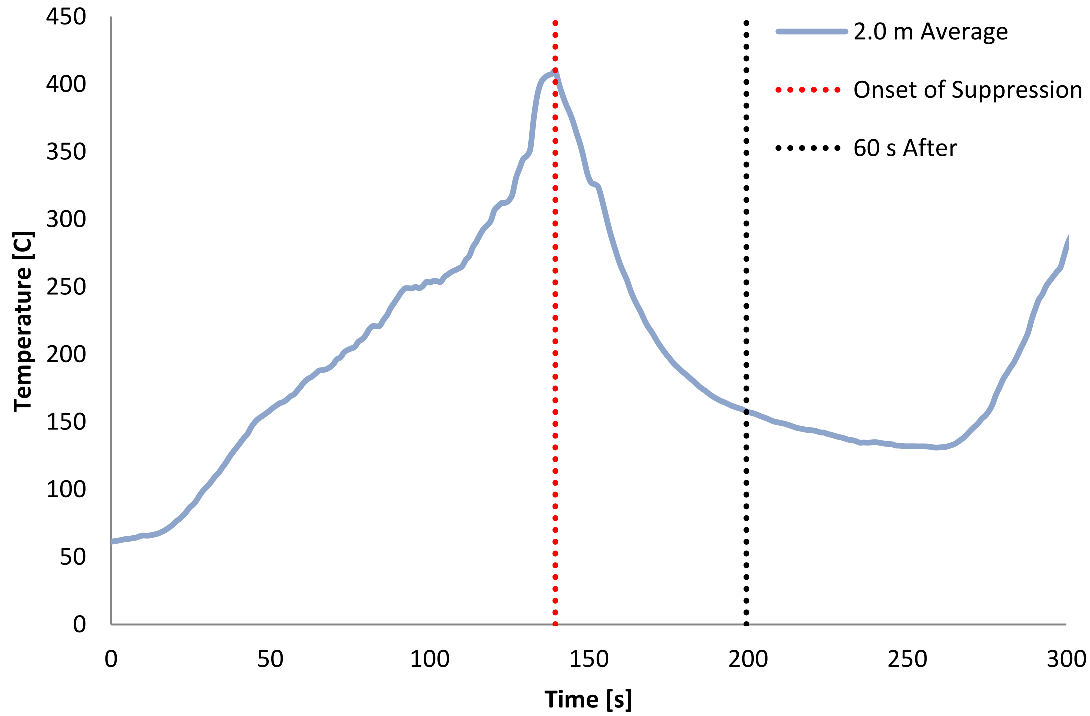


Figure 5-56. Test 3b, Door Open: DSPA 5-4 Average Upper Layer Cooling Rate

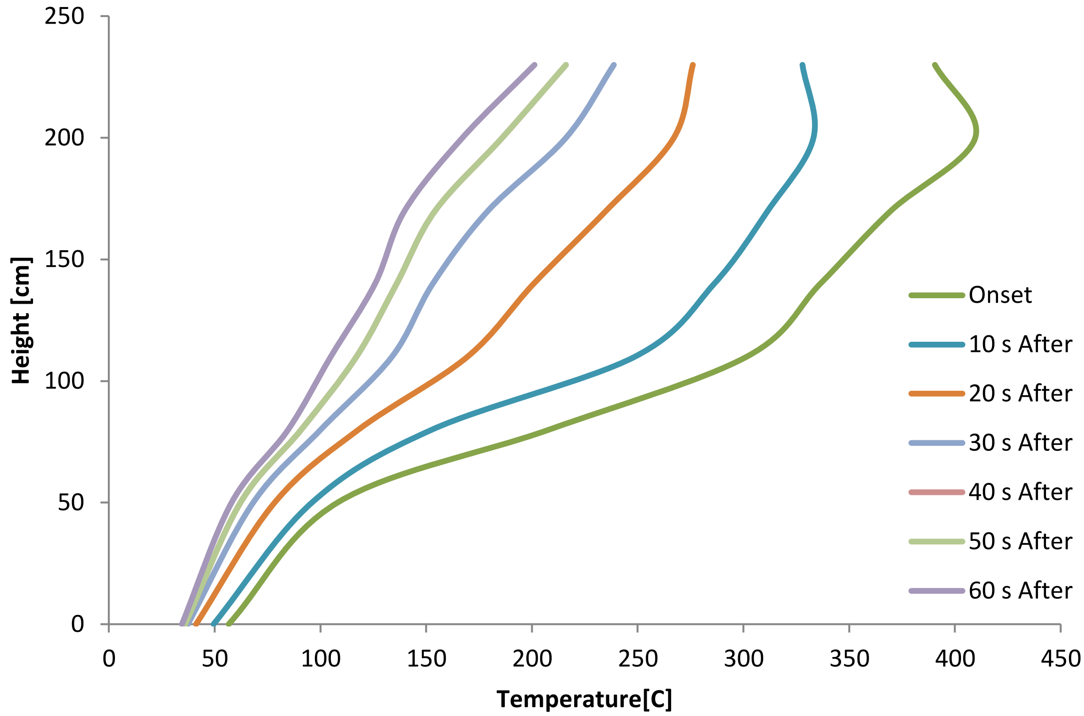


Figure 5-57. Test 3b, Door Open: DSPA 5-4 Suppression Effect on Average Thermal Stratification

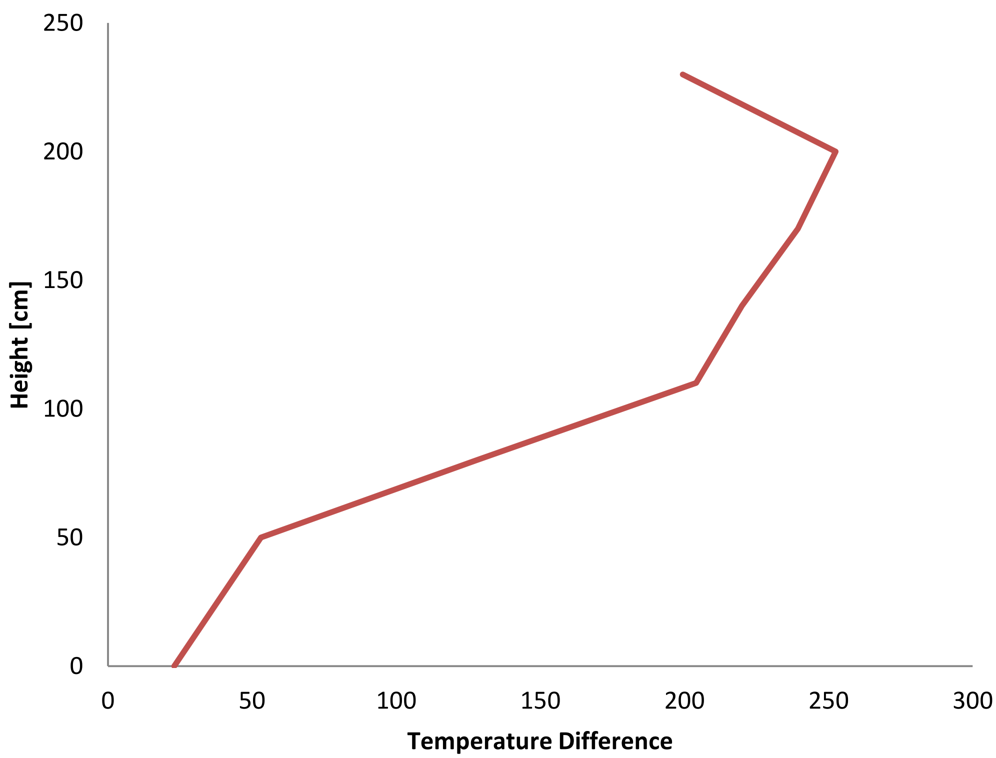


Figure 5-58. Test 3b, Door Open: DSPA 5-4 Average Temperature Difference due to Suppression

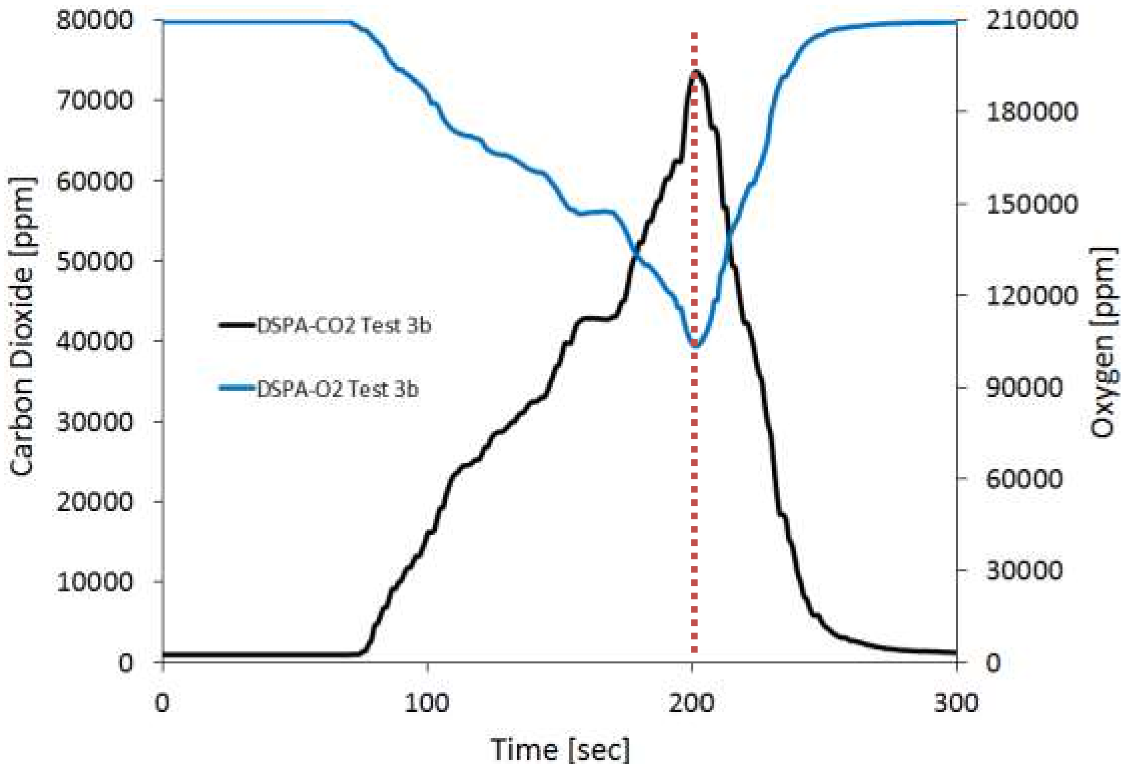


Figure 5-59. Test 3b, Bilge Fire Test: DSPA's Carbon Dioxide and Oxygen concentrations

5.6.6 Summary and Discussion of Test 3a and 3b: Obstructed Diesel Bilge Fire

This section summarizes the results of the obstructed diesel bilge fire suppression tests for both StatX FR and DSPA 5-4 aerosol extinguishers. It is important to note again that in Test 3a the door was closed immediately after the aerosol units were activated.. In contrast, Tests 3b were conducted with the door fully open to present a greater challenge to the aerosol suppression units as well as to facilitate observation of the test itself.

The ambient conditions of each of the four bilge fire tests along with their respective results for peak average temperatures, cooling rates, and total cooling effect are compiled in Table 5-6. For comparison, the effects of oxygen starvation (closing the door) during an obstructed diesel characterization fire are also shown in the Table 5-6. The average temperature differences that yield the values of total cooling effect during aerosol suppression and during oxygen starvation of the fire are combined in Figure 5-60. In tests with the compartment door closed, the StatX FR had a larger impact on the environment than the DSPA 5-4 unit, with a StatX FR cooling rate of 4.2 C/s and total cooling of 337 m·K versus 3.2 C/s and 235 m-K for the DSPA 5-4. When the door was open, however, the Stat-X FR did not suppress the fire, whilst the DSPA 5-4 performed in a fashion similar to the StatX FR in the test with door was closed, having a cooling rates of 3.2 C/s and total cooling effect of 370 m·K. The addition of aerosol from either unit resulted in a significantly higher rate of cooling and higher total cooling effect than seen when the door was closed and no aerosol was added.

5.6.6.1 Test 3a: Obstructed Diesel Bilge Fire Suppression Results Summary

Table 5-7 combines the results from Test 2c with those from Test 3a to compare the difference in cooling rates and cooling effects between aerosol activation just inside the door of the compartment (Test 2c) and activation in the bilge (under the fire in the water pan) (Test 3a) when the door of the fire compartment is closed after activation of the unit. Since the fire scenario and compartment environment are the same for Test 2 and Test 3, this provides a good comparative measure relating to where aerosol units should be located relative to the fire source to best suppress a marine machinery space fire. The StatX FR unit activated in the simulated bilge (Test 3a) had an 82% higher cooling rate and a 43% higher total cooling effect when compared to unit activation inside the door frame (Test 2c). The DSPA 5-4 unit activated in the simulated bilge had a 28% higher cooling rate and an 11% higher total cooling effect when compared to unit activation inside the door frame. Therefore, since significantly higher cooling rates were seen in Test 3a for both units versus those seen in Test 2c, results suggest that activation of an aerosol unit in the bilge under an obstructed diesel fire can be a more effective suppression technique than simply placing the aerosol unit near the door of the fire compartment.

5.6.6.2 Test 3b: Obstructed Diesel Bilge Fire Suppression Results Summary

Considering the relatively minor suppression effect that both StatX FR and DSPA 5-4 units had on the Test 2 obstructed fires with the door held open at 30 cm, it is remarkable that such a high cooling rate and cooling effect were achieved during Test 3b with the door fully open. This difference might be explained by considering that aerosols generated by an aerosol unit submerged in water under the burning diesel fuel were more effective at interacting chemically to suppress the fire and also at absorbing heat to reduce the radiant heat flux from the hot enclosure surfaces back down onto the unburned diesel fuel. Though the results are not yet fully explained and should form the subject of further research, the present results do suggest that for large or breached compartments with obstructed fires, activation of the aerosol in a location under the fire (i.e. in a bilge) might extinguish the fire more effectively than activation directly beside the fire which may have little effect on the fire and the environment in the fire compartment. Another benefit of activating pyrotechnically generated aerosol units while submerged in water is that their own incendiary potential is greatly reduced since the water absorbs the heat generated by the thermal decomposition of potassium nitrate.

Table 5-6. Summary of Test 3a and 3b Results: Obstructed Diesel Bilge Fire

Test	Ambient Temp [^{o}C]	Ambient RH [%]	Ambient Wind Speed [m/s]*	Ambient Wind Direction	Peak Average Temp [^{o}C]	Cooling Rate (^{o}C/Sec)**	Total Cooling Effect [m·K]
3a: StatX FR	19	52	1.7	SW	310	4.2	337
3a: DSPA 5-4	14	44	1.2	S	278	3.2	235
3b: StatX FR	15	49	1	S	377	5***	431
3b: DSPA 5-4	14	72	3	S	273	4.2	370
Closed Door	18	33	0.5	W	220	1.9	164

*Note 1: Ambient wind speed taken at door of compartment between wind blocks to assess air flow at the door during suppression testing.
**Note 2: Cooling rates assessed from 60 seconds after peak average temperature.
***Note 3: Cooling rate is only for the 27 seconds between peak average and lowest average temperature since the fire was not extinguished in this test.

Table 5-7. Comparison of Suppression Effect on Obstructed Diesel Fires by Aerosol Activation in the Bilge versus Activation inside the Door Frame

Test	Ambient Temp [^{o}C]	Ambient RH [%]	Ambient Wind Speed [m/s]*	Ambient Wind Direction	Peak Average Temp [^{o}C]	Cooling Rate (^{o}C/Sec)**	Total Cooling Effect [m·K]
2c: StatX FR	20	33	0.7	W	255	2.3	235
3a: StatX FR	19	52	1.7	SW	310	4.2	337
2c: DSPA 5-4	17	50	1.1	SW	221	2.5	211
3a: DSPA 5-4	14	44	1.2	S	278	3.2	235
Closed Door	18	33	0.5	W	220	1.9	164

*Note 1: Ambient wind speed taken at door of compartment between wind blocks to assess air flow at the door during suppression testing.
**Note 2: Cooling rates assessed from 60 seconds after peak average temperature.

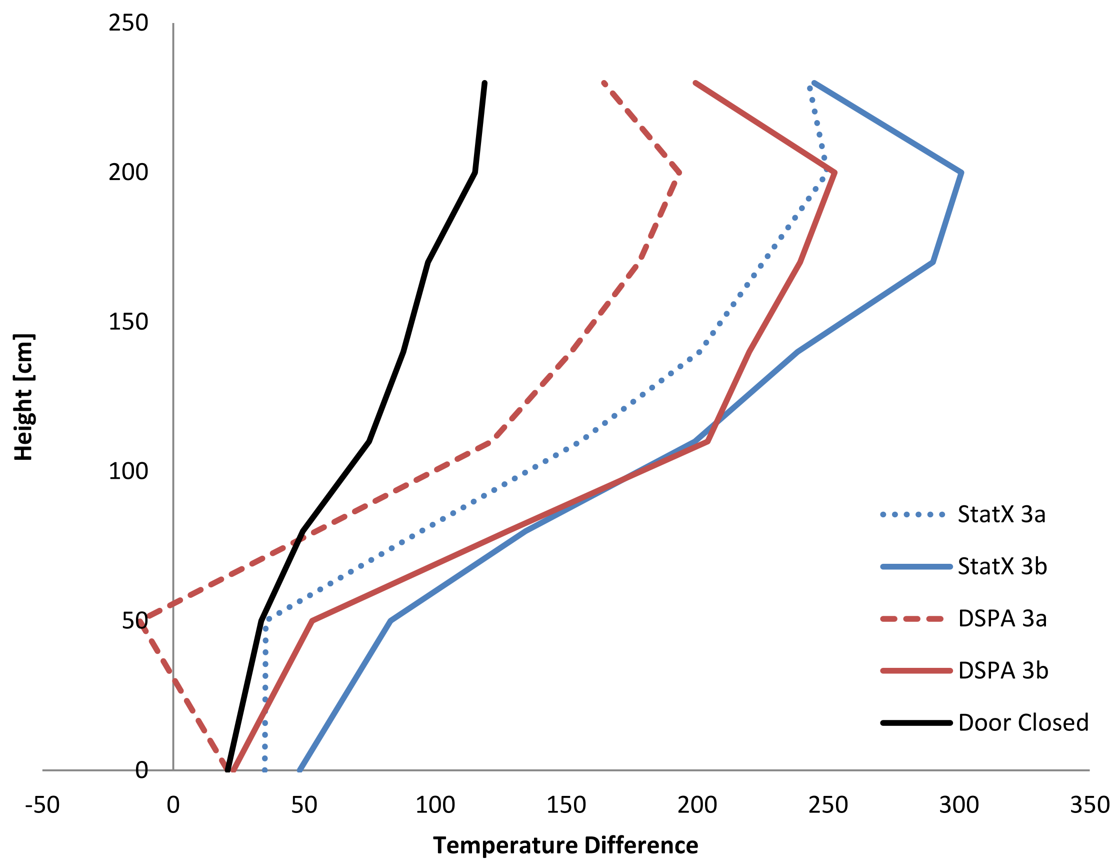


Figure 5-60. Summary of Average Temperature Difference Caused by Aerosol Suppression on an Obstructed Bilge Fire

5.7 Discussion of Test 4: Softwood Crib Fire Suppression

5.7.1 Fire Suppression Techniques for Test 4: Softwood Crib Fire

Test 4 was designed to investigate suppression of a 4-crib softwood fire using the StatX FR and the DSPA 5-4 handheld aerosol extinguishers. The compartment setup for this test is shown in Figure 5-61. The cooling rate of the upper gas layer, total cooling effect on the compartment, and average effect on thermal stratification were again investigated. Additionally, concentrations of oxygen and carbon dioxide, which change in proportion to fire growth and decay, serve as additional indicators of the effects of suppression.

Prior to suppression testing, a wood crib characterization test was conducted to determine the compartment environment without aerosol suppression, determine the effects of ventilation control (closing the compartment door) on a fully developed wood crib fire, confirm the pre-burn time, heat the compartment and to remove moisture from the ceramic fibre insulation in the compartment walls. Upon completion of the pre-burn, the four softwood cribs were stacked vertically. Thermocouple and gas analysis data acquisition was started and the video recordings commenced for internal colour and low wavelength cameras, internal IR camera and external colour video camera. Ambient conditions were recorded and a tray containing methanol was placed below the wood crib and was ignited using a butane lighter. The compartment door was fixed at 30 cm for the pre-burn period of approximately 4-6 minutes until a fully developed compartment fire was established. At this point, the aerosol unit under test was activated and placed precisely on the floor inside the door frame without changing the opening fraction of the door itself, and the door was closed. The activation time and discharge duration of the units were recorded and visual observations were made throughout the suppression tests. Temperature, gas concentration, and video data were analysed after the test to determine the suppression efficacy of aerosol agent in each test.

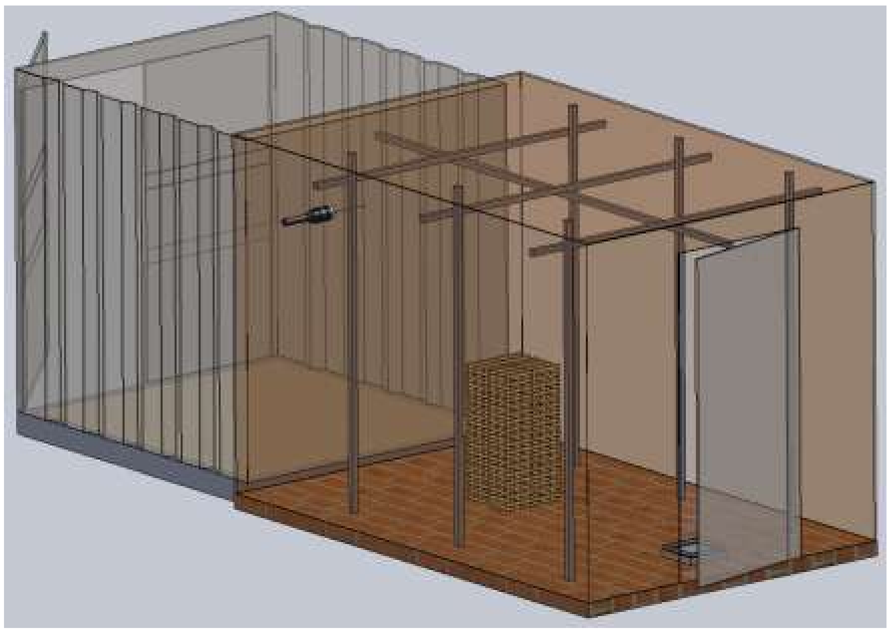


Figure 5-61. UW Shipping Container Burn Room Setup for Test 4: Softwood Crib Fire Suppression

5.7.2 Suppression Results for Test 4: StatX FR, Softwood Crib

The StatX FR unit in Test 4 successfully suppressed the softwood crib fire, as confirmed via internal IR camera footage recorded. However, due to the deep seated embers of a Class A fire, the softwood continued to smolder so the fire was not completely extinguished by the aerosol unit. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-62. From the Figure, the cooling rate was determined to be 206^{o}C/min or 3.4^{o}C/second from the onset of suppression to 60 seconds afterwards. The changes in compartment thermal stratification during suppression are shown in 10 s intervals in Figure 5-63, and the average temperature difference from top to bottom of the compartment is shown in Figure 5-64. In this test, the average temperature difference seen at locations below 1.1 m above the floor of the compartment is negative, indicating that there is actually a temperature increase in these locations over the 60 second suppression period. Integrating the curve in Figure 5-64 using methods outlined earlier gives a global cooling effect of 147 m·K throughout the compartment. Oxygen and carbon dioxide concentrations throughout the suppression test are plotted in Figure 5-65, and show the expected decrease in oxygen concentration and increase in carbon dioxide concentration as the fire grows up to the onset of suppression. From the onset of suppression, the oxygen concentration begins to rise and carbon dioxide decreases as the fire is suppressed. The rise in oxygen concentration occurs more slowly in this test when compared to Test 1 because the deep seated embers of the Class A fire continued to burn and also because the compartment door was closed. At about 410 seconds, the door is opened and the oxygen concentration quickly rises; however, since the fire was never fully extinguished, the fire also begins to grow again as new oxygen is introduced and there is no longer sufficient suppression agent in the compartment to control the fire.

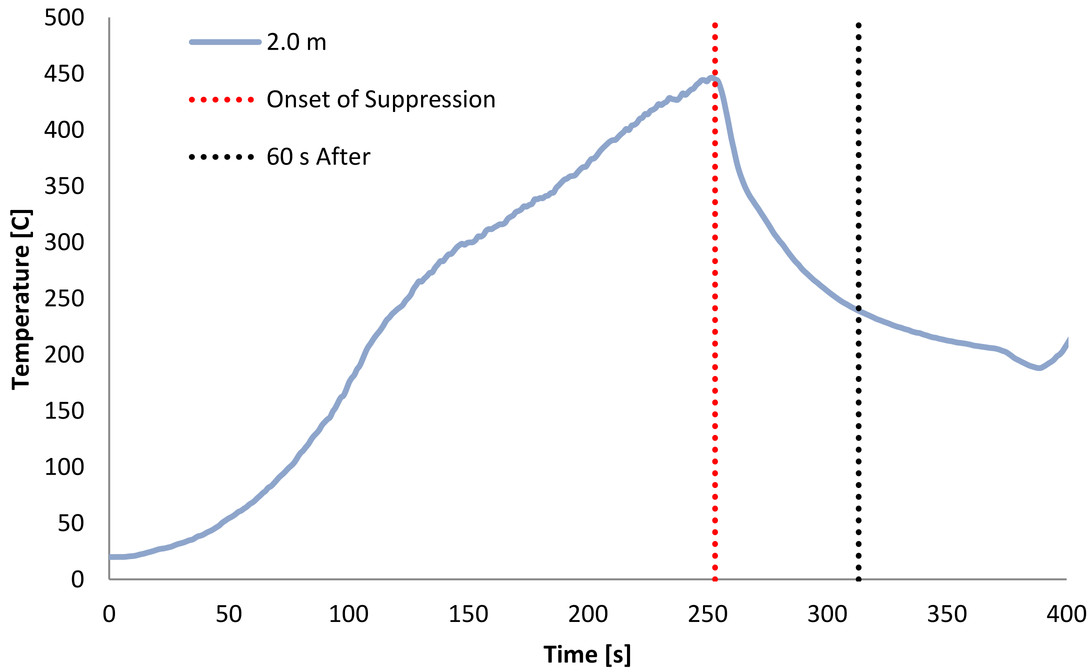


Figure 5-62. Test 4: StatX FR Softwood Crib Fire Upper Layer Temperature Cooling Rate after Aerosol Released and the compartment door was closed

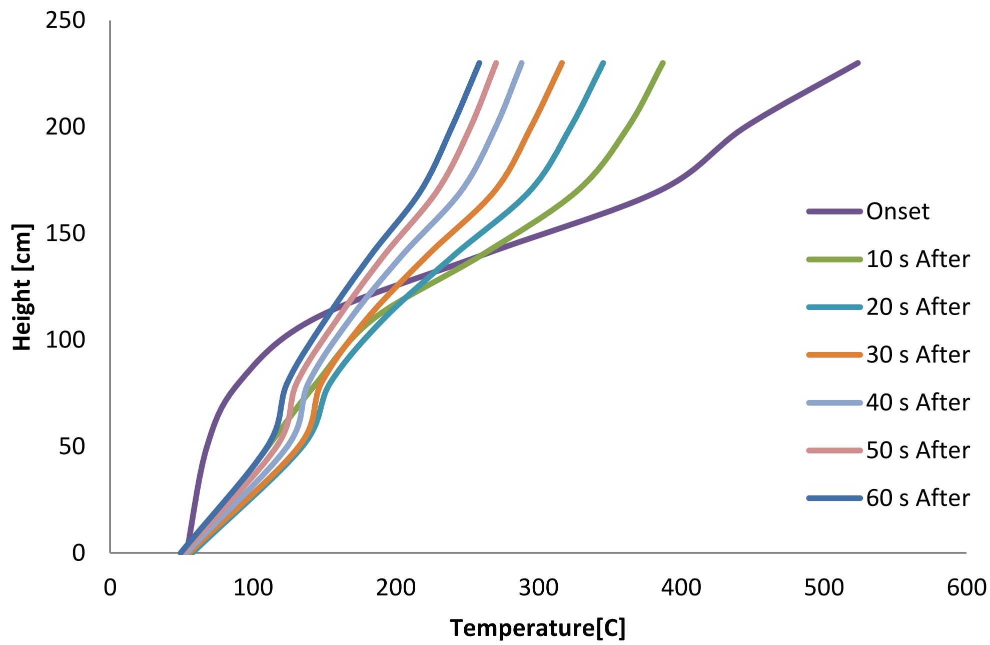


Figure 5-63. Test 4: StatX FR, Suppression Effect on Average Thermal Stratification after Aerosol Released and the compartment door was closed

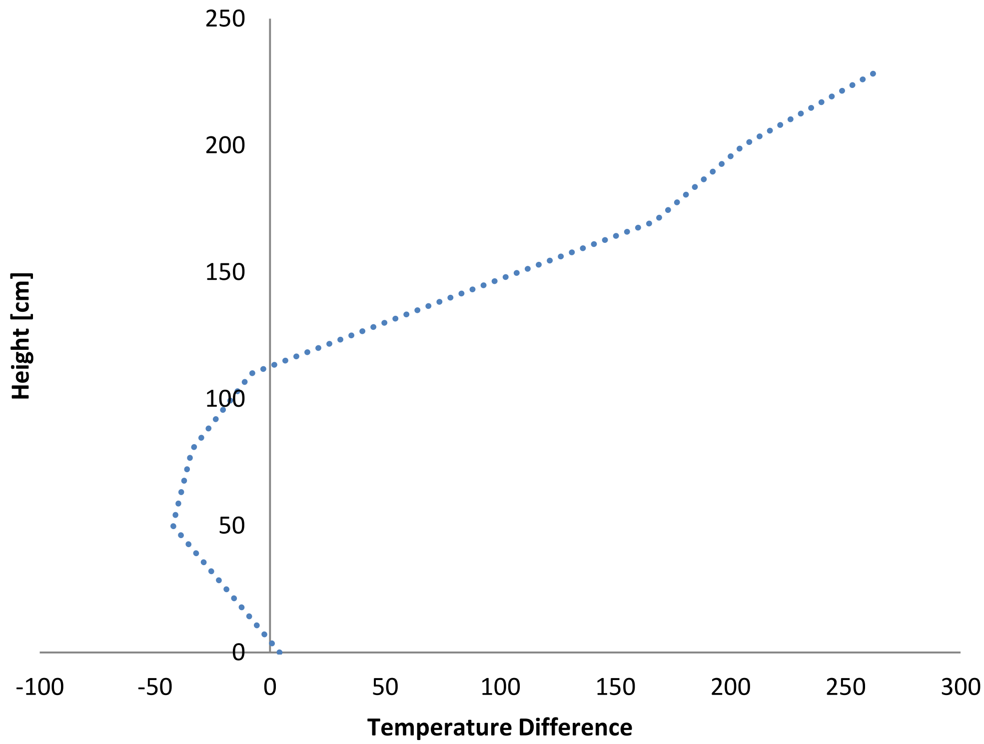


Figure 5-64. Test 4: StatX FR Average Temperature Difference Due to Aerosol Agent Suppression and closing the compartment door from the onset of suppression to 60 after

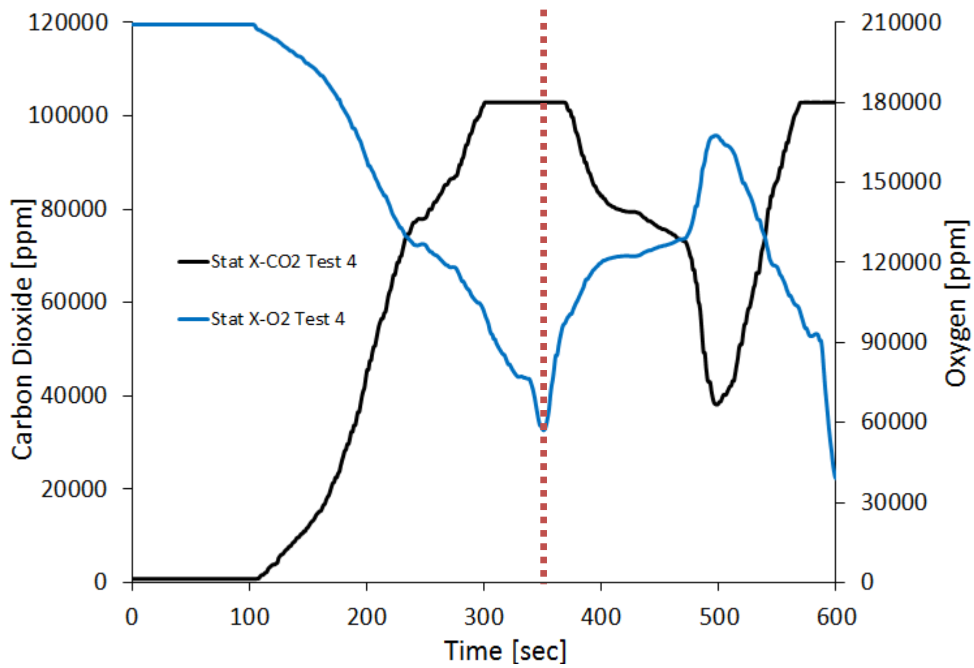


Figure 5-65. Test 4, Softwood Crib: StatX FR Carbon Dioxide and Oxygen concentrations due to aerosol suppression and closing the compartment door

5.7.3 Suppression Results for Test 4: DSPA 5-4, Softwood Crib

The DSPA 5-4 unit in Test 4 successfully suppressed the softwood crib fire, as confirmed via internal IR camera footage recorded. Again, due to the deep seated embers of a Class A fire, the softwood continued to smolder so the fire was not completely extinguished by the aerosol unit. A plot of the average compartment temperatures determined using thermocouples positioned 2 m above the floor of the compartment versus time is shown in Figure 5-66. From the Figure, the cooling rate was determined to be 186°C/min or 3.1°C/second from the onset to 60 seconds after suppression. The change in compartment thermal stratification during suppression are shown in 10 s intervals in Figure 5-67 and the average temperature difference from top to bottom of the compartment is shown in Figure 5-68. In this test, the average temperature differences seen at locations below 0.8 m above the floor of the compartment are negative, indicating a temperature increase over the 60 second suppression period. Integrating the curve at Figure 5-68 gives a global cooling effect through the compartment of 154 m·K. Oxygen and carbon dioxide concentrations throughout the suppression test are plotted in Figure 5-69, showing the decrease in oxygen concentration and increase in carbon dioxide concentration that is anticipated as the fire grows up to the onset of suppression. From the onset of suppression, the oxygen concentration begins to rise and carbon dioxide decreases as the fire is suppressed. At about 450 seconds the door is opened and the oxygen concentration quickly rises up to atmospheric levels before the wood crib fire begins to grow again. Again in this test, the fire was not fully extinguished, but the oxygen concentrations seen before the door was opened were much higher in this test than in the StatX FR softwood crib test, suggesting that the DSPA 5-4 unit had greater impact in terms of suppressing a Class A fire.

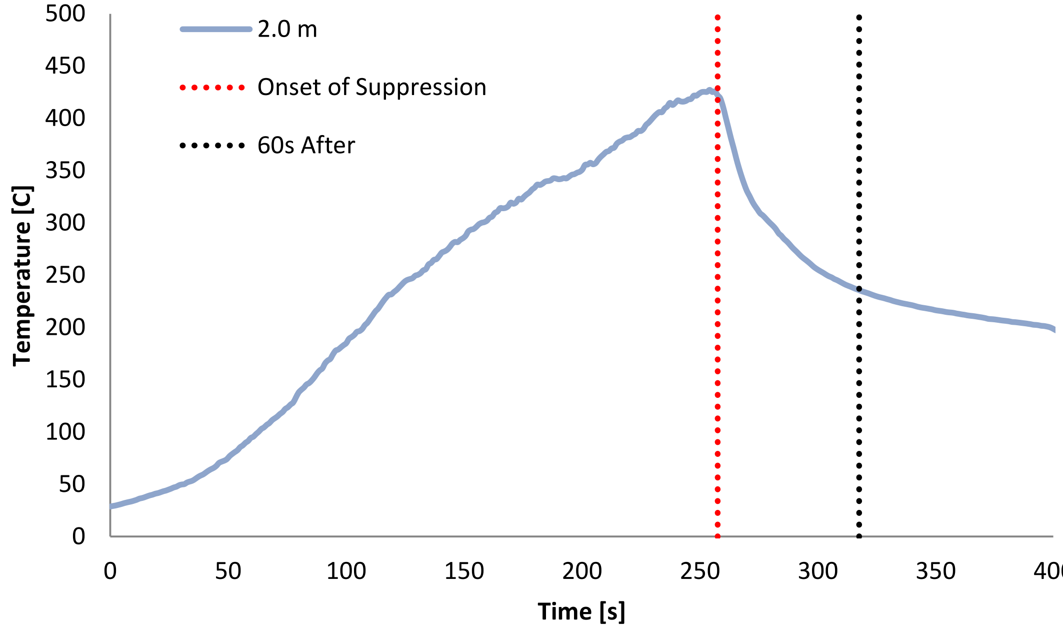


Figure 5-66. Test 4 DSPA 5-4 Softwood Crib Fire Upper Layer Temperature Cooling Rate after Aerosol Released and the compartment door was closed

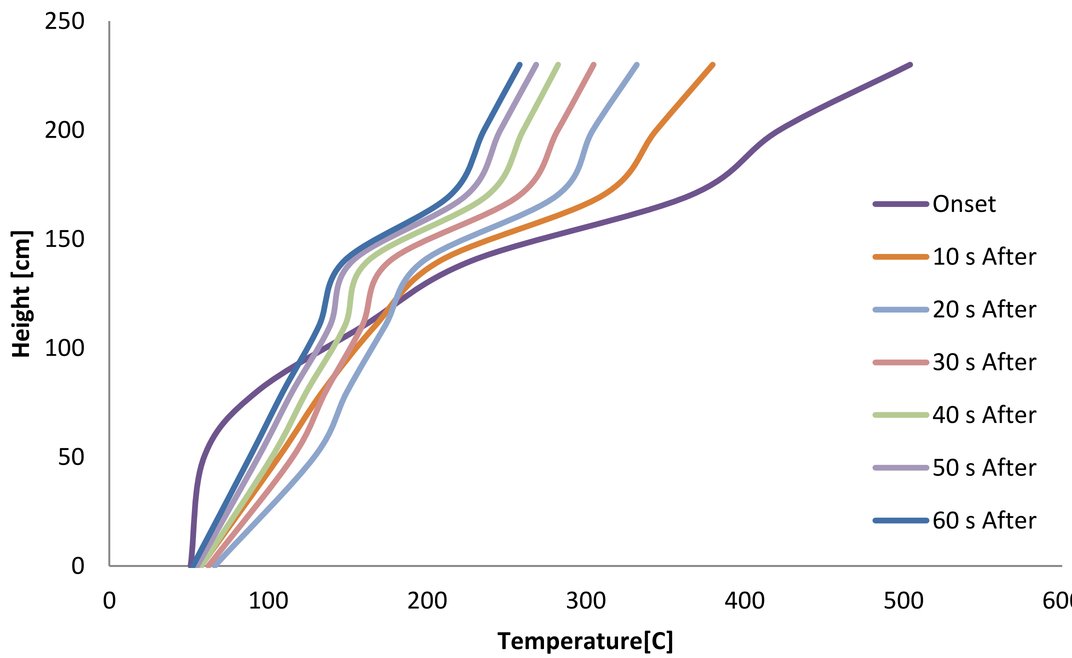


Figure 5-67. Test 4: DSPA 5-4, Suppression Effect on Average Thermal Stratification after Aerosol Released and the compartment door was closed

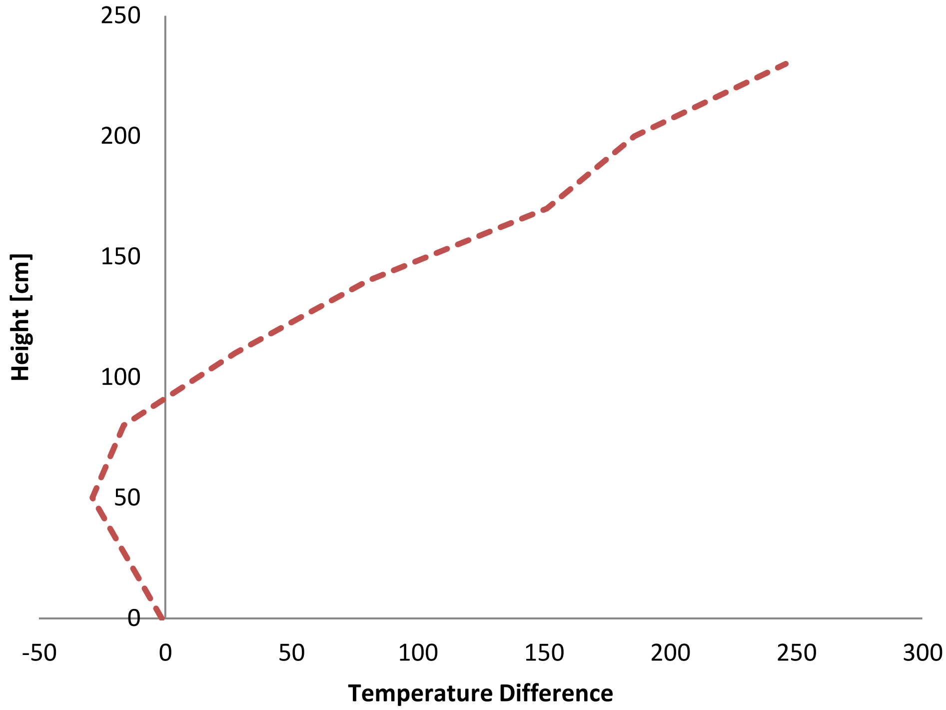


Figure 5-68. Test 4: DSPA 5-4 Average Temperature Difference Due to Aerosol Agent Suppression and closing the compartment door from the onset of suppression to 60 seconds after

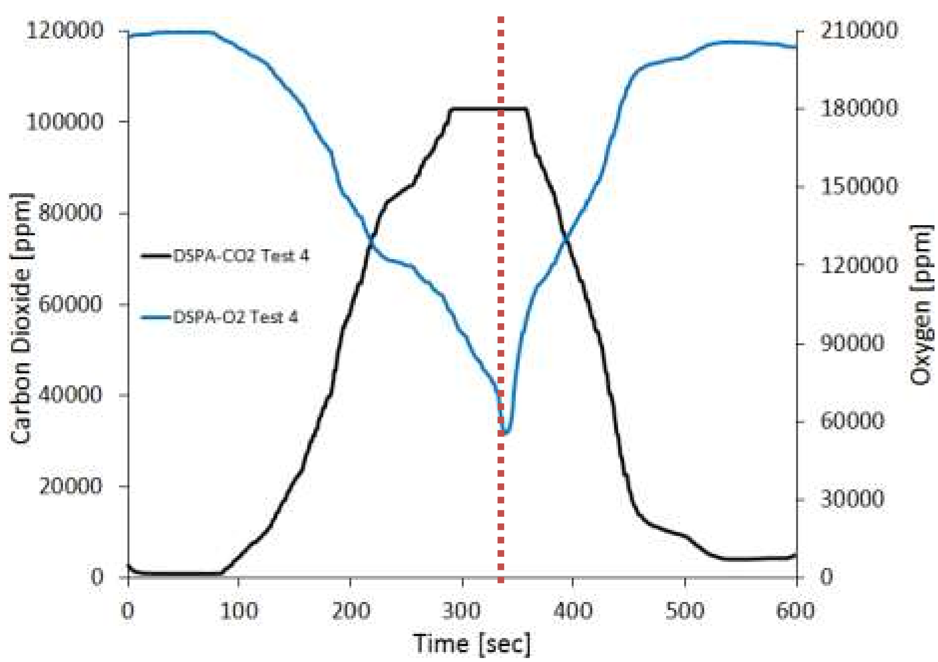


Figure 5-69. Test 4, Softwood Crib: DSPA's Carbon Dioxide and Oxygen concentrations due to Aerosol Agent Suppression and closing the compartment door

5.7.4 Summary and Discussion for Test 4: Softwood Crib Fire

The softwood crib fire suppression tests were both conducted by activating the aerosol units after the 4-6 min pre-burn time and closing the door. Comparison of these results to those measured during suppression of a softwood fire using oxygen starvation alone therefore provide an indication of the amount of cooling due to aerosol agent suppression over and above that of oxygen starvation. From the summary of results in Table 5-8 and Figure 5-70, it can be seen that suppression using StatX and DSPA aerosol units resulted in similar cooling rates, 3.4 and 3.1°C/s respectively, and total cooling of the compartment, 147 m·K and 154 m·K respectively. Use of either unit resulted in higher cooling rates and higher total cooling than using only fire confinement and suppression by closing the door. The addition of aerosol from a StatX FR unit resulted in cooling rates 38% higher and total cooling effects 31% higher than those for oxygen starvation, while aerosol from the DSPA 5-4 unit resulted in cooling rates 24% higher and total cooling effects 38% higher than for oxygen starvation. Since the door was kept closed for suppression tests with both aerosol units, these tests show the benefit of using aerosol agent when it is confined within the compartment and most effectively works to suppress the flames and lower temperatures in the fire compartment.

It is of interest to more closely examine the plots of oxygen concentration with time measured during the StatX FR and the DSPA 5-4 softwood crib suppression tests noting also that the compartment door was kept closed for two minutes after activation of each aerosol unit. In tests using the DSPA 5-4 unit, oxygen concentrations rose more quickly after activation reaching a concentration of nearly 20% just prior to opening the compartment door. At this same time after activation, the oxygen concentration was holding fairly steady at about 12% (compared to 21% in a normal atmosphere) in tests using the StatX FR unit. Although the result merits further investigation, this suggests that the DSPA unit may have had a significantly greater suppression effect on the Class A fire than the StatX FR aerosol extinguisher.

Unlike the diesel pool fires used in tests 1, 2 and 3, the softwood crib fires in Test 4 generated a great deal of heat while smoldering in an oxygen deprived environment. Compartment cooling observed when the door was closed relates to a decrease in hot gas production from the fire as it decays due lack of oxygen. At the same time, however, the heat and radiation generated from the smoldering embers can generate unburned fuel vapour in the compartment. This creates a fuel rich, oxygen deprived environment with hot embers as ignition sources and can lead to situations of rapid fire growth should oxygen be reintroduced into the compartment. The aerosol agents in both tests cooled the environment more than closing the door alone; however, the temperatures within the compartment on average were still very high (above 200°C after two minutes). Therefore, there is a very real possibility of rapid fire growth when oxygen is reintroduced and aerosol agent is vented out of the compartment. In these controlled laboratory tests, the result of opening the door was re-flash of the fire once the aerosol escaped. In larger compartments with more synthetic fuel loads, rapid fire growth in these situations could be very dangerous. For this reason, careful overhaul of a Class A fire using safe door and hatch procedures will normally be required after aerosol suppression. As an additional precaution, prediction of the potential for rapid fire growth can be facilitated if the temperature and stratification of the fire environment are known by the use of sensing equipment, such as thermocouple arrays, prior to reintroducing oxygen.

Table 5-8. Summary of Test 4: Softwood Crib Fire Suppression Results

Test	Ambient Temp [^{o}C]	Ambient RH [%]	Ambient Wind Speed* [m/s]	Ambient Wind Direction	Peak Average Temp [^{o}C]	Cooling Rate** (^{o}C/Sec)	Total Cooling Effect [m·K]
4: StatX FR	22.6	50	0.5-1.0	W	246	3.4	147
4: DSPA 5-4	24.7	50	0.5-1.0	W	235	3.1	154
Closed Door	22.6	50	0.5-1.0	W	295	2.5	112

*Note 1: Ambient wind speed taken at door of compartment between wind blocks to assess air flow at the door during suppression testing.
**Note 2: Cooling rates assessed from 60 seconds after peak average temperature.

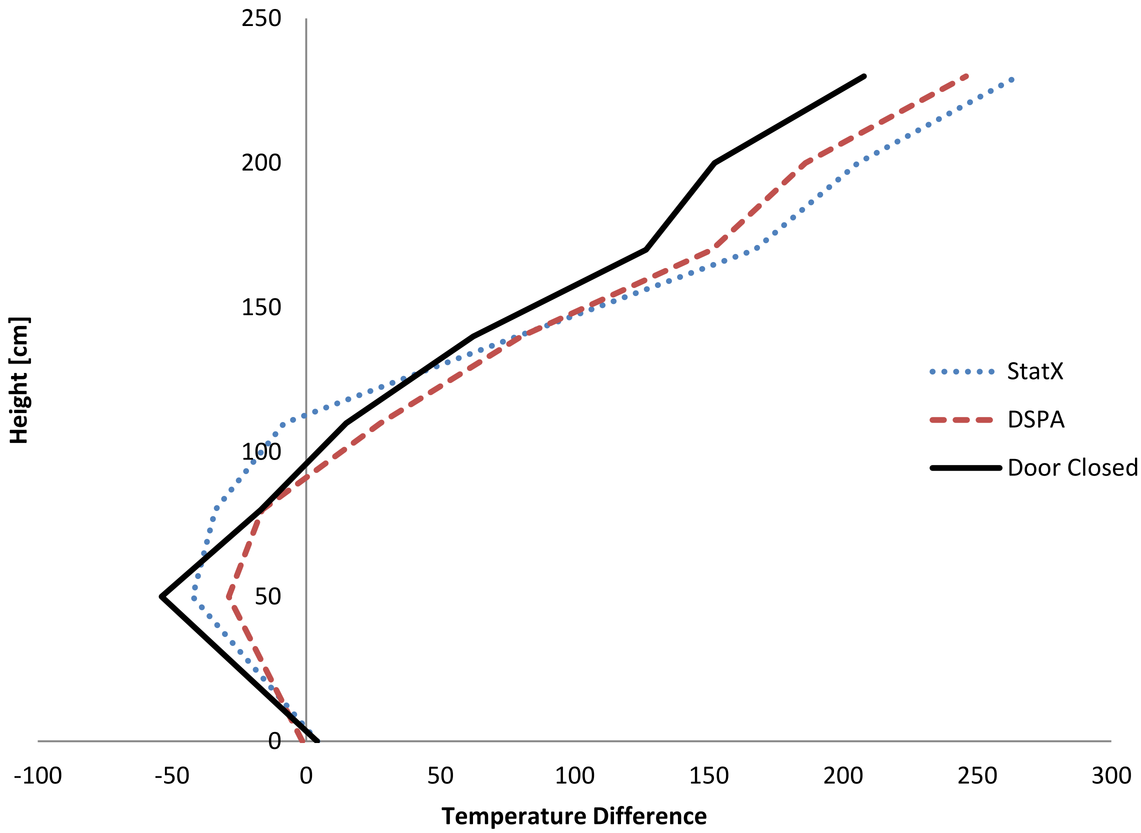


Figure 5-70. Summary of Average Compartment Temperature Difference Caused by Suppression

6 Aerosol Only Agent Analysis

Chapter 5 contained results focussed towards investigation of the effectiveness of the handheld aerosol units for suppressing fires in typical scenarios encountered on board ship. Also of interest to the use of aerosols is determination of the potential for residue, toxic gas formation or corrosion of equipment in the event of accidental discharge of an aerosol unit or after suppression of a fire. For this, it was decided to characterize the compartment environment after aerosol units have been discharged, but in the absence of a fire. This Chapter contains results of these 'aerosol agent only' tests.

In each test, an aerosol unit, either StatX FR or DSPA 5-4, was discharged into the compartment without a fire. Aerosol dispersion, particle suspension and settling characteristics and the visibility throughout the compartment were determined, while temperature and gas concentration data were collected to study heat and toxic gases that might be generated during discharge of the unit. Functioning electronic devices were placed within the compartment for several of the agent only tests to assess the possibility of aerosol powder or other residue building up on the electronics, as well as what impact that might have on the operation of the devices. Finally, a fully outfitted firefighter with SCBA was situated in the closed compartment during agent only tests to evaluate powder residue on the breathing apparatus (BA) and personal protective ensemble (PPE), as well as to conduct a series of fuel re-ignition tests using a butane lighter.

6.1 Aerosol Only Agent Analysis Technique

For these tests, a firefighter donned full breathing apparatus and protective ensemble and entered the container burn room, remaining there for the ten minute duration of the test. The firefighter activated an aerosol unit and placed it in the frame utilised for suppression testing, just inside the compartment door. He then moved to the back corner of the compartment and made regular observations regarding particle distribution, particle suspension and overall obscuration of visibility within the compartment. In order to contain the aerosol agent in the compartment, the door of the shipping container was held closed, but not locked, by safety personnel situated outside the container. The container burn room was well lit throughout the test by the use of two 500 W halogen lamps. After aerosol activation, the firefighter observed the particulate distribution within the compartment and also attempted to ignite a butane lighter at regular intervals throughout the test. All observations were relayed back via handheld radio to testing facilitators positioned outside the shipping container. After the ten minute observation period, the container door was opened and still photographs were taken immediately to record post-test aerosol residue on the electronics and on the firefighter.

For tests of possible residue deposits from the aerosol units, three to four electronic components or devices were chosen for testing and cleaned using compressed air prior to the test. Each unit was then placed on the floor of the container burn room, positioned around the location in which the aerosol unit was to be activated. The power was turned on to at least one device in each test in order to determine potential impacts of aerosol deposition on operating electronic equipment, and also since aerosol residue could be attracted differently to components with different static charges.

Temperature differences that occurred in the compartment during activation and generation of the aerosol from each unit were recorded using an IR camera situated in the burn room and the same thermocouple rakes used in the suppression tests. Gas analysis during the agent only tests was conducted by moving the gas sampling probe used in the suppression tests to a location at the front of the compartment, as shown in Figure 6-1. It was positioned to be within 30 cm of the StatX FR and the DSPA 5-4 units in order to record gas concentrations while they were generating the aerosol agent. Data acquisition was done using the same system as employed in the fire suppression tests.

Figure 6-1. UW Shipping Container Burn Room Set-up for Test 5, Agent Analysis with Front Gas Sampling Position

6.2 Aerosol Only Agent Analysis Results and Discussion

6.2.1 StatX FR Aerosol Agent Analysis Results and Discussion

The StatX FR unit was tested in the UW shipping container with the electronic devices shown in Figure 6-2. Figure 6-3 shows the location at which the aerosol units were activated, which is the same frame on the floor used for the suppression tests. The electronic devices in the burn room included a Cathode Ray Tube (CRT) monitor (powered on), an inkjet printer, and a computer tower with side panel removed. The container door was held closed while the firefighter activated the StatX FR unit from within.

Figure 6-4 shows a plot of the average compartment temperature with time during activation and generation of aerosol from the StatX FR unit. It can be seen that the compartment temperature increased by 22^{o}C and the average upper gas layer (taken at the 2.0 m horizontal plane) temperature increased by

32^{o}C as a result of activation of StatX FR unit alone. Thermocouples closest to the StatX FR unit were attached to the front two vertical rakes (V3 and V4) located 0.8 m from the unit during activation. Analysis of the temperature versus time data from those rakes, shown in Figure 6-5, revealed that the front right (V4) TC at 0.5 m was exposed to the greatest temperature increase, which peaked at 137^{o}C above ambient.

Plots of gas concentration versus time are shown in Figure 6-6. Oxygen and carbon dioxide concentrations fluctuate throughout the test, indicating relatively minor dilution of oxygen and generation of carbon dioxide local to the aerosol unit during activation. The oxygen concentration in the vicinity of the aerosol unit did not drop below 20% at any time. In the ten minutes following activation, the concentrations also varied due to the presence of a small flame that persists at the base of a StatX FR unit for several minutes after activation.

The aerosol agent filled the compartment immediately and appeared to be evenly distributed throughout. Once the StatX FR unit finished generating aerosol, the visibility in the well-lit compartment was assessed to be 25 cm. Ignition of the butane lighter was attempted every two minutes without success, meaning that the concentration of the aerosol in the compartment was sufficiently high to prevent ignition of the lighter flame. Two minutes after aerosol generation had ceased, the visibility increased to and held steady at 30 cm for the remainder of the 10 minute test. Ten minutes following unit activation, the compartment door was opened, allowing the aerosol particles to escape. As the compartment environment cleared, the firefighter remained in the back corner of the compartment continuously attempting to ignite the butane lighter as the concentration of aerosol decreased. It took 49 seconds from the time when the door was opened to the time when the butane lighter was successfully ignited.

A thin residue of aerosol particles had collected on the electronics and on the firefighter's BA and PPE during the test and was visible after the test (Figure 6-7). The computer monitor that was powered on continued to operate normally throughout and after the test.

Figure 6-2. Electronics Exposure and Compartment Setup for StatX FR Agent Analysis Test

Figure 6-3. Location of Unit Activation for StatX FR Agent Analysis Test

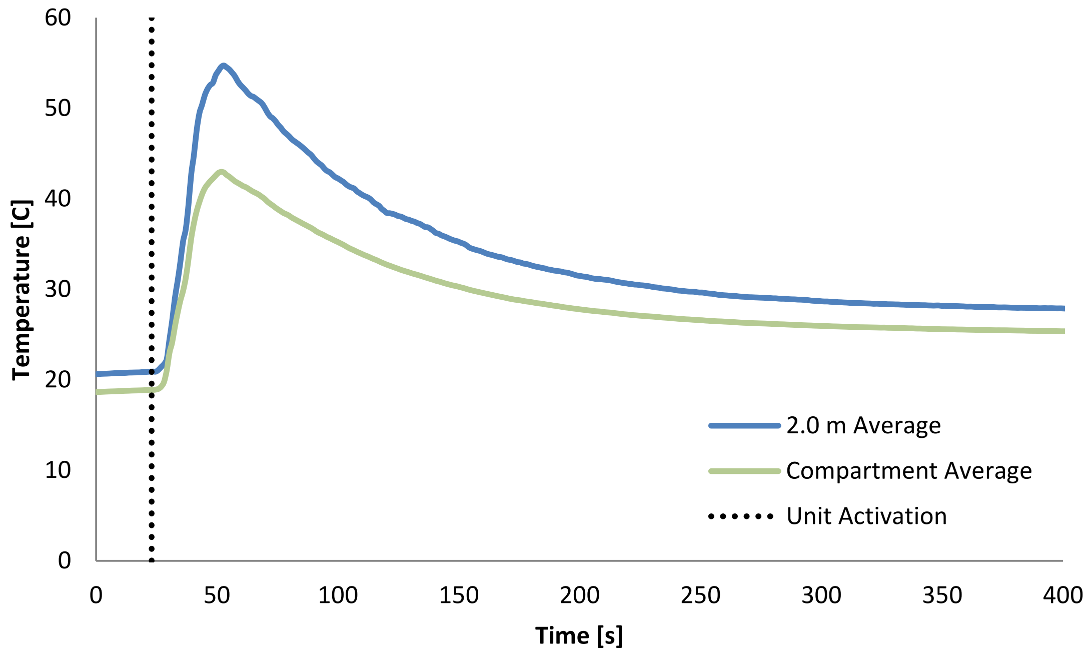


Figure 6-4. Average Upper and Average Compartment Temperature Increase due to StatX FR Unit Activation in UW Shipping Container

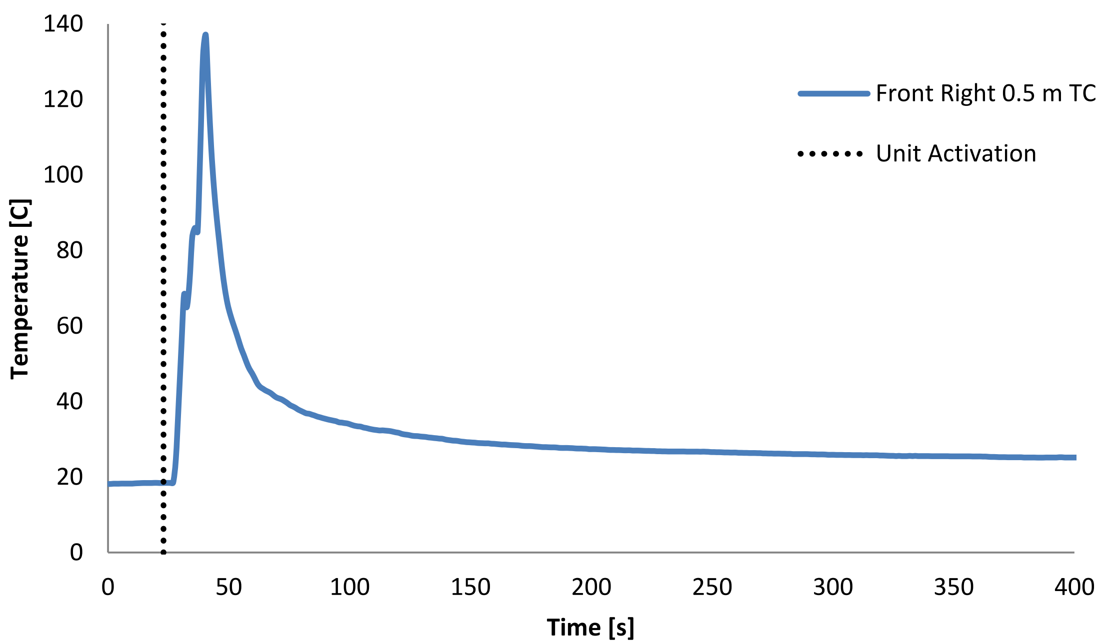


Figure 6-5. Local Temperature Increase at Front Right of UW Shipping Container due to StatX FR

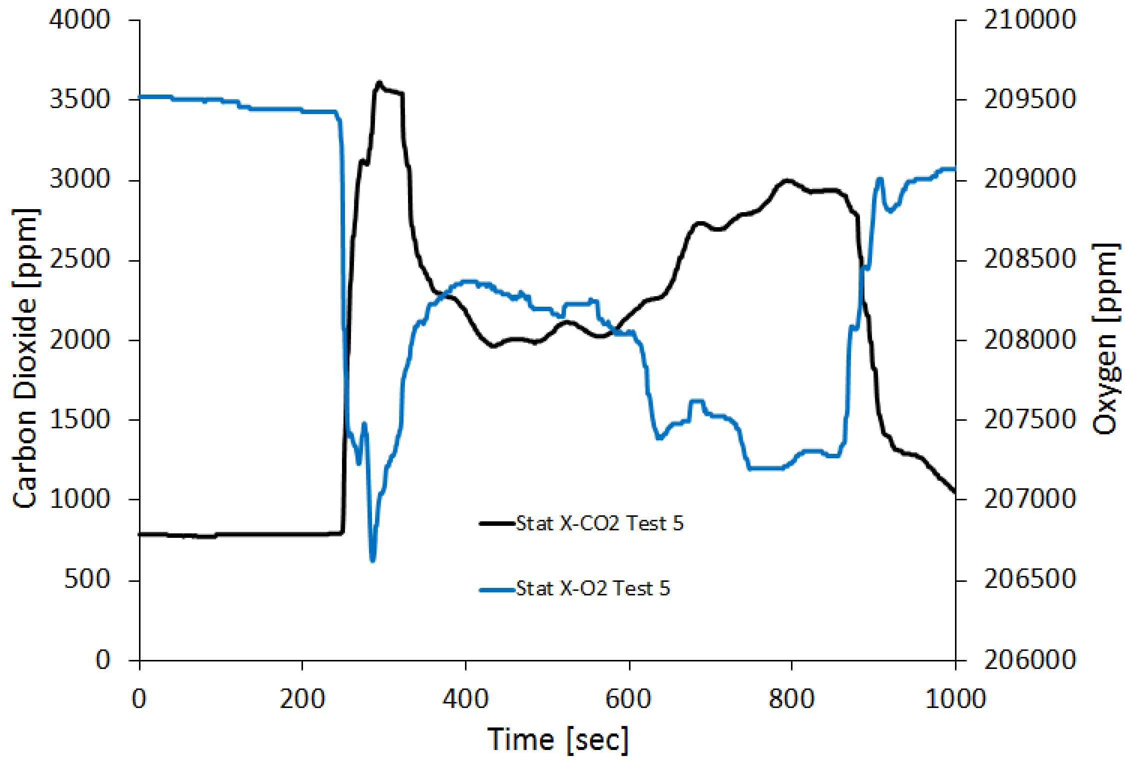


Figure 6-6. Test 5, Agent Analysis: StatX FR Local Carbon Dioxide and Oxygen concentrations

Figure 6-7. Aerosol Powder Collection on Firefighter Protective Ensemble and Breathing Apparatus

6.2.2 DSPA 5-4 Aerosol Agent Analysis Results and Discussion

The DSPA 5-4 unit was tested in the UW shipping container with the electronic devices shown in Figure 6-8. The devices included a (CRT) monitor, VCR, and a computer tower with side panel removed (powered on). The container door was held closed and the firefighter activated the DSPA 5-4 unit from within.

Figure 6-9, shows a plot of the average compartment temperature with time during activation and generation of aerosol from the DSPA 5-4 unit. It can be seen that the compartment temperature increased by 24^{o}C and the average upper gas layer (2.0 m) temperature increased by 31^{o}C as a result of activation of the DSPA 5-4 unit alone. Thermocouples closest to the DSPA 5-4 unit were attached to the front two vertical rakes (V3 and V4) located 0.8 m from the unit during activation. None of the 16 TCs on V3 and V4 measured temperatures exceeding 60^{o}C.

Plots of gas concentration versus time are shown in Figure 6-10. Oxygen and carbon dioxide concentrations fluctuate throughout the test, indicating relatively minor dilution of oxygen and generation of carbon dioxide local to the aerosol unit during activation. The oxygen concentration in the vicinity of the aerosol unit dropped below 20% for an instant before climbing to and holding steady at 20.7% as the door was opened. In general and as expected, measured values of carbon dioxide concentration followed the inverse trends.

The aerosol agent filled the compartment immediately and appeared to be evenly distributed throughout. Once the DSPA 5-4 unit finished generating aerosol the visibility in the well-lit compartment was assessed to be 15 cm. Ignition of the butane was attempted every two minutes without success, meaning that the concentration of the aerosol in the compartment was sufficiently high to prevent ignition. Two minutes after aerosol generation had ceased, the visibility increased to and held steady at 25 cm for the remainder of the 10 minute test. Ten minutes following unit activation, the compartment door was opened, allowing the aerosol agent to escape. The firefighter remained in the back corner of the compartment continuously attempting to ignite the butane lighter as the concentration of aerosol decreased. It took 85 seconds from the time when the door was opened to the time when the butane was successfully ignited.

A thin residue of aerosol particles collected on the electronics and the firefighter's BA and PPE during the test (Figure 6-11). The open VCR positioned 60 cm away from the DSPA 5-4 was spattered with carbon slag as shown in Figure 6-12. The computer tower that was powered on continued to operate normally throughout and after the test.

Figure 6-8. Electronics Exposure and Compartment Setup for DSPA 5-4 Agent Analysis Test

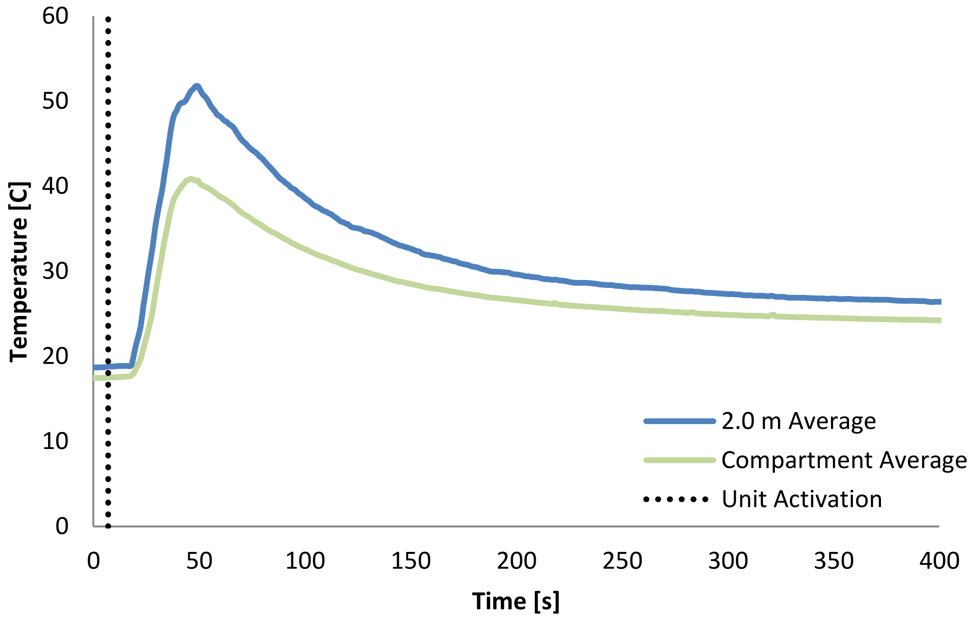


Figure 6-9. Average Upper and Average Compartment Temperature Increase due to DSPA 5-4 Unit Activation in UW Shipping Container

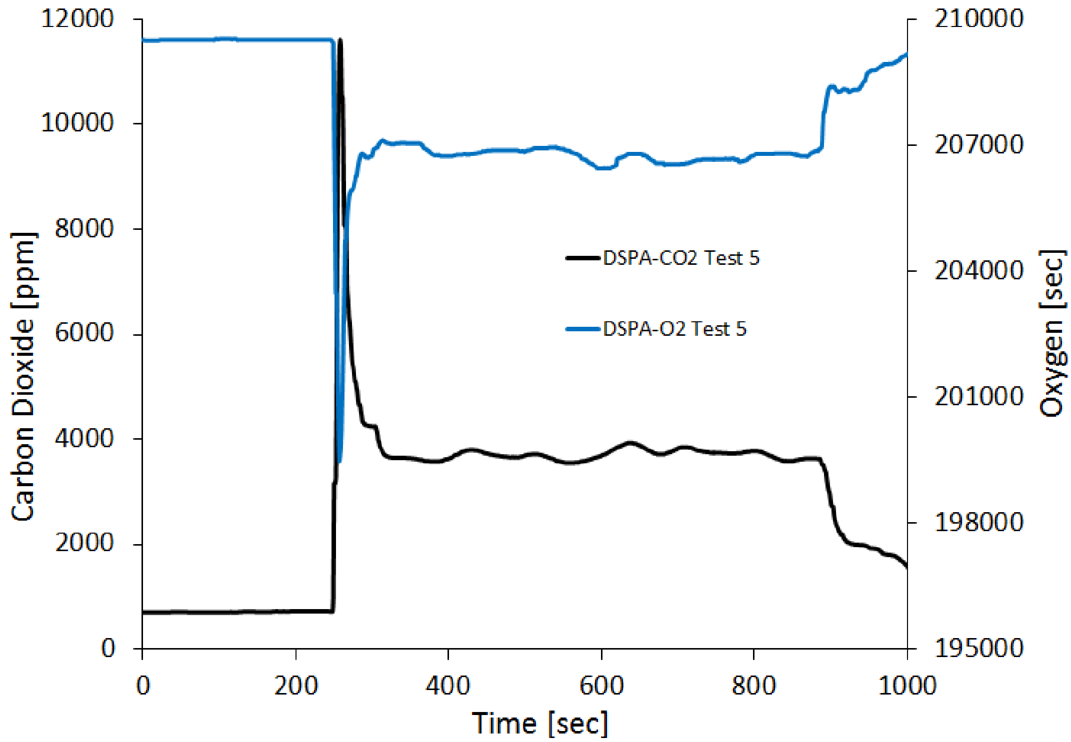


Figure 6-10. Test 5, Agent Analysis: DSPA 5-4 Local Carbon Dioxide and Oxygen concentrations

Figure 6-11. Aerosol Powder Collection on Firefighter Protective Ensemble and Breathing Apparatus

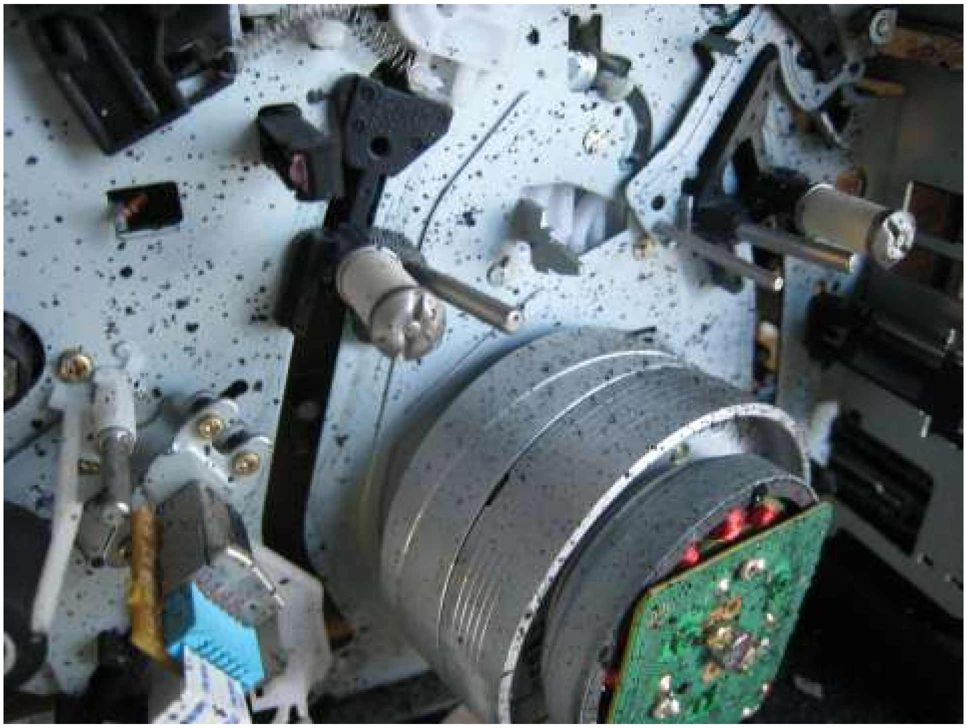


Figure 6-12. Slag Distribution on VCR from DSPA 5-4 Activation 60 cm Away

6.3 Summary and Discussion of Aerosol Agent Analysis Tests

The agent analysis tests for both the StatX FR and the DSPA 5-4 allowed for qualitative and quantitative assessment of aerosol distribution throughout the compartment and potential impact of aerosol generation, discharge and residue on the surroundings if a handheld unit were to be employed in a marine compartment with electronics. Both units were almost identical in all aspects measured; generating an even cloud of aerosol agent that quickly filled the compartment and raised the average temperature by about 20°C above ambient. The agent behaves very much like thick smoke in the confined compartment, reducing visibility down to 25-30 cm in a well-lit compartment. The powder residue on the electronic devices within the compartment was visible with the human eye and could be wiped away with a cloth; however, it is clear that any devices that are in a room during aerosol activation would experience some deposition of powder on their exposed surfaces. On more complex equipment with dozens of circuit boards and micro-processors, the residue removal and component cleaning process could be costly and time consuming. Any other immediate and/or longer-term corrosive effects of aerosol deposition on surfaces, with and without water present, should be analysed further in future work.

The StatX FR units produce a small flame for several minutes after aerosol activation, which may lead to the slightly lower local oxygen concentrations measured during the ten minutes after StatX activation in contrast to the DSPA 5-4 activation. There was a relatively minor dilution of oxygen concentration in the vicinity of the units and an equally minor production of carbon dioxide during activation. The concentration of oxygen did not drop below 18%, the minimum concentration to support human life [71], for any instant in either test. Carbon dioxide concentrations remained below 0.4% with the exception of an instantaneous spike to 1.2% after activation of the DSPA 5-4 unit. Normal atmospheric concentration of carbon dioxide is between 0.036% and 0.039% depending on global location [72]. As an asphyxiant gas, carbon dioxide can cause drowsiness with continuous exposure in concentrations of 1%, but generally will not cause suffocation and unconsciousness until concentrations reach 10% [73].

Both StatX FR and DSPA 5-4 units generated sufficiently large quantities of aerosol and distributed them throughout the compartment appropriately to successfully prevent ignition of a butane lighter throughout the 10 minute test. In both cases, even after the compartment door was opened and much of the aerosol escaped, ignition did not occur for approximately one minute. This suggests that, as long as a compartment is confined, aerosol agents will remain suspended and inhibit re-ignition of unburned fuel for many minutes after activation of a handheld unit. In a compartment larger than the rated volume, or where the ventilation cannot be controlled, the concentration of aerosol agent may drop below that required for suppression and inhibition of re-ignition. Additional aerosol agent analysis tests would have to be conducted to investigate these latter situations.

7 Safe Storage Tests

One known issue surrounding the use of pyrotechnically generated aerosol extinguishers in the RCN is that their formal classification as pyrotechnic devices. Under this classification, the only way aerosol extinguishers may be brought onboard naval vessels is if they are stored and secured in upper deck lockers. This will obviously make them ineffective as first response extinguishers simply due to the time required to draw them from these strictly controlled lockers. The reality is that they will need to be exempted or declassified as pyrotechnics before they can be effectively employed onboard ship regardless of their efficacy in suppressing marine fires.

Safe storage testing of pyrotechnically generated aerosol units such as the StatX FR and DSPA 5-4 was deemed necessary to provide estimates of the potential consequences should a unit activate while in its supplied storage case. This testing is not intended to determine the probability of such an event, but instead was designed to better understand the potential consequences of such an event and guide development of simple and low cost mitigating strategies for the safe storage of aerosol units in readily available locations throughout naval warships.

To quantitatively assess potential consequences, then, several instrumented tests were conducted. Both variants of aerosol extinguishers were activated whilst stored in their storage cases and measurements were made of the temperatures internal to the case, the radius of hot gases being expelled from the case, and the overall reaction of the storage cases to such an event.

7.1 Safe Storage Test Plan Development

An initial test was conducted using one StatX FR unit enclosed in a small Pelican case to establish parameters for the safe storage tests. One Type K thermocouple was installed in the case as shown in Figure 7-1. The StatX FR unit was activated, placed in the case as it would be when stored and the case was closed. The test was recorded using a colour video and a thermal imaging camera. As seen in Figure 7-2, the internal temperature of the case as measured by the thermocouple rose quickly to 780^{o}C and remained above 600^{o}C for 30 seconds. From the thermal imaging camera, a screen capture of which is shown in Figure 7-3, most of the hot gases generated within the case were expelled through the two sides of the case rather than from the front and back. An estimate of temperature was made using the IR camera data and suggested that the hot gases being expelled were at temperatures of approximately 300^{o}C to a radius of 0.6 m around the case. Figure 7-4 shows the Pelican case after the test. The internal foam packing has burned and the case is melted through at the side seals and on the bottom.

Figure 7-1. StatX Safe Storage Preliminary Test Rig

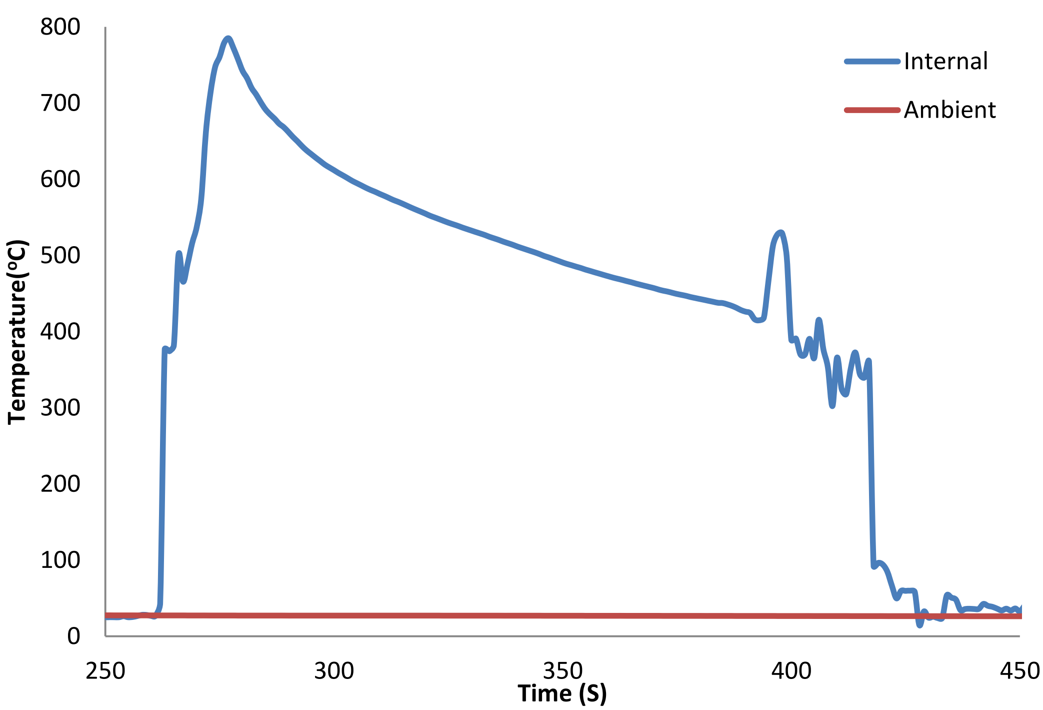


Figure 7-2. Internal Temperature Profile of StatX FR Unit Activation in Closed Pelican Case

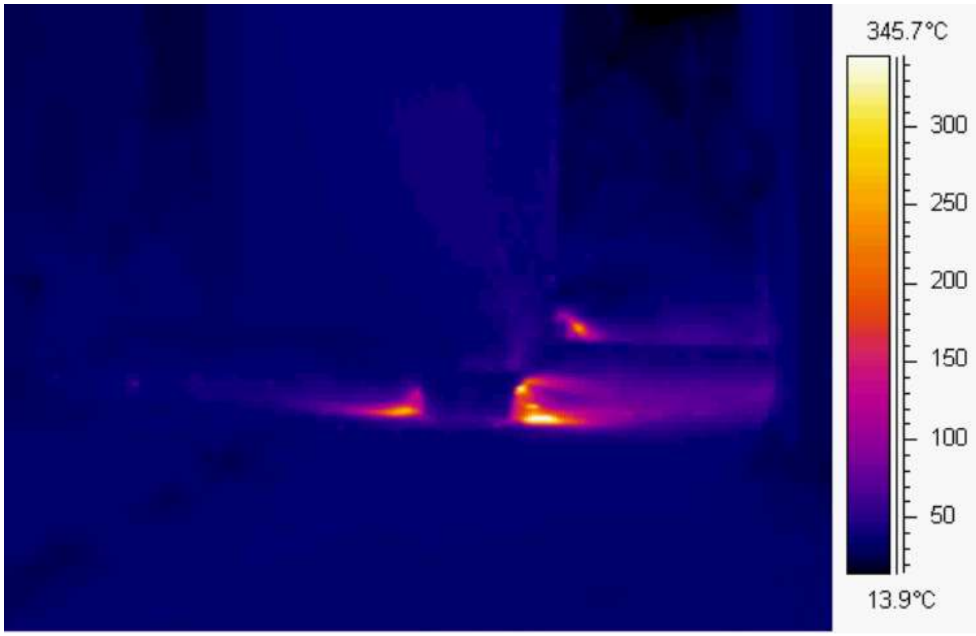


Figure 7-3. Infra-Red Thermography Screen Capture of Hot Gases Exiting StatX FR Pelican Case

Figure 7-4. StatX FR Pelican Case Following Enclosed Unit Activation

7.2 Safe Storage Test Rig Design and Development

A general appreciation for what might happen when a unit is activated within a closed Pelican case was understood from the results of the preliminary StatX FR safe storage test outlined above. Based on this information, a test rig was designed and built for further experimentation. This rig is shown in Figure 7-5. Two, 2 m lengths of uni-strut were joined at right angles and 8 evenly spaced Type K thermocouples were suspended 20 cm above the test bed floor, to allow assessment of the hot gas distribution in a radius around a burning storage container. In addition, two thermocouples were added to measure internal temperatures at the right and left sides of the storage case and two additional thermocouples were located just outside the side seals of the storage case to measure the temperatures of hot gases being expelled from the case during testing. In these second tests, two StatX FR units were placed in the storage case (Figure 7-6) but only one was activated before the case was closed and centred under the TC rakes. In another test one DSPA unit was placed in its storage container, centred on the test rig and activated remotely with the case already closed (Figure 7-7). More details of the thermocouple locations and data file names can be found in Appendix D.

Figure 7-5. Safe Storage and Incendiary Potential Test Rig

Figure 7-6. StatX FR Safe Storage Test Setup

Figure 7-7. DSPA Safe Storage Test Setup

7.3 Measurements and Data Collection

Temperature data from all 20 thermocouples was recorded via the National Instruments Field Point data logger to a custom Labview program at a sampling rate of 1.125 per second. Colour video and infra-red thermography were also recorded throughout the tests.

7.4 Safe Storage Tests Results and Discussion

7.4.1 StatX FR Safe Storage Test Results and Discussion

The StatX FR units are normally stored with two units in each case as shown in Figure 7-6. For this test, it was decided to activate one of the two units before closing the case and centering it under the TC rakes of the test rig. This allowed assessment of the potential domino effect arising from activation of one unit when a second unit was stored in the same storage case.

The left unit in the StatX FR case activated quickly (3.5-5 seconds) and the case was closed and locked just before the generator began producing aerosol. The case was centred under the thermocouple rakes with the seal thermocouples positioned just outside either edge. The case was kept closed during activation and was opened about one minute after. The test results below show the temperatures while the case was closed as well as when it was re-opened.

7.4.1.1 StatX FR Internal Case Temperatures

Figure 7-8 below shows the internal case temperature profiles generated by activation of the left StatX FR unit in the two-unit yellow case provided by the manufacturer. The left thermocouple was closest to the activated FR unit and it recorded temperatures that exceeded 700^{o}C in three seconds after activation, with a peak temperature of 852^{o}C reached after about 7 seconds. The right thermocouple registered a peak temperature of 607^{o}C in seven seconds similar to the timing seem for the left thermocouple. The thermocouple on the right side of the case recorded lower temperatures throughout the test, however, as it was insulated from the activated unit by foam and the second un-activated FR unit.

7.4.1.2 StatX FR Edge Seal Temperatures

The two thermocouples located just outside the left and right edge seals of the closed storage case measure temperatures representative of the hot gases escaping during unit activation. As seen in Figure 7-9, the temperature at the left seal, i.e. that side on which the FR unit was activated, reached a peak temperature of 459^{o}C in four seconds and remained above 100^{o}C for 17 seconds. Much less gas was expelled through the right hand seal and hot gas temperatures on that side of the case stayed below 50^{o}C throughout activation.

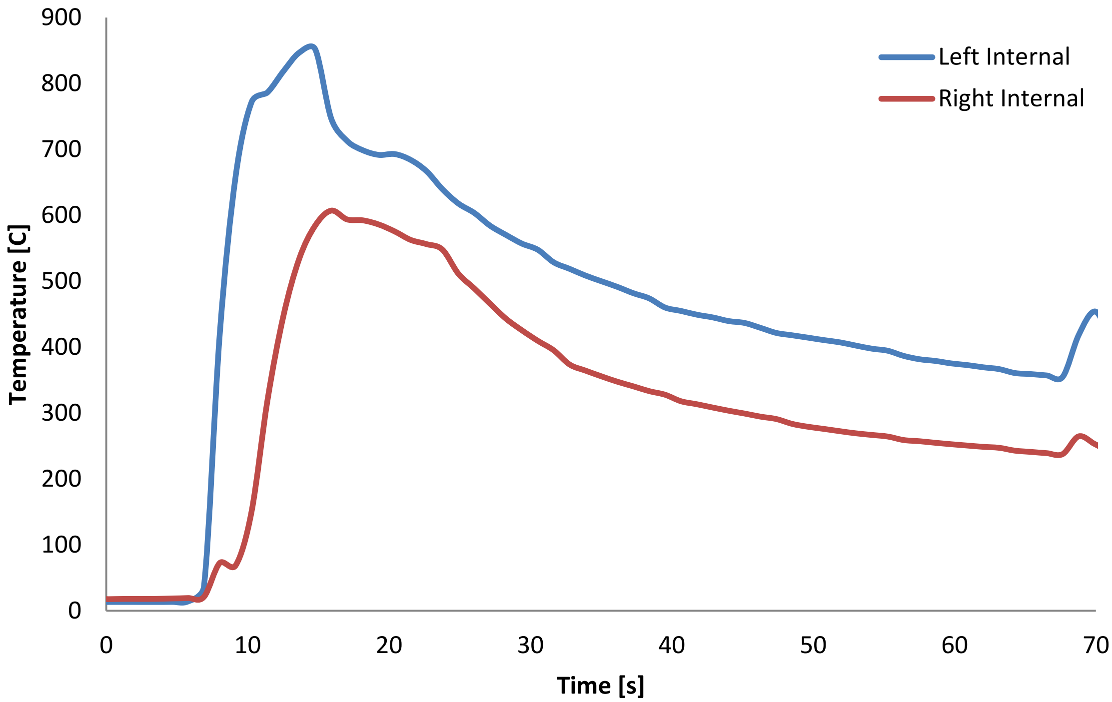


Figure 7-8. StatX Safe Storage Test Internal Case Temperatures During One-Unit Activation

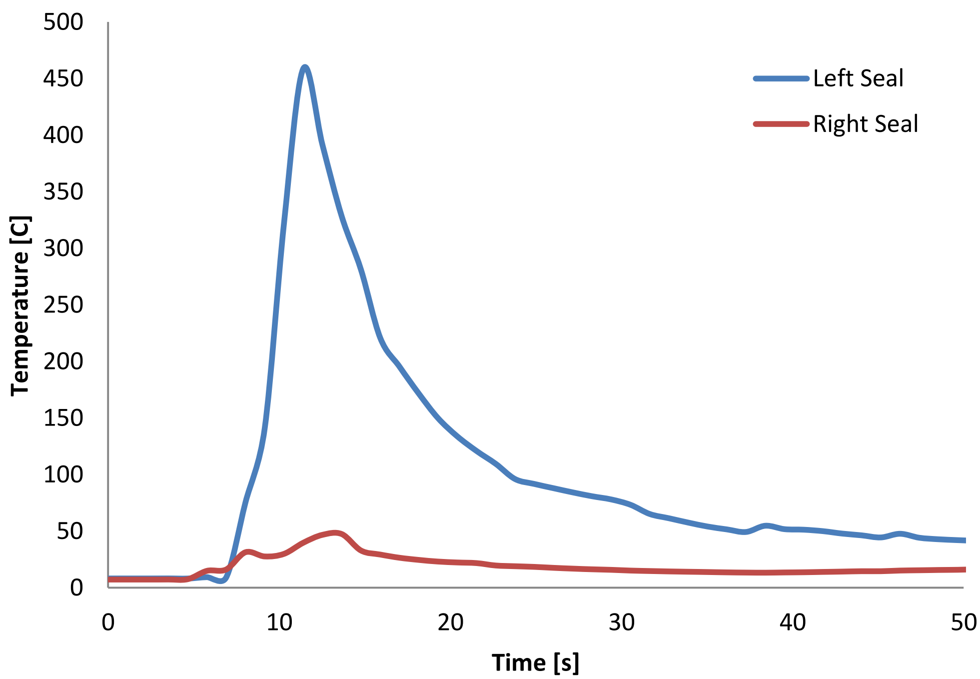


Figure 7-9. StatX FR Safe Storage Test Edge Seal External Temperatures for One-Unit Activation

7.4.1.3 StatX FR Radius of Heat Produced

On the purpose-built test rig utilized for the safe storage testing, four sets of four thermocouples were spaced at equal distances from the centre in each direction. An average of each set of four temperatures measured at the same distance from the centre of the rig provides data on the heat issued from the storage containers at radii of 0.127 m, 0.381 m, 0.635 m, and 0.787 m.

Figure 7-10 shows the average temperature profiles measured with time at each of the four radii around the storage case during the activation of one enclosed StatX FR unit. The temperature increases are due to hot gases being expelled from the closed case. None of the average temperatures measured at any radius from the case exceeded 35°C. The gradual temperature increase at the 0.127 m away from the case is due to heat transfer from the top of the storage case which is located only 3 cm below the four respective thermocouples on that radius. These results show that, on average, there is little heat distributed around the case during activation of an enclosed aerosol unit. However, since temperatures near the left seal of the case, plotted in Figure 7-9, exceeded 450°C, it was decided to look at the other thermocouples on that rake to estimate the heat that might have been directed along that axis. Figure 7-11 shows temperature time traces measured by the left seal thermocouple, at 0.220 m, as well as by the other four thermocouples on the rake to the left of the unit. This plot reveals that the highest temperature registered by the four other thermocouples is at 0.381 m, which peaks at 106°C or 350°C cooler than the peak temperature measured at the left seal (0.220 m). Moving away from the case in the same direction, all the temperatures remain below 45°C. The rapid temperature drop is due in part to the fact that the hot gases being expelled from the case are rising above the horizontal rake of thermocouples, confirmed by analysis of the IR thermography footage. Modifications to the present rig would be required to better investigate heat generated during accidental discharge of a stored aerosol unit.

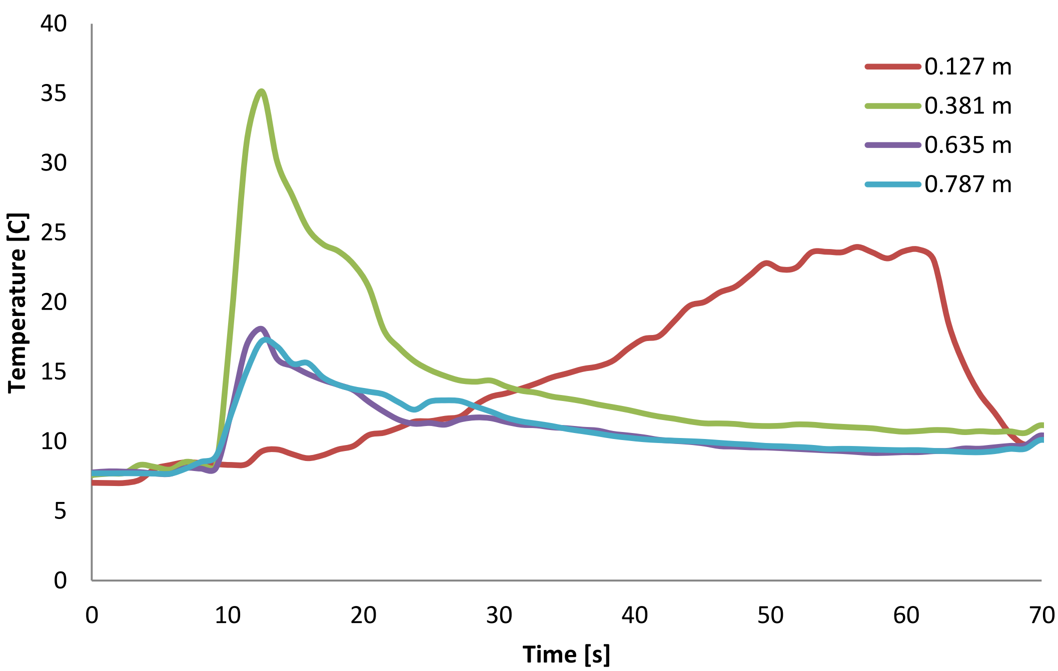


Figure 7-10. Radius of Heat Generated from StatX FR Enclosed Activation

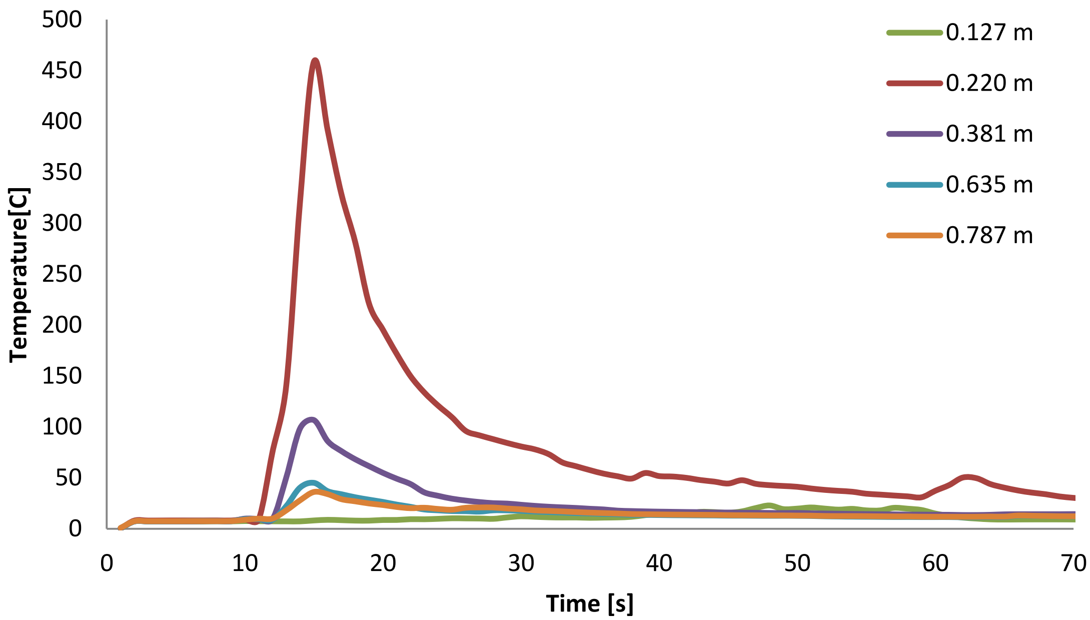


Figure 7-11. StatX FR Temperature Profile in Direction of Hot Gas Blowout

7.4.1.4 StatX FR Second Unit Auto-Activation in Fire

The StatX FR safe storage test consisted of activating only one of the two units stored in the manufacturer supplied storage case. During activation, temperatures internal to the case exceeded 800°C but the second stored aerosol unit did not activate. The case was opened about 1 minute after the start of the safe storage test and melted foam inside the case ignited, such that flames engulfed the second stored but un-activated FR unit. Figure 7-12 shows the internal case temperatures as a function of time including the initial activation of one unit in the storage case, through to when the case was opened, and finally to the time at which the second unit self-activated due to direct flame impingement. Looking only at the period of time when the case was open, the second unit was exposed to temperatures in excess of 600°C for 90 seconds before it activated. Once activated, the temperature on the right side of the case, where the second unit was located, increased rapidly to a peak of over 1300°C. Video and IR thermography of activation of the second unit reveal that the aerosol generation and dispersion from an auto-ignited StatX FR unit differs considerably from one that is activated normally using the internal fuse. The cloud of aerosol produced upon accidental activation of the unit was not as dense and did not remain suspended in the air to same extent as that generated under normal activation of the unit.

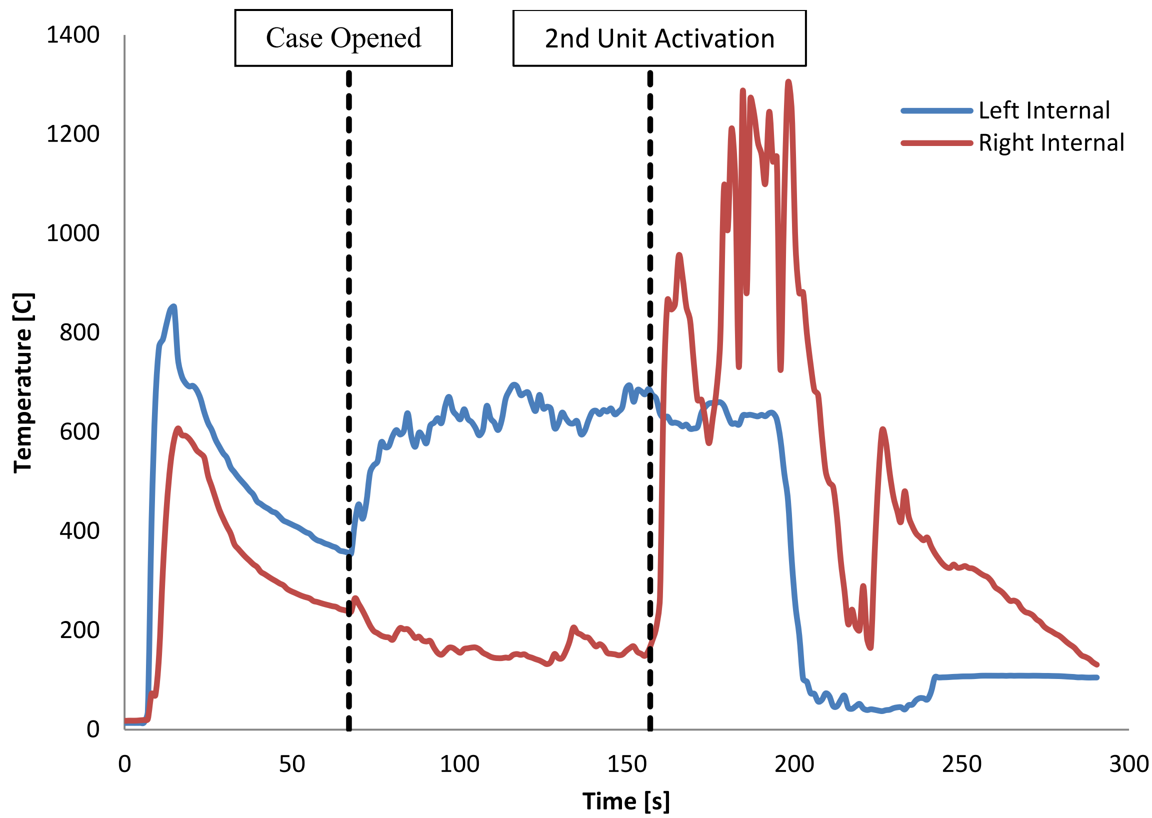


Figure 7-12. Auto Ignition of Second StatX FR Unit Engulfed in Flame

7.4.2 DSPA 5-4 Safe Storage Test Results and Discussion

The DSPA 5-4 is normally stored in a commercial-off-the-shelf (COTS) Pelican case as shown in Figure 7-7. This is the same size Pelican case that the manufacturer recommends for the larger DSPA 5 unit, which is an aerosol suppression unit designed to protect compartments up to 60 m^3. The version of aerosol extinguisher used in this test is the DSPA 11-4, which is the fitted version of the DSPA 5-4 but has the same active agent and the same quantity of agent as does the DSPA 5-4. Using the DSPA 11-4 allowed for remote activation of the unit using a DC current while keeping the storage case closed and centered under the thermocouple rakes on the test rig. Temperature data was recorded within the case, directly external to the side seals of the case, and on the uniform grid of thermocouples located on the Uni-Strut rakes described above. Colour and IR video were also recorded.

The case was kept closed during activation of the DSPA unit and for about one minute thereafter. The test results below show temperatures while the case was closed, as well as when it was re-opened.

7.4.2.1 DSPA 5-4 Internal Case Temperatures

Figure 7-13 shows the internal case temperature versus time profile resulting from remote activation of the DSPA unit in the COTS Pelican case provided by the manufacturer. The unit was centered in the Pelican case, being equidistant from the left and right internal thermocouples. The left thermocouple recorded temperatures that exceeded 700°C in 6 seconds with a peak of 794°C at about 12 seconds after activation. The right TC exceeded 700°C in 8 seconds and peaked at 821°C in 15 seconds. The average internal case temperature remained above 700°C for 17 seconds before cooling rapidly as the unit stopped generating aerosol.

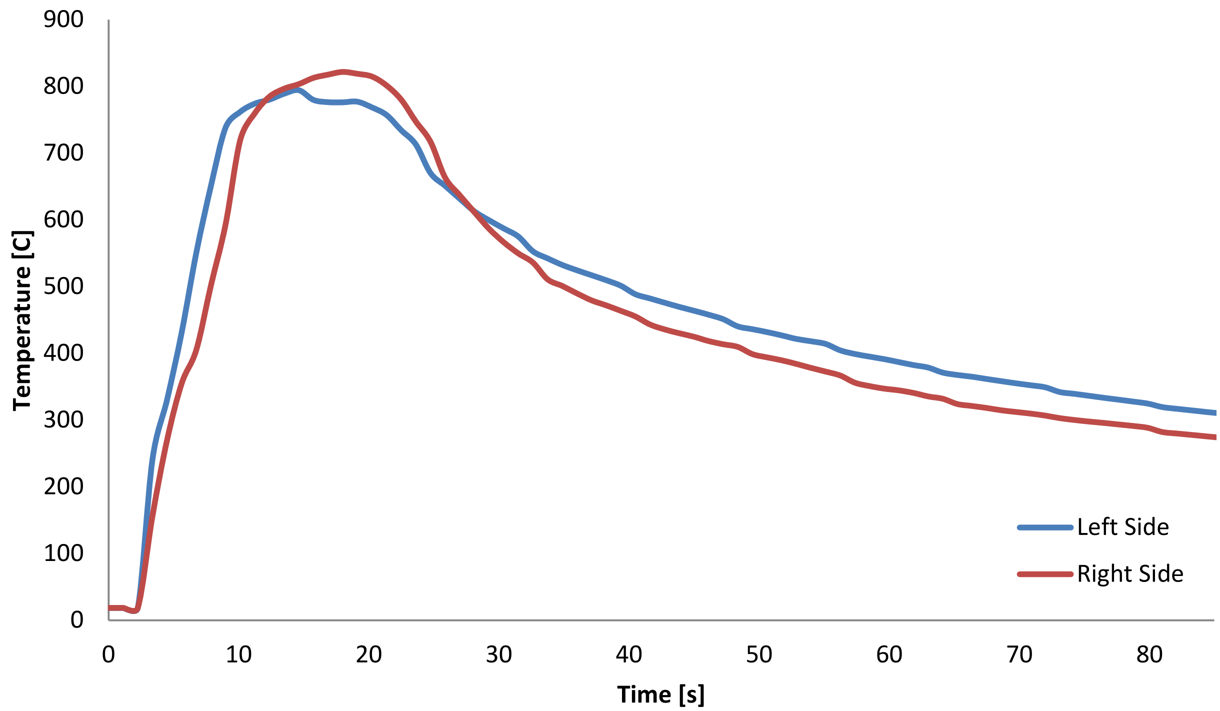


Figure 7-13. DSPA 5-4 Safe Storage Test Internal Case Temperatures during Unit Activation

7.4.2.2 DSPA 5-4 Edge Seal Temperatures

The two thermocouples located just outside the left and right edge seals of the closed storage case measure temperatures representative of the hot gases that are expanding and escaping from the case during activation of the unit. As seen in Figure 7-14, the temperature at the right seal reached a peak of 328°C in nine seconds and remained above 100°C for 52 seconds. Much less hot gas was expelled through the left seal. The temperatures at that seal did, however, rise above 100°C in eight seconds and remained above 100°C for 16 seconds.

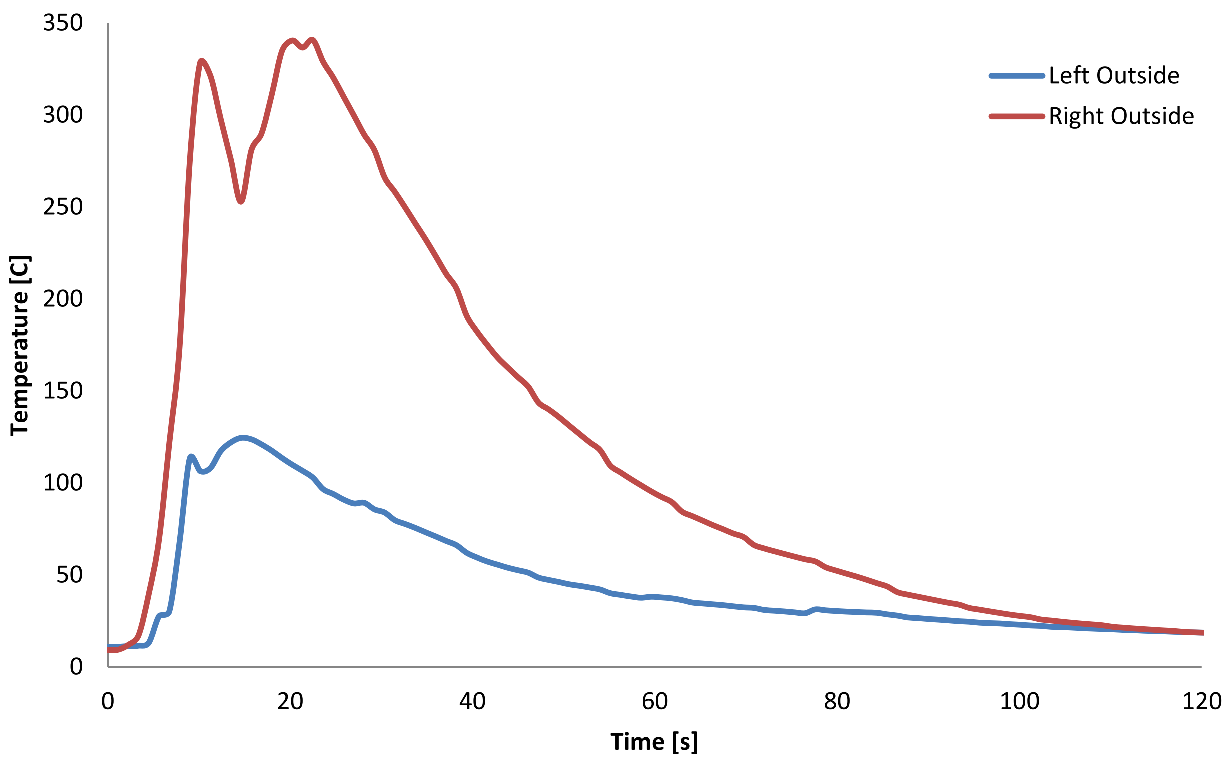


Figure 7-14. DSPA 5-4 Safe Storage Test Edge Seal Temperatures during Unit Activation

7.4.2.3 DSPA 5-4 Radius of Heat Produced

The same test rig utilized for the safe storage testing of the StatX FR units was used in this test. An average of each set of four temperatures corresponding to the same distance from the centre of the rig again provided data on the heat issued from the storage containers at radii of 0.127 m, 0.381 m, 0.635 m, and 0.787 m in four directions.

Figure 7-15 shows the average temperature profiles measured with time at each of the four radii around the storage case during activation of one enclosed DSPA 11-4 unit. The temperature increases are due to hot gases being expelled from the closed case. None of the average temperatures measured at any radius from the case exceeded 26^{o}C. The gradual temperature increase at the 0.127 m away from the case is due to heat transfer from the top of the storage case which is located only 3 cm below the four respective thermocouples on that radius. These results show that, on average, there is little heat distributed around the case during activation of an enclosed DSPA 11-4 aerosol unit. However, since temperatures near the right seal, plotted in Figure 7-14, exceeded 336^{o}C, it was decided to look at the other thermocouples on that rake to estimate the heat that might have been directed along that axis. Figure 7-16 shows temperature time traces measured by the four thermocouples on the rake situated on the right side of the case. The right seal temperature, at 0.220 m, is omitted from this plot. From Figure 7-16, it is clear the temperatures measured along this rake, which is aligned in the direction along which hot gases are issuing from the case, were not much higher than average temperatures seen in the other directions and shown in Figure 7-15. The temperatures at all four distances from the centre remained below 40^{o}C, indicating that the right seal temperature is by far the highest and locations beyond the seal remained relatively cool. It must also be mentioned, however, that the rapid temperature drop is due in part to the fact that the hot gases being expelled from the case are rising above the horizontal rake of thermocouples along a given axis so the highest temperatures at positions away from the case seals may not have been captured in these results.

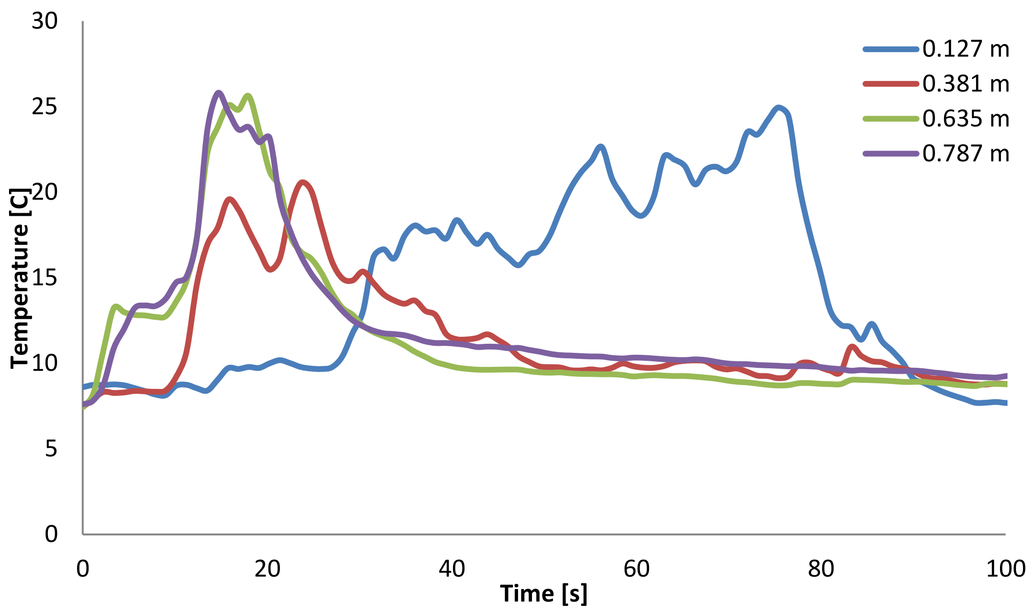


Figure 7-15. Radius of Heat Generated from DSPA 5-4 Enclosed Activation

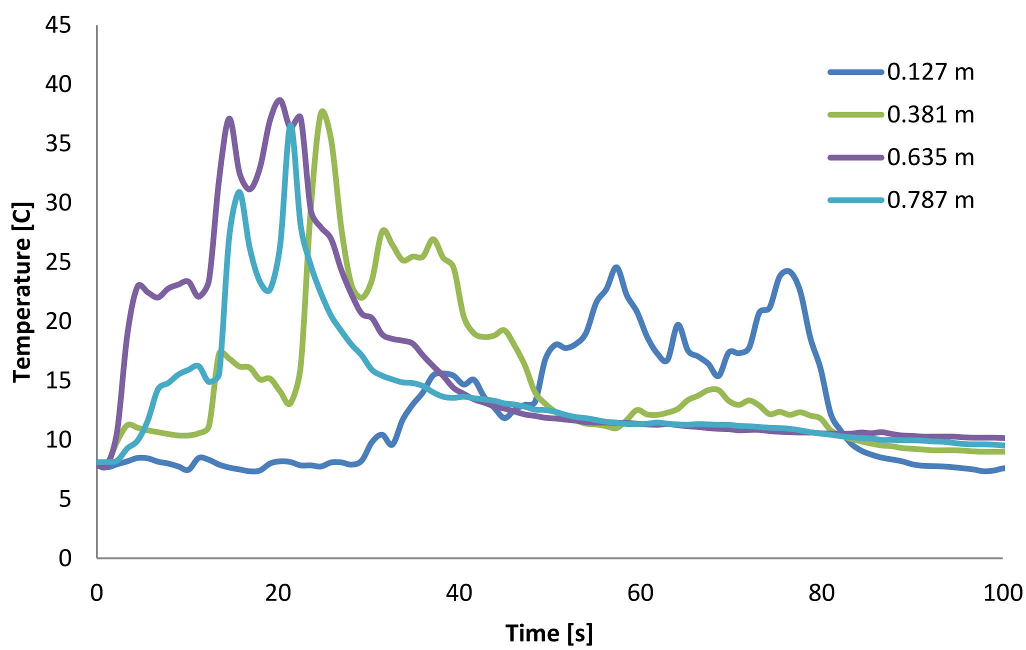


Figure 7-16. DSPA 5-4 Temperature Profile in Direction of Hot Gas Blowout

7.4.3 Safe Storage Testing Summary of Results

The safe storage tests conducted in this study provided a quantitative measure of the consequence of an aerosol unit activating inside its manufacturer-supplied case. Results reveal that internal case temperatures during inadvertent unit activation can exceed 800°C for several seconds and that the temperatures of hot gases which expand and escape from the side seals of the cases can exceed 400°C.

The tests indicated that the storage cases were able to contain most of the heat generated during inadvertent activation of either aerosol unit; however, temperatures in the ranges measured during these tests need to be respected. By means of comparison, structural steel has an annealing temperature of approximately 740°C and a melting point of approximately 1400°C depending on the percentage of carbon [70]. Although the temperatures reported here are well below the melting point of structural steel, they are above the annealing point, which is the point where yield and tensile strengths are reduced significantly. Given the short exposure times expected during inadvertent activation of an aerosol unit this may not pose a significant risk, but it is a situation that should certainly be considered during future deliberations on the use and safe storage of aerosol extinguishers on board vessels.

As shown in Figure 7-17 and Figure 7-18, activation of aerosol extinguishers within their storage cases led to melting and burning of the foam packing. In most cases, this also caused the storage cases to melt in several locations. Under the correct circumstances, this could potentially lead to ignition or burning of adjacent flammables. While the temperatures at the edge seals were shown to exceed 400°C, they decreased rapidly with distance from the storage case. Additionally, the fire suppression agent is carried with the hot gas, which works to decrease the risk of igniting adjacent fuel sources, especially if onboard racks are built to absorb/deflect any hot gases that might issue from the edge seals in the unlikely case of an accidental release of an aerosol generator while in storage. Both cases were opened approximately one minute after the aerosol units ceased generating their suppression agent. The DSPA case did not ignite into flames at this point, while the StatX case did ignite. StatX FR units continue to produce a small flame for 1-3 minutes after activation, which produced a piloted ignition source for the already molten foam and plastic of the storage case, causing their vapours to burn once oxygen was introduced.

The storage of more than one unit in each case brings with it a higher level of consequence than storage of single units in each case, since auto-activation of a second stored unit by heat exposure can occur unexpectedly. As shown by the StatX FR safe storage test, an accidental or an unplanned activation of a second unit can produce local temperatures that exceed 1300°C. This should be considered a significant risk to personnel and equipment. As such, un-activated aerosol units that might be exposed to heat present an added variable and risk that needs to be appreciated and accounted for in any fire scenario. The situation can be fairly easily mitigated using a relatively small amount of cooling water, for example, but nonetheless the potential scenario should be considered in the siting of unit storage areas and final development of SOPs. Other scenarios where auto-activation could be a concern are dud fuses, or fires in compartments with aerosol generators stored or fitted. While auto-activation of the aerosol generator does supply fire suppression agent to a compartment, it is still an uncontrolled and unexpected release of significant heat that can pose a hazard to personnel and equipment that are in the vicinity.

Figure 7-17. StatX FR Safe Storage Test Case after Unit Activation

Figure 7-18. DSPA 5-4 Safe Storage Test Case after Unit Activation

8 Incendiary Potential Tests

Since the StatX FR and the DSPA 5-4 produce flames and hot gases reaching 800°C (as with all pyrotechnically generated aerosols), a series of incendiary potential tests were developed to assess the impact of activating small aerosol extinguishers in large volumes. It is understood that the heat and hot gases produced from aerosol extinguishers are somewhat negated by the fire suppression agent generated in the compartment volume and pale in comparison to the total heat produced by, and damage from, a fire. This stage of work, however, seeks to understand the potential for pyrotechnically generated aerosol extinguishers to start a fire if they are used incorrectly and/or are activated in a compartment much larger than that for which the aerosol unit was designed. The risk scenario imagined is a large mess or wardroom in a major warship with a volume of 70-100 m^3 and containing a high Class A fire load. Even assuming that this volume is confined properly, it is still 3-5 time larger than the rated volume of either the StatX FR or the DSPA 5-4 handheld aerosol extinguishers. If smoke from bacon grease in the back pantry generates a Damage Control System (DCS) Alarm and is thick enough to cause RRT members to back away, a handled aerosol unit could be activated and thrown into the compartment prior to confinement. The question here, then, is how much incendiary potential will the unit add to the fire scenario if it lands on the couch cushions? Other scenarios in naval applications where the incendiary potential of aerosol agents may be of concern are proximity to ammunition, to fuel storage and transfer systems, and to casualties. The radius of heat produced from these devices needs to be better understood in order to properly influence SOP and training programs.

8.1 Incendiary Potential Test Development

With the amount of heat produced by the StatX FR and the DSPA 5-4 during aerosol generation, it is important to understand their incendiary potential to ensure that SOP may be developed to mitigate risks. To begin to understand this potential, each unit was activated in open air on a piece of polyurethane (PU) foam located on the safe storage and incendiary potential test rig outlined in Section 7.2. The PU foam slabs were 63.6 cm x 68.6 cm x 10.2 cm and contained no fire retardants. The tests were conducted outside, in low wind and with wind baffles in place, and a light rain as shown in Figure 8-1. The goal was to assess the potential for the units to ignite the PU foam as they generated the aerosol fire suppression agent in an open volume.

As shown in Table 8-1, there are many factors and variables that impact the flame spread over combustible solids [54]. The incendiary potential tests conducted on the StatX FR and the DSPA 5-4 sought to minimize these variables for one type of fuel, polyurethane foam, at the same initial temperature and conditioned to the same moisture content (40% RH). The tests were conducted with the same ambient conditions and the same orientation, while the wind effects were minimised thru the use of 2.4 m x 2.4 m baffles on each side of the test rig. It is important to note that varying any of these conditions will produce different results and this is merely a starting point for understanding the incendiary potential of handheld pyrotechnically generated aerosol extinguishers. Using un-upholstered, flat, non-fire-retarded PU foam in open air can be considered a worst case scenario for a test of the incendiary potential of an aerosol unit.

Figure 8-1. Incendiary Potential Test Setup and Ambient Conditions

Table 8-1. Factors affecting rate of flame spread over combustible solids

Material Factors		**Environmental Factors**
Chemical	**Physical**	
Composition of fuel	Initial temperature	Composition of atmosphere
Presence of retardants	geometry	Pressure of atmosphere
	Surface orientation	Temperature
	Density	Imposed heat flux
	Thickness	Air Velocity
	Thermal Capacity	
	Thermal Conductivity	

8.2 Properties of Polyurethane Foam

Polyurethane (PU) is a polymer that is commonly used in foam seat cushions, foam insulation, seals, gaskets, synthetic clothing, carpeting and upholstering materials, and adhesives. Although the RCN seeks to limit the amount of non-fire retarded synthetic materials onboard warships, their presence does exist in the form of packaging, electronics, personal clothing, bedding, and furniture. Therefore, non-fire retarded PU foam was chosen as the fuel for incendiary potential testing.

Some of the common properties for PU foam are listed in Table 8-2 below [54]. When fire retardants are not added, PU foam melts and burns relatively easily, producing a heat release rate of approximately half that of diesel fuel but roughly 50% higher than cellulose based fuels (i.e. plant products such as wood) [62].

Table 8-2. Properties of Polyurethane Foam

Density (kg/m^3)	Heat Capacity (kJ/kg.K)	Thermal Conductivity (W/m.K)	Heat of Combustion (kJ/g)	Melting Point (°C)	Flame Point (°C)
20	1.4	0.034	24.4	~100	~340
Thermal Resistance, α (m^2/s)	Thermal Inertia, $k\rho c_p$ ($W^2.s/m^4.K^2$)	Critical Radiant Heat Flux (kW/m^2)	Critical Surface Temperature (°C)	Rate of Flame Spread (mm/s)	
1.2×10^{-6}	9.5×10^2	~15	>300	3.7	

8.3 Measurements and Data Collection

For each test, the foam slab and aerosol unit were positioned on the purpose-built test rig also utilized for the safe storage testing, positioned such that four thermocouples were spaced at equal distances from the centre in each direction. An average of each set of four temperatures corresponding to the same distance from the centre of the rig provides data on the heat issued from the aerosol units at radii of 0.127 m, 0.381 m, 0.635 m, and 0.787 m. Additionally, the two thermocouples that had previously been used to measure edge seal temperatures during the safe storage tests were positioned to provide temperature data at a radius of 0.254 m.

Temperature data from the 20 thermocouples on the rig was recorded via the National Instruments Field Point data logger to a custom Labview program at a sampling rate of 1.125 per second. Colour video and Infra-red thermography of the tests were also captured.

8.4 StatX FR Incendiary Potential Test Results

Prior to commencing the test, the data logger measuring TC temperatures and the IR and colour video cameras were started. Following this, the StatX FR aerosol extinguisher was activated and placed in the centre of the foam slab centered under the intersection of the two thermocouple rakes.

Figure 8-2 shows the profiles of average temperature measured with time at five radii around the StatX FR unit during after activation. As the aerosol was generated, temperatures at the 0.127 m radius rose rapidly to exceed 800°C. Since the StatX FR unit disperses aerosol thru three rows of concentric rings at the bottom of the extinguisher, some heat was directed downward directly into the PU Foam, causing it to melt and allowing the StatX FR unit to fall into the pool of molten polymer. Because the StatX FR unit dropped beneath the surface of the 10.2 cm thick foam slab, the radius of heat from the unit was no longer accurately measured. After the unit stopped generating aerosol, at about 20 seconds after activation, the temperature at the 0.127 m radius dropped quickly. At this point also, the StatX FR unit had melted, vaporised and ignited the PU foam, so temperatures measured at the respective radii following the initial 20 seconds after activation were due to the burning of the foam slab.

Due to wind conditions and the direction of the hot gases relative to the aerosol generation, it is difficult to assess a true radius of heat produced during this test. Images taken by the IR camera helped to provide a better appreciation for the three dimensional flow of sparks and hot gases from the StatX FR unit. From the IR thermography taken during the test, it can be seen that hot gases with temperatures in excess of 300°C, extend out to the edge of the test rig, which is approximately 1 m from the location where the unit is activated. Figure 8-3 shows four screen captures from the IR thermography for the 20 second period during unit activation and initial generation of aerosol. Following this, the PU foam continued to burn until extinguished with water.

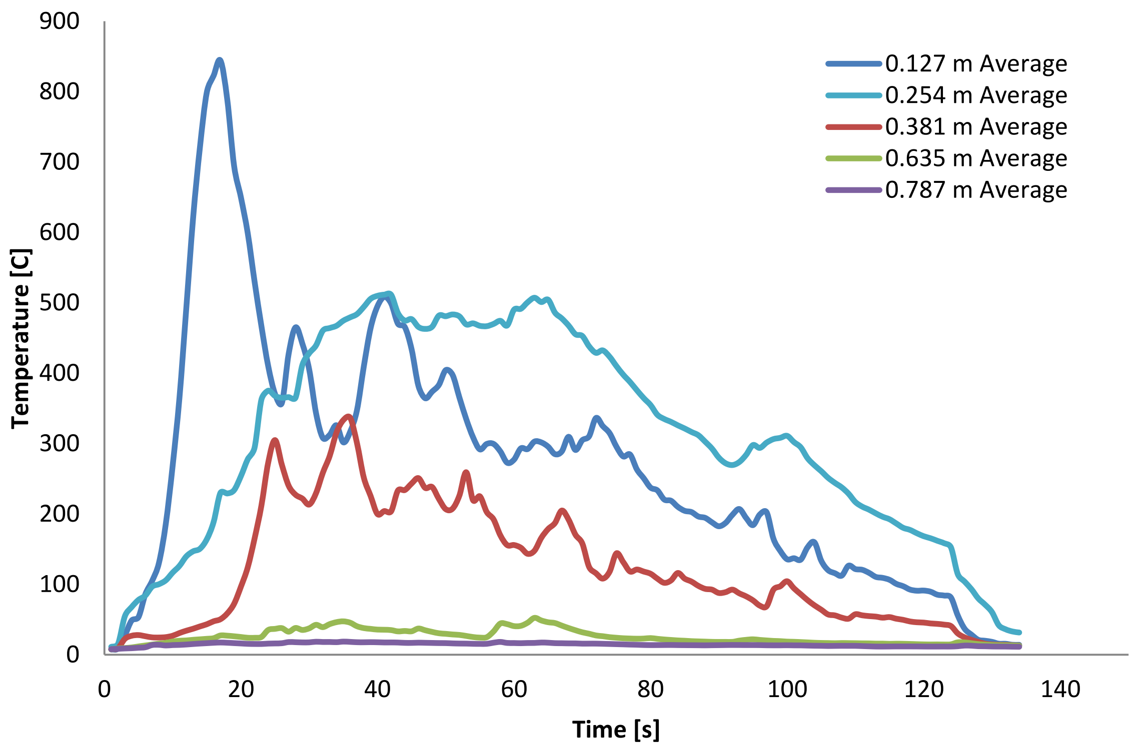


Figure 8-2. StatX FR Incendiary Potential Test Radius of Heat Produced by Aerosol Unit and PU Foam

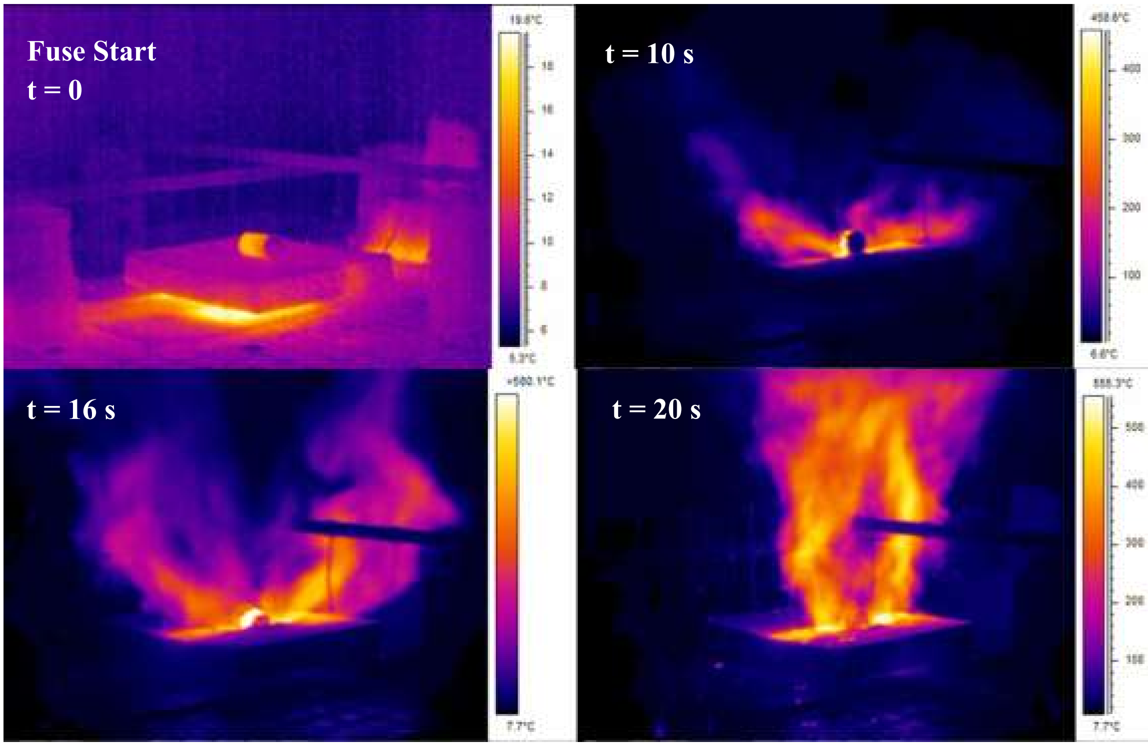


Figure 8-3. StatX FR Incendiary Potential Test IR Thermography Prior to, during and after Activation

8.5 DSPA 5-4 Incendiary Potential Test Results

Prior to commencing the test, the data logger measuring TC temperatures and the IR and colour video cameras were started. One DSPA 5-4 aerosol extinguisher was activated and placed in the centre of the foam slab centered under the intersection of the two thermocouple rakes.

Figure 8-4 includes plots of the profiles of average temperature measured with time at five radii around the DSPA 5-4 unit during and after activation. Unlike the StatX FR unit, the aerosol agent from the DSPA 5-4 unit is dispersed around the circumference of the unit in a direction parallel to, and located 5 cm above, the surface of foam slab. For this reason, the radius of heat was more easily measured in this test and the DSPA unit did not melt itself into a pool of molten PU foam. In fact, the DSPA unit remained on a pedestal of un-melted foam while the foam around the unit began to melt, vaporise and burn. As a result, the temperatures at the 0.127 m radius are the lowest of those measured across the five radii. Looking at the 0.787 m radius, the average temperature peaked at 555^{o}C in 15 seconds and remained above 400^{o}C for almost 10 seconds. The average temperature of the 0.254 m radius peaked at 1028^{o}C. The heat produced during thermal decomposition of potassium nitrate to produce potassium carbonate aerosol far exceeds the ignition temperature for the PU foam and the aerosol suppression agent did not suppress the ensuing fire. The unit stopped generating aerosol about 20 seconds after activation, at which time the temperatures dropped to values representative of those expected during steady state burning of the foam alone.

Due to wind conditions and the direction in which the hot gases were issued relative to the aerosol generation, it was again difficult to assess a true radius of heat produced using the data from the 20 thermocouples in the test rig. The IR camera helped to provide a better appreciation for the three dimensional flow of sparks and hot gases from the DSPA 5-4 unit. From the IR thermography taken during the test it can be seen that hot gases exceeding 500^{o}C extend out to the edge of the test rig, which is approximately 1 m from the location of unit activation. Figure 8-5 shows four screen captures from the IR thermography for the 20 second period of unit activation and aerosol generation, after which the PU foam continued to burn until extinguished with water.

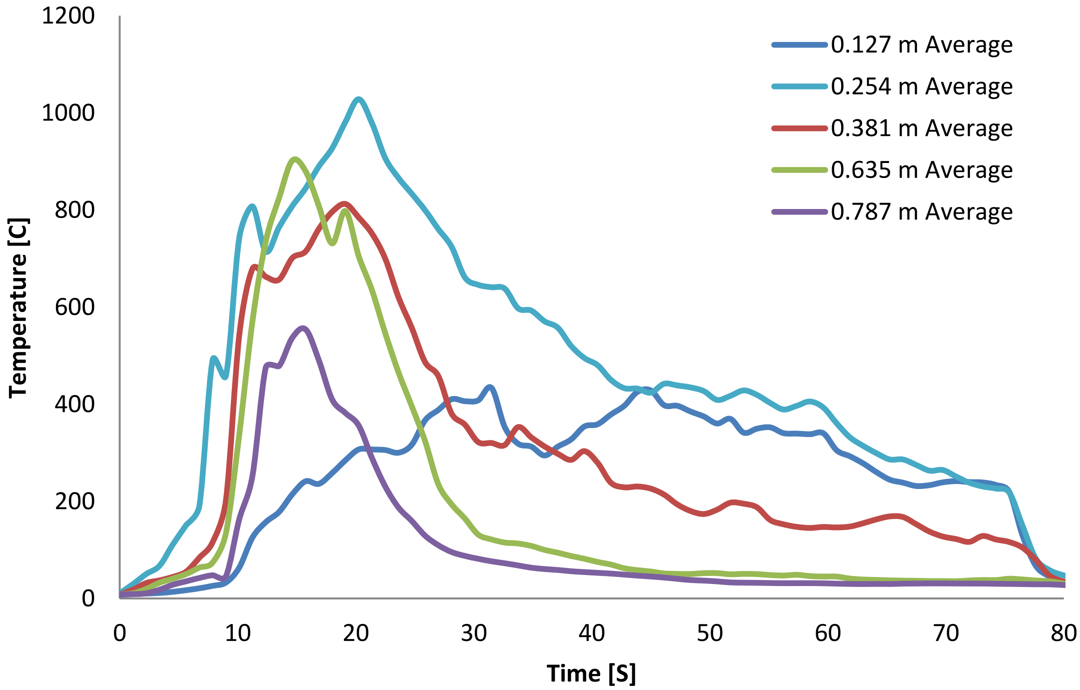


Figure 8-4. DSPA 5-4 Incendiary Potential Test Radius of Heat Produced by Aerosol Unit and PU Foam

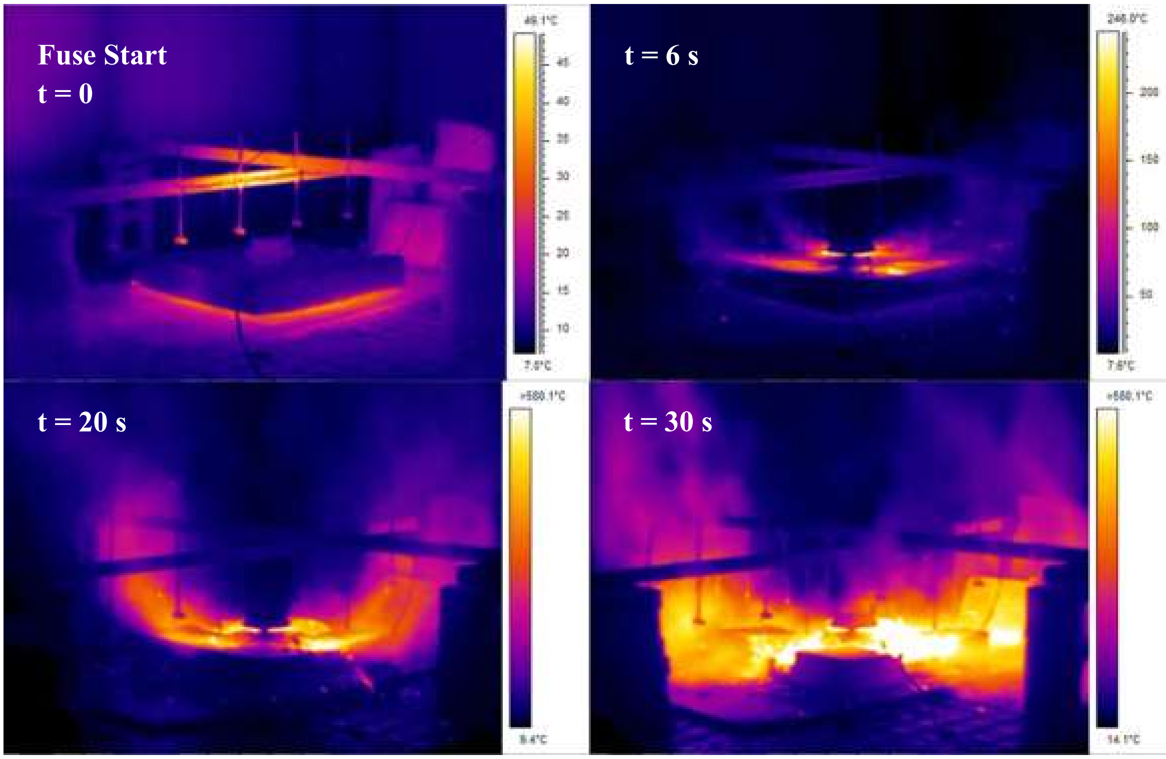


Figure 8-5. DSPA 5-4 Incendiary Potential Test IR Thermography Prior to, during and after Activation

8.6 Incendiary Potential Test Summary and Discussion

The incendiary potential tests conducted using the StatX FR and the DSPA 11-4 (same active agent as the DSPA 5-4 but may be remotely activated) aerosol extinguisher units reveal that both units have the potential to ignite secondary fuel sources since they generate sufficient heat to melt, vaporize and ignite PU foam during aerosol generation. When the potassium carbonate suppression agent cannot be confined to the immediate area in which the unit has been activated, the natural buoyancy of the aerosol agents causes them to rise above the burning material. In terms of volume, these tests were a worst case scenario since, although the winds were very light, the tests themselves were conducted in open air with no confinement of the aerosol particles.

Temperatures measured in these tests are a combination of temperatures indicative of thermal decomposition of potassium nitrate and those indicative of burning PU foam, so it is difficult to ascertain a radius of heating that can be attributed to the aerosol units themselves. Analysis of IR thermography suggests that hot gases (ranging from 200-500°C) and sparks from the aerosol units extend to the edges of the test rig, which is about 1 m. Further testing should be conducted to more accurately determine the possible radius of heating from the aerosol extinguishers themselves.

The StatX and the DSPA 5-4 generate aerosols, and therefore heat, in different ways so their effects on the foam slab were different. The StatX units direct heat from concentric rings around the bottom of each unit, while the DSPA units direct it around the circumference of the unit and parallel to the surface it rests on. Therefore, a StatX FR unit will always direct heat downward onto the surface it is sitting on. In the case of a PU foam slab, this resulted in the aerosol unit melting a hole through the slab and falling to the bottom of the slab while still generating aerosol. On the other hand, the DSPA unit melted the foam around it but the foam directly beneath the unit was damaged to a much lesser extent. For the case of units landing on a couch cushion then, it is reasonable to assume that both units can melt the cushions and bury themselves into the couch, creating a difficult fire to control and overhaul. The potential for this is assessed to be higher with the StatX FR unit than the DSPA 5-4. Further testing could be undertaken in a more controlled fashion by using a compartment of volume double that for which the aerosol units are rated, (i.e. 40 m^3), and using common furnishings. Future testing of this nature would help to better understand the incendiary potential of handheld aerosol units.

9 Conclusions and Recommendations

This research focussed on a scientific evaluation of the fire suppression efficacy of two variants of handheld pyrotechnic aerosol extinguishers against simulated, repeatable, marine fire scenarios. An instrumented single fire compartment experiment was set up and instrumented and a sequence of live fire suppression tests run with fuel loading and ventilation parameters set to produce a consistent and repeatable fully developed fire environment. Key suppression parameters such as upper gas layer cooling rate, impact on thermal stratification, and total compartment cooling effect were measured for a variety of representative fire situations. Aerosol only and dedicated fire tests were conducted to evaluate ancillary issues such as potential aerosol particulate deposition on equipment, as well as the safety, safe storage and incendiary potential of the pyrotechnically activated aerosol units. While the testing was designed to evaluate handheld aerosol extinguishers, the analysis and hence, many of the conclusions and recommendations below, pertain to the broader subject of pyrotechnically generated aerosol agents in general, both as possible Halon 1301 replacement agents or as may be scaled to suit multiple marine, and other similar fire, applications. In the following sections, conclusions and recommendations are summarized for each series of evaluation tests undertaken in this research, beginning with those related to the location of aerosol units for optimum suppression efficiency, through those related to the use of aerosols for suppression of class A and class B fires, and ending with those related to safe storage and incendiary potential of the handheld units in naval applications.

9.1 Location of Aerosol Activation

The suppression testing conducted in the course of this work revealed the importance and significance of both compartment confinement and the location of activation of handheld aerosol units. In this respect several conclusions can be drawn.

Test results indicate that the only consistent way to achieve fire extinguishment of a fully developed diesel fire in an unconfined or breached compartment is to locate the source of oxygen feeding the fire and activate the aerosol units such that the aerosol agent is carried to the seat of the fire along with the oxygen that is being drawn in by the fire. Otherwise, the light aerosol particles are easily dispersed by the turbulent and buoyant hot gas flows within the compartment volume and/or are carried out of the compartment with the upper layer gases and do not effectively suppress the fire.

In preliminary tests conducted in the UW shipping container with the door held open at 30 cm, StatX FR and DSPA 5-4 units had very little effect on fully developed diesel fires even when they were activated beside the diesel pan itself. The micron-sized potassium carbonate particles of the aerosol agent were not entrained into the reacting zone (flames) and thus no significant suppression occurred prior to the aerosol being dispersed and carried out of the compartment. This result was surprising to both manufacturers, as they had expected much more effective suppression, even with the compartment door open a small fraction (30 cm). It is felt that, generally speaking, the interactions between the small aerosol particles and the buoyancy of hot expanding gases in a fully developed fire environment was not fully understood. In this respect, pre-flashover fire environments or fires early in their growth stage would be much less challenging for the StatX FR and the DSPA 5-4.

The iterative process that was required for determining the optimum location of aerosol activation revealed that open diesel fires could be extinguished if the units were activated on the floor just inside the door of compartment where the aerosol suppression agent could be carried to the fire with the natural draw of oxygen. In these results, combining the aerosol generation pathways with the draw of combustion air appeared to be the only way to achieve consistent fire extinguishment without closing the compartment door. The chosen location for aerosol activation also provided a repeatable scenario for measuring suppression efficacy without changing the compartment ventilation for the present tests.

For the Test 1 open fires that were extinguished with the door open, the efficacy of both aerosol units were similar and mimic the effect of confinement of a compartment with subsequent oxygen starvation of the fire. The fires were suppressed and then extinguished causing rapid temperature drops in the compartment. To have this efficacy on a well-ventilated, fully developed diesel fire environment shows that micron-sized potassium carbonate aerosol agents are effective fire suppressants; however, it was only under very controlled circumstances that this effect could be achieved. In a larger compartment with multiple paths for gas flow in and out, determining an effective location for aerosol activation may be challenging, especially in an environment obscured by smoke. This should be less of a concern in the context of large fitted systems with multiple aerosol generators distributed throughout the compartment. Such systems are normally overdesigned to accommodate for obstructions and ventilation leakage and as such, should perform better against unconfined fully developed fires.

From the opposite perspective, the present testing has confirmed again the importance and efficacy of fire compartment confinement on its own in terms of suppressing, and possibly even extinguishing, a fire.

9.1.1 Recommendations for Handheld Aerosol Unit Activation

- In a fully developed fire environment that cannot be confined, it should be considered and appreciated that the buoyancy and turbulent flow of the hot combustion gases can disperse the micron-sized potassium carbonate particles and carry them away from the fire just like smoke;
- If a compartment cannot be confined fully, AT personnel should make an assessment of the flow of cool air that is naturally being drawn into the compartment by the fire and activate the handheld aerosol units on that path;
- StatX FR and DSPA 5-4 units should always be coupled with proper, complete and effective compartment confinement, remembering that confinement on its own can starve, suppress and extinguish the fire; and
- Confinement of a fire compartment or a fire zone within a naval warship remains the quickest and most effective first response to a fire that is too large for portable extinguishers, limiting fire growth, fire spread, and smoke and toxic gas contamination.

9.2 Aerosol Suppression of Obstructed Class B Fires

As seen from the results of Test 2 and 3, aerosol suppression efficacy can vary greatly due to the location in which a unit is activated relative to the fire as well as by the effects of ventilation. Tests 2a and 2b were suppression tests conducted on obstructed diesel fires with the compartment door open at 30 cm and the aerosol units placed just inside the door after activation. Although this strategy had been successful for suppression of open diesel fires in the same compartment, the presence of the engine obstruction mock-up over the same fire greatly reduced the impact of the aerosol agent on the obstructed diesel fire. The aerosol particles were not able to penetrate the flaming zones of the fire and also could not suppress the fire and cool the environment sufficiently to overcome the effects of radiant heat from the hot steel enclosure down to the unburned fuel. Thus, although some minimal effect was seen, the fire was not extinguished.

An additional suppression test (Test 2c) was conducted with the compartment door closed after the unit was activated. This combined the effects of aerosol suppression with oxygen starvation of the fire. Comparison of suppression results from Test 2c against results observed when the fire was only starved of oxygen, provided a measure of suppression efficacy of the aerosols. The main issue to be highlighted from these results, however, is that these small aerosol extinguishers may have little effect on an obstructed Class B fire if the compartment cannot be confined and/or it has a volume larger than 20 m^3.

In Test 2c, it was seen that compartment cooling rates and total cooling effects could be increased by 30-40% when aerosol suppression was combined with compartment confinement in comparison to using oxygen starvation alone. This is a significant improvement in suppression efficiency and these controlled test results suggest that StatX FR and DSPA 5-4 units are of substantial benefit against obstructed Class B fires as long as the compartment is not larger than the rated volume for the aerosol units being used and that it can be completely confined after the aerosol units have been activated. The additional impact of the aerosol, then, will reduce the heat transfer to adjacent compartments and will reduce the risk for rapid fire growth when oxygen is re-introduced to the fire environment during overhaul.

Comparison of results from Test 2c (Obstructed diesel fire, door closed) and Test 3a (Obstructed bilge diesel fire, door closed) reveals that the aerosol units that were activated under the fire and submerged in water as might be the case in a bilge fire situation had a significantly greater impact in terms of suppressing the fire and cooling the compartment than those activated and placed near the door of the compartment. For the case of aerosol generation under water, aerosols generated from both units significantly impacted the obstructed diesel fire even when the compartment was door fully open (Test 3b). The DSPA 5-4 unit actually extinguished the fire for this scenario. Considering that the same units had very little impact on the behaviour of the same obstructed diesel fire when activated in the open compartment with the compartment door held at 30cm (Test 2a and 2b), the results of the simulated bilge tests clearly indicate the benefits of activating aerosol extinguishers at locations under the fire. Another benefit of activating pyrotechnically generated aerosol units while submerged in water is that their own incendiary potential is greatly reduced over activation in the open.

9.2.1 Obstructed Class B Fire Suppression Recommendations

- If a compartment is larger than the rated volume for a particular aerosol unit and/or if the compartment cannot be confined, it is possible for handheld aerosol extinguishing units to have very little effect in terms of suppressing an obstructed fire. Therefore, when possible, aerosol units should be activated under obstructed fires or under bilge fires; and

- When it is not possible to activate aerosol units under an obstructed fire within a breached compartment, it is recommended that the aerosol unit(s) be activated at the point of air intake feeding to fire. This will help to ensure that the aerosol agent is carried to the flames by the fire's natural pull for oxygen.

9.3 Aerosol Suppression of Class A Fires

The results of the aerosol suppression of softwood crib fires (Test 4) show that aerosol agents do not reach the deep seated smoldering embers of a Class A fire so that overhaul with water is still normally required. Smoldering, oxygen deprived, Class A fires can generate enough heat to cause unburned fuel within a compartment to vaporize, creating a fuel rich environment with hot embers as ignition sources. Under certain circumstances, if oxygen were re-introduced into the compartment for overhaul, this combination could lead to scenarios involving rapid and unexpected fire growth.

The performance of both the StatX FR and the DSPA 5-4 in suppressing Class A softwood crib fires was very similar. They both cooled the upper gas layer about 30% faster than closing the door alone and they both had a total cooling effect on the compartment that was about 30% greater than just closing the door. This cooling effect is significant in that it decreases the risk of rapid fire growth when oxygen is reintroduced and the aerosol agent concentration is diluted or the aerosol escapes.

In Class A fires, re-ignition of some of the fuel in the compartment is expected, as seen with this testing and multiple other test scenarios at the UW Fire Research Facility. Indeed, deep seated embers still burning after suppression of the class A fires caused the test fires to re-flash when the compartment door was opened. Therefore overhaul of the fire scene with water is still required.

A main issue or danger is the possibility of igniting hot fuel vapours that have been generated and accumulated within the compartment while it was confined awaiting an AT. The present test results suggest that use of aerosol agents may reduce this risk by decreasing the compartment temperatures; however, the risk is not completely averted. While the added cooling due to aerosols makes the environment safer when compared to oxygen starvation alone, it cannot be assumed that fire extinguishment is achieved and unburned fuel vapours can accumulate in the vicinity of the fire. The lack of oxygen and the presence of the aerosol agent in suspension prevent re-ignition and rapid fire growth when ventilation is controlled; however, care must be taken when breaching the fire zone for overhaul to avoid a dangerous rapid growth scenario. It is very difficult to predict the onset of a dangerous rapid fire growth scenario, and as such, care should always be taken when reintroducing oxygen to a fire environment with or without the previous use of aerosol agents. As an additional precaution, prediction of the potential for rapid fire growth can be facilitated if the temperature and stratification of the fire environment are known by the use of sensing equipment, such as thermocouple arrays, prior to reintroducing oxygen.

9.3.1 Class A Fire Suppression Recommendations

- Regardless of whether aerosol agents have been used, prior to breaching the fire compartment or fire zone it should be assumed that rapid fire growth is possible upon reintroduction of oxygen to a compartment;
- The fire zone should remain confined until the moment the AT is 100% ready to commence water overhaul. The temperatures will continue to drop and the aerosol agent will continue to suppress flames as long as confinement is maintained; and

- Temperature data within the fire compartment will assist Damage Control (DC) personnel in determining the optimum dwell time for aerosol agent. The RCN should consider installing thermocouple arrays in critical or high fire risk compartments to provide DC personnel with a greater situational awareness prior to breaching a primary fire zone.

9.4 Aerosol Only Agent Analysis

Agent analysis tests were conducted to evaluate the generation of aerosol agent from StatX FR and the DSPA 5-4 units alone, without a fire scenario. The aim was to better understand the distribution, suspension, obscurity, re-ignition potential, compartment temperatures, oxygen dilution and carbon dioxide production, and aerosol residue deposition on electronics and firefighter and protective ensemble. The testing revealed that both aerosol units generated agent quickly and evenly to fill and fully obscure an appropriately sized room with suspended suppression agent. Both agents behaved very much like smoke and left a thin residue on the compartment walls, the exposed electronics, and the firefighter's BA and PPE. Visibility within the compartment was reduced to 25-30 cm throughout the tests despite the use of two 500 W halogen lights. The obscurity caused by aerosol particulates was similar to that of a smoke filled compartment and the constant level of obscurity observed over a 10 minute test period indicated the ability of the aerosol to remain suspended at the proper concentration for at least ten minutes. This was also verified by failed attempts to ignite a butane lighter at the 2 m height in the compartment through the ten minute tests of both the StatX FR and the DSPA 5-4. The combined results suggest that as long as the agent is maintained within a confined space of the rated design volume for a unit, ignition of unburned fuel will be inhibited even in the presence of an ignition source such as sparks or hot surfaces.

Average compartment temperatures rose by about 25^{o}C on activation of both units. This attests to the large amount of heat produced by pyrotechnically generated aerosol devices during activation. Locally, the units were found to increase gas temperatures above 100^{o}C out to a 1 m radius. Gas analysis conducted during the agent analysis tests suggested that dilution of oxygen and production of carbon dioxide due to the aerosol units alone are not enough to make the environment uninhabitable or toxic to humans without BA.

9.4.1 Aerosol Only Agent Analysis Recommendations

- Due to deposition of aerosol particulate on surfaces during use, the potential corrosiveness of the aerosol agent residue, along with other residues of compounds likely to be generated during fire suppression using aerosol agents, should be further investigated to understand their impact on sensitive and mission critical equipment;

- Activation of aerosol agents basically creates a fully obscured environment similar to a smoke filled compartment and thermal imaging cameras will be required for clearing casualties and compartment overhaul;
- The majority of the aerosol agents (those that have not yet settled onto compartment surfaces) can be exhausted as smoke once fires are overhauled;
- Aerosol agent residue should be removed from electronic equipment as it can absorb moisture and can possibly track electrical currents across sensitive micro-circuitry; and
- The micron-sized potassium carbonate particles are easily affected by ventilation and will escape an unconfined compartment, reducing suppression efficacy and increasing potential for re-ignition of unburned fuel vapours. The importance of combining fire zone confinement with aerosol agent suppression cannot be overstated.

9.5 Aerosol Safe Storage Tests

Safe storage testing was conducted in order to obtain some quantitative measure of the consequence of an uncontrolled, unplanned, or accidental activation of a StatX FR or a DSPA 5-4 pyrotechnically generated aerosol extinguisher within its supplied storage case. This testing did not assess the probability of such an occurrence, as that would require specific risk analysis and manufacturers' data.

For each test, one StatX FR or one DSPA 5-4 extinguisher was activated and enclosed within its supplied case. Internal case temperatures, edge seal temperatures, and the radius of heating produced in four directions out to 0.787 m around the device were measured. Temperatures inside the cases for both the StatX FR and the DSPA 5-4 tests exceeded 800°C during the generation of aerosol agent. In both cases, the internal gas pressure buildup was relieved through the sides of the case at the edge seal. Very little hot gas was expelled from the front clasps or the rear hinges of the cases. The hot gases that did escape from the edge seals were between 300-400°C, which poses a significant thermal hazard. Remembering that the values of temperature decreased rapidly with distance from the unit and that fire suppression agent is carried with the hot gas, the risk of igniting adjacent fuel sources should not be high, especially if onboard racks are built to absorb/deflect any hot gases that might issue from the edge seals in the unlikely case of an accidental release of an aerosol generator while in storage.

In both tests, the storage cases remained relatively intact and contained the majority of the flames and sparks produced by the aerosol generators. That was remarkable, considering that these cases are commercial off the self (COTS) and were exposed to temperatures exceeding 800°C for 10-20 seconds with only small hot gas blowouts. The foam within the cases melted completely. When the DSPA 5-4 case was re-opened after unit activation, the vapours from the foam did not ignite upon re-introduction of oxygen. However, the foam did re-ignite when the StatX FR case was re-opened. StatX FR units continue to produce a small flame for 1-3 minutes after activation, which produced a piloted ignition source for the already molten foam and plastic of the storage case, causing their vapours to burn. This situation was exacerbated by having a second un-activated StatX FR unit in the same case. As was seen during the StatX FR safe storage test, the activation of the first unit while enclosed in the case did not cause the second unit to activate despite the high temperatures. When the case was opened, however, the foam ignited and burned, engulfing the second un-activated FR unit in flames. The second unit was engulfed in flames for 90 seconds before activating itself, producing large jets of flame with gas temperatures exceeding 1300^{o}C. In a fire scenario, pyrotechnically generated aerosol units exposed to heat and/or flame may auto-activate unexpectedly in the proximity of personnel, causing burns and injuries. Other scenarios where auto-activation could be a concern are dud fuses, or fires in compartments with aerosol generators stored or fitted. While auto-activation of the aerosol generator does supply fire suppression agent to a compartment, it is still an uncontrolled and unexpected release of significant heat that can pose a hazard to personnel and equipment that are in the vicinity.

The temperatures produced by these aerosol extinguishers are well above the ignition temperatures of most Class A and Class B combustibles. While it is understood that fire suppression agent is being generated throughout the period of high temperature, it should not be assumed that this suppression agent is directed towards, or maintained in, the vicinity of any combustible material that may be exposed to the heat. The amount and radius of heating of the hot gases expelled from the sides of the case during accidental activation is also a danger to personnel not in protective clothing and breathing apparatus.

9.5.1 Safe Storage Recommendations

- It is recommended that failure, reliability, and accidental discharge data be obtained from the manufacturer or users of the aerosol units in order to qualitatively assess the probability of an unplanned/uncontrolled activation of an aerosol unit within its storage case. This probability can be combined with the measure of consequence to assess the overall risk, which can then either be mitigated, accepted, or avoided;
- Because of the uncertainty of auto-activation of a second unit, it is recommended that no more than one unit be stored in each separate case;
- If storing more than one unit in each case, SOP should dictate not to open the case unless an AT is present and prepared to conduct an overhaul. Therefore, this situation should be treated as an Emergency Stations;
- Units should be stored away from combustible material;
- The risk of auto-activation should be assumed for any aerosol unit exposed to heat and the units should be cooled immediately by fully outfitted AT personnel;
- Further tests and studies should be conducted to determine effective procedures for preventing auto-activation of aerosol units that have been exposed to heat;
- Storage racks should be designed assuming that, in the event of unplanned generation of aerosols from any unit, most hot gas will be expelled from the side seals of the case;
- Use of alternate or fire retarded foams in the storage case should be investigated to ensure the best product is chosen to deal with the heat that pyrotechnically generated aerosol units can generate. It should not be assumed that a more robust, less flammable material will be better, since other material may have beneficial impacts through better heat retention and insulation. It may be best to have a material that melts easily, but all options should be considered and tests should be performed to determine the optimal components in the storage case; and
- Further testing should be conducted on aerosol generation arising from auto-activated units to determine the quality and distribution of suppression agent produced.

9.6 Incendiary Potential of Pyrotechnically Generated Aerosol Devices

The incendiary potential testing conducted on both the StatX FR and the DSPA 5-4 aerosol extinguishers provides a basic understanding of the potential consequences of a worst case scenario of misuse or accidental discharge of a handheld aerosol unit in the presence of a secondary source fuel. Understanding this consequence is important to the development of risk mitigation strategies, SOP, and training programs that will promote safe use of the devices. When considering use in a naval application, there are many compartments that are larger than the rated volumes for the StatX FR and the DSPA 5-4 handheld units, and in a naval threat environment, there may be circumstances such as battle damage that prevent the control of ventilation and/or confinement of compartments. From the suppression testing performed to date, it is clear that pyrotechnically generated aerosol agents are effective fire suppressors and extinguishers, but only if they are confined to the affected compartment and present in at least the design concentration. It stands to reason then, that the incendiary potential of the StatX FR and the DSPA 5-4 can only be counteracted fully when the compartment is confined. The heat and sparks produced by both units carry out to about 1 meter, as measured during the incendiary potential tests, and are well above the ignition temperature of most Class A and Class B materials commonly found onboard naval vessels. In fact, the temperatures measured for both units were at times above the annealing temperature for carbon steel. This level of heat generation poses a significant risk to ammunition, fuel tanks/lines, casualties, and AT personnel who would carry/hold the devices close to their bodies. The heat, flames and sparks emitted from the StatX FR and the DSPA 5-4 during generation and distribution of the potassium carbonate aerosol agent are sufficiently strong to cause burning or melting within a 1 meter radius of a device. Furthermore, ignition of the fuels they heat can only be prevented if the aerosol agent being produced remains near and, indeed surrounds, the affected area in a sufficient concentration to suppress any flames.

StatX FR units continue to produce a small flame for 1-3 minutes after activation. This is essentially a piloted ignition source that continues after the aerosol suppression agent has been dispersed.

Mitigating the potential for a fire extinguisher to cause ignition is not a normal thought process for personnel; however, it is very important that all personnel understand and appreciate the heat that issues from handheld pyrotechnically generated aerosol units. When used correctly, at a safe distance from ammunition, bulk fuel storage and transfer mains, and casualties, the aerosol agent can effectively suppress a fire within a controlled volume. The scenarios that will require use of handheld aerosol extinguishers will be unique, bridging a gap between a failed first response with portable extinguishers and the arrival of a fully dressed AT with charged foam hoses. If their use is restricted to this unique scenario, the risk of misuse will be greatly reduced.

9.6.1 Incendiary Potential Recommendations

- SOP and training programs should help personnel appreciate the production of heat from pyrotechnically generated aerosol units and highlight the risks involved with improper use of the devices;
- Units such as the StatX FR and the DSPA 5-4 should only be used by trained professionals who can assess the fire scenario and ventilation conditions, the local threats, and the presence/proximity of casualties prior to activation;

- It is not recommended that handheld aerosol extinguishers replace the existing array of portable extinguishers onboard naval vessels;
- It is recommended that aerosol extinguishers be considered for use only in unique fire scenarios where first response has failed, in which case they can be used to prevent, or at least stall, fire growth until the AT arrives;
- The authority to activate an aerosol extinguisher should be considered in a similar fashion to the authority to activate bilge eductors in a flood scenario due to increased risk;
- Further controlled testing should be conducted using common furnishings in large volumes (i.e. double the rated volume or 40 m^3) to determine the incendiary potential of the StatX FR and the DSPA 5-4 in a less challenging scenario;
- Further testing of the units alone should be conducted in a controlled environment to more accurately assess the radius of heat produced in all three dimensions;
- Further testing should be conducted to assess the impact of aerosol unit activation in close proximity to a firefighter and a casualty.

10 Closure

In this work, the suppression of various fires using pyrotechnically generated, condensed micron-particle potassium carbonate aerosol technology has been explored and evaluated, mainly in the context of handheld extinguishers. The primary objective was to scientifically evaluate the suppression efficacy of the aerosol agent against simulated, fully-developed, full-scale, marine compartment fire scenarios including: open diesel fires, obstructed diesel fires, obstructed bilge diesel fires, and Class A (solid combustible - softwood) fires. Secondary objectives of the research were to evaluate the onboard storage requirements of pyrotechnically generated aerosol units, evaluate the incendiary potential and radius of heat produced from pyrotechnically generated aerosol units, to assess the aerosol agent generation, distribution, suspended dwell time, re-ignition prevention, and residue deposition, and to assess aerosol suppression agents as a potential Halon 1301 replacement.

The mechanism of aerosol fire suppression is primarily through the surface phenomena of heat absorption and chemical chain reaction inhibition, which are both inversely proportional to particle size. There is also a small effect of oxygen dilution by the addition of inert gases to the environment. The 18 full-scale live fire suppression tests along with several preliminary suppression tests conducted using handheld aerosol extinguishers have proven that micron-sized potassium carbonate aerosols generated in a medium of chiefly nitrogen and carbon dioxide inert gases are extremely effective fire suppressants when contained in the fire environment at the design concentration. Conversely, the same tests have proven how easily the light and buoyant aerosols can be dispersed by the turbulent, fire-generated flows, to be carried out of a fire compartment with the hot combustion gases before having any significant suppression effect. If a compartment is not confined, aerosols particles may never reside long enough to absorb significant heat or to be entrained into the flaming reacting zones to chemically inhibit the fire. Aerosol fire suppression, then, must be coupled with as near to complete confinement as possible. This confinement will maintain the aerosol agent in the fire environment and it will starve the fire of oxygen, working together to cause the fire to decay rapidly. The challenge in naval scenarios will be those situations where confinement is not possible due to hull or bulkhead breaches caused by battle damage. In those cases, handheld aerosol units may still be effective at fire knockdown if they are positioned such that the aerosol particles are generated directly in the path of oxygen feeding the fire. This location may not be coincident with the seat of the fire.

Ideally, aerosol fire suppressants, as with all fire suppression systems, will be employed as early in the fire growth stage as possible in order to have the best extinction results and minimize fire damage. This is not always possible, though, since as Babruskas has shown, most fires reach the fully developed state on an average of 3.5 minutes after ignition regardless of fuel sources or types within a compartment [56]. Therefore, when considering the utility and efficacy of a fire suppression agent, the worst case, or fully developed, fire environment scenario needs to be considered. The drastic variability in the well-ventilated, fully developed fire suppression results of this work would to tend to support Krasnyndky's theory (discussed in Section 3.4) that aerosols should only be used for suppressing fires early in their growth stage for the majority of cases [24]. However, the results do provide guidance on how to achieve higher rates of suppression efficacy in all stages of fire development. Additionally, based on the findings of this research, aerosol suppression agents can significantly increase the cooling rates and cooling effects over oxygen starvation alone when they are properly confined within a fire environment. Of course, in this case, the fire will decay rapidly just due to oxygen starvation alone but the added cooling effect of aerosol agents gives a qualitative measure of their efficacy and ability to render a fire environment more safe from re-ignition and rapid fire growth once oxygen is reintroduced during overhaul.

The case of Class A, solid combustible fires is one where significant lessons have been confirmed. While aerosols do provide a fairly significant cooling effect, via heat absorption to the particle mass, they do not penetrate the char layers to reach the deep embers that can persist even with oxygen deprivation. They do not absorb the same amount of heat as fire suppressants such as water, nor do they separate the fuel from the oxygen as with phosphate film forming agents (i.e. AFFF). When combined with proper confinement, however, aerosols can suppress Class A fires and prevent fire growth. They can also provide significant cooling over oxygen starvation alone. In most cases, though, overhaul with water and/or foam will still be required ensuring that oxygen is reintroduced to the environment in a safe manner.

The safe storage and incendiary potential tests, and respective quantitative assessments made in this work have sought to understand the possible worst case consequences of pyrotechnically generated handheld aerosol extinguishers onboard naval vessels. It is understood that the probability of the scenarios occurring as tested is extremely low; however, it is not zero. The heat, flames, and gases produced by the combustion of the solid tablet of both variants of aerosol extinguishers are too high to ignore. It is given and understood that an effective fire suppression agent is being produced simultaneously with the flames and hot gases but they still represent a significant thermal hazard that can only be mitigated if said suppression agent is directed, maintained and confined to the same area as the heat and flames themselves. Handheld pyrotechnically generated aerosols do not have as much of a cooling medium to arrest flames and absorb heat as seen in some well-designed fitted aerosol systems. Additionally, they are thrown into compartments and can come to rest within dangerous proximity to fuel tanks and transfer mains, ammunition, Class A combustibles, and casualties. This is not to say that they should not be used onboard naval vessels but rather, it is to ensure the thermal hazard is appreciated and properly mitigated by rigorous training and sound SOP.

In addition to the thermal hazard that pyrotechnically generated aerosols present, their toxicity and possible corrosivity are of concern when considering their use within a naval vessel as either a fitted system or as small handheld extinguishers. Depending on the solid compound formulation, pyrotechnically generated aerosols have been shown to produce several toxic gas species at levels exceeding safe human exposure limits (discussed in Section 2.5.1). The toxic gases include but are not limited to oxides of nitrogen, carbon monoxide, and hydrogen cyanide. Additionally, the long-term physiological effects are unknown for micron potassium salt particles that can embed themselves deep into the alveoli of human lungs. The gases and the respective quantities produced by aerosol extinguishers may, by comparison, be almost negligible when one considers the toxic gases being produced by a compartment fire of numerous cellulose-based, petroleum-based or synthetic fuels. The issue is more pronounced for training scenarios and for accidental discharges in occupied spaces. To understand this risk, the exact pyrotechnic composition should be obtained prior to procurement and all SOP should include BA when handling aerosol extinguishers. Both the toxicity and corrosivity should be further investigated to more fully understand the risks to humans and to equipment.

Fires, or uncontrolled combustion, are complex physical and chemical phenomena for which there are no one-size-fits all suppression solutions. Pyrotechnically generated micron potassium carbonate aerosols have been proven in this work and in others to be effective fire suppression agents when utilised in conjunction with strict ventilation control. As with any suppression agent or system, there are trade-offs that need to be understood in order to maximise the fire protection they can provide and to minimize any negative effects to humans and critical equipment.

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Appendix A: DSPA-5 Material Safety Data Sheet

Material Safety Data Sheet	Version: 5.0
DSPA-5 Intervention generator	Revision date 27/03/2012

1. Identification of the substance / preparation and the company

Product name and code: DSPA-5 Intervention Generator

Material uses: Can be used by fire departments as first responder to suppress fires (A, B, C and F Class fires) in close rooms in all kind of buildings and transport sector (trains, trucks, cars, ships).

Identification company:
DSPA.nl B.V.
Huizenseweg 1020
6534 AN Nijmegen-NL
P.O. Box 6572
6503 GB Nijmegen-NL
The Netherlands
Tel: +31(0)24 35 22 573
Fax: +31(0)24 37 87 583
Mail: info@dspa.nl
Website : www.dspa.nl

Emergency telephone no.: Tel: +31 (0)30-2748888, only for the doctor. National Poisons Information Centre Utrecht, The Netherlands

2. Hazards identification

The preparation is not classified according to Directive 1999/45/EC or Directive 67/548/EEC and its amendments.

Remark: Content of the DSPA Generator consist of solid blocks that are not friable and are contained in a rigid steel casing. During normal transport, storage and handling, the contents cannot come into contact with a combustible material.

If DSPA Generator is activated exposure to aerosol suppression agent may cause temporary, mild irritation of mucous membrane if inhaled.

When using and handling in accordance with the regulations the undamaged fire extinguisher does not present any health dangers.

3. Composition / Information on ingredients

Hazardous ingredients

Ingredient	% weight	CAS#	EG#	Classification
Potassium nitrate	>50	7757-79-1	231-818-8	O; R8
Phenol formaldehyde, Novolac resin	5-15	N/A	N/A	Xi; R36,R37

4. First aid measures

General: Seek medical advice in case of symptoms which are obviously due to inhalation of combustion gasses.

Inhalation: Remove to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs provide artificial respiration or oxygen by trained personnel. Give nothing by mouth. If unconscious, place in recovery position and seek medical advice

Ingestion: If swallowed, wash out mouth with plenty of water. Do not induce vomiting. Keep at rest and seek medical ad-vice.

Eye contact: Remove possible contact lenses. Contamination of the eyes must be treated by thorough irrigation with water for 15 minutes, with the eyelids held open. Do not rub or scratch eyes. A doctor (or eye specialist) should be consulted immediately.

Skin contact: Rinse with plenty of water for at least 15 minutes. Re-move any contaminated clothing or contact lenses.

5. Fire fighting measures

Extinguishing media: NONE - THIS IS AN EXTINGUISHING AGENT
The DSPA-5 Generator can be used by fire departments as first responder to suppress fires, water must be used as an additional suppression agent.

Special hazards according substance or preparation itself, combustion products or resulting gases:

Combustion products may include: carbon monoxide, car-bon dioxide, aerosol and smoke.

Protection of fire-fighters: Firemen have to wear self-contained breathing apparatus and complete protective clothing.

6. Accidental release measures

Personal precautions:	Eliminate all sources of heat and ignition. People dealing with major spillages should wear personal protective clothing (suitable gloves and filter mask FFP-2 if dust is formed).
Environmental precautions:	Do not discharge into drains or sewers. If significant quantities are being released in the environment, inform the authorities according to the local rules.
Clean up methods:	Improper discharge could result in the deposit of small, localized areas of highly concentrated agglomerated particulate on that surface. If left untended, an agglomerated mass may take on moisture and may cause non-progressive surface discoloration of unprotected metal surfaces. Any agglomerated particulate must be cleaned up with a water/alcohol solution no later than 24 hours following a discharge. Collect spilled material by hand, e.g. with a dustpan and duster or a vacuum cleaner. Collect the waste product in suitable drums for disposal. Wash the spillage area clean with plenty of water.

7. Handling and storage

Handling:	When handling observe the usual precautionary measures for chemicals. Avoid contact with heat, sparks, flames and other ignition sources. Do not use equipment producing an open flame or electrical equipment which may cause sparks. Prevent dust formation and inhalation of dust. If intense aerosol is released from a dry sprinkler powder system, respiratory protection is required.
Storage	Store in accordance with local regulations. Store in original DSPA packaging at room temperature. Prevent product temperatures above 75 °C and below -50 °C. Keep away from heat sources. Product is hydroscopic; prevent contact with other liquids.
Specific use(s):	Extinguishing material in case of a fire. Only use in combination with the ignition device of DSPA.

8. Exposure controls - Personal protection

Limits of exposure:	No occupational exposure limits are determined for the preparation and/or for the components. After activating the DSPA, as dense aerosol or dust is formed.
General protective and hygienic measures:	The usual precautionary measures are to be adhered to when handling chemicals.
Respiratory protection:	Required at inadequately ventilated workplaces. As respirable dust in case of application of the material as extinguishing material, use respiratory protection (FFP-2 mask EN149: 2001).
Skin and body:	Wear suitable protective clothing (preferable heavy cotton or disposable coverall) and eye / face protection.
Hands:	Wash hands before breaks and at the end of work. Protective gloves of neoprene or butyl rubber should be worn when handling with the product. Use heat-resistant gloves for handling as extinguishing material in case of a fire.
Eyes:	Use safety eyewear (tight fitting goggles) or a full-face shield. Eye – wash.

9. Physical and chemical properties

General information:

Appearance:	Solid, pressed compound in rigid steel casing.
Odour:	None

Important health, safety and environmental information.

pH:	N/A
Boiling point:	N/A
Flash point:	N/A
Explosive properties:	N/A
Vapour pressure:	Not available.
Relative density:	1,9 (water = 1).
Solubility in water:	Not very soluble (<1%)
Auto activation temperature:	> 270°C

10. Stability and reactivity

Stability	Not self-reactive substance. Stable under recommended storage and handling conditions.
Conditions to avoid	Avoid high temperatures, heating, open fire and ignition sources, and prevent the effects of a grinding motion and impact forces that may result in ignition.
Materials to avoid:	Upon dismantling an intact generator, the contents shall be treated as an oxidizing material.

11. Toxicological information

Acute toxicity from the components:

Product information:	Potassium nitrate, CAS# 7757-79-1.
LD50 (oral, rat):	3.015 mg/kg.
Product information:	Phenol formaldehyde, Novolac resin CAS# N/A.
LD50 (oral, rat):	> 2.000 mg/kg.
LD50 (dermal, rabbit):	> 2.000 mg/kg.
Further information:	When using and handling in accordance with the regulations the undamaged generator does not present any health dangers. After activating the generator, slightly irritations to skin due to increase of the pH value and slightly irritation of respiratory due to an increase of smoke (aerosol).

12. Ecological information

Ecological hazards are not present at undamaged generator.

Ecotoxicity from the components.

Product information:	Potassium nitrate, CAS# 7757-79-1.
LC50:	22,5 mg/l (96 hrs, gambusia affinis
EC50:	226 mg/l (72 hrs, daphnia magna, crustacea
Product information:	Phenol formaldehyde, Novolac resin CAS# N/A.

No ecological data on this components are known.

Persistence / degradability:	From the components poor biologically degradable.
WGK:	1 (Wassergefährdungsklasse or water pollution class, German Water Resources Act., limited water pollutant).

Other information

Ozone Depletion Potential (ODP) = 0

Global Warming Potential (GWP) = 0

13. Disposal conditions

Within the present knowledge of the supplier, this product is not regarded as hazardous waste, as defined by Directive 91/689/EC. Comply with all local, state and federal/international regulations.

14. Transport information

Classification as ADR/RID material for road transport.

UN number:	3178
Proper shipping name:	Flammable Solid, Inorganic, n.o.s
ADR/RID class:	4.1

ADR Label:	
Packaging group:	II
Hazard ID:	40
Remark:	Method of packaging P002

Classification as IMDG material for sea transport.

UN number:	3178
Proper shipping name:	Flammable Solid, Inorganic, n.o.s.
IMDG Class:	4.1
Marine Pollutant:	No
EmS:	F-A,S-G

Classification as ICAO/IATA material for air transport.

UN number:	3178
Proper shipping name:	Flammable Solid, Inorganic, n.o.s.
ICAO/IATA Class:	4.1
Passenger	
Packing instruction:	415
Maximum quantity:	15 kg
Cargo	
Packing instruction:	417
Maximum quantity:	50 kg
Further information:	Division 4.1 articles present no significant hazard as properly packaged for transport.

15. Regulatory information

EU Directive:	This preparation is not classified as dangerous according Directive 1999/45/EC or Directive 67/548/EC and its amendments.
Hazardous symbol:	None
EU labelling classification:	None
R – (risk) phrases:	None
Safety phrases	S15: Keep away from heat S35: This material and its container must be disposed of in a safe way

16. Other information

List of relevant R- and S-phrases referred to under headings 2 and 3:

R8 - Contact with combustible material may cause fire.
R36: Irritating to eyes
R37: Irritating to respiratory system

History:	Date of previous issue	13 August 2010
	Version	4.0

The data given here is based on current knowledge and experience. The purpose of this Safety Data Sheet is to describe the products in terms of their safety requirements. The data does not signify any warranty with regard to the product's properties. In all cases, it is the responsibility of the user to determine the applicability of such information and recommendations and the suitability of any products for its own particular purpose.

Appendix B: StatX First Responder Material Safety Data Sheet

Stat-X

MATERIAL SAFETY DATA SHEET

Fireaway LLC
11503 K-Tel Drive
Minnetonka, MN 55343

MSDS# 003
DATE: 10/06

For information only, call 1-952-935-9745. For emergencies, call CHEMTREC: DOMESTIC NORTH AMERICA 800-424-9300 INTERNATIONAL 703-527-3887 (COLLECT).

1. PRODUCT

Stat-X - **First Responder®.**

2. COMPOSITION/INFORMATION ON INGREDIENTS

Components – Chemical (Hazardous Components ≥ 1%)	**CAS#**	**COMMENTS:**
Potassium Nitrate	7757-79-1	Components are blended and pressed into a highly stable, molded form. Molded composition is contained within a sealed double-walled stainless steel housing – no environmental exposure.
DCDA	461-58-5	
Organic Resin	9003-35-4	
Appearance & Odor:		Beige to white in color. No odor.
Auto-Ignition Temperature:		300°C
Solubility in Water:		Slightly Soluble

3. HAZARD IDENTIFICATION

Possible exposure to aerosol suppression agent if generator is activated. May cause temporary, mild irritation of mucous membrane if inhaled.

4. FIRST AID MEASURES

Contact Method:	**Procedure:**
Inhalation	Remove to fresh air
Eye Contact	Flush with water
Skin Contact	Wash with soap and water.
Ingestion	Not a likely route of exposure.
Seek medical attention for further treatment, observation, and support if necessary.	

5. FIRE FIGHTING MEASURES

In the event of a fire, evacuate the area and inform emergency services. Ignition of *Stat-X* produces a fire-suppression aerosol. Water may be used as an additional suppression agent.

6. ACCIDENTAL RELEASE MEASURES

If these devices are spilled they can be safely recovered by hand and should be inspected for damage prior to repacking. Suspect or damaged articles should be labeled and consigned for correct destruction.

7. HANDLING AND STORAGE

Store in temperate conditions. Avoid shock, electric currents, static discharge, excessive heat and extended periods of storage at temperatures greater than 65°C.

8. EXPOSURE CONTROL/PERSONAL PROTECTION

Respiratory Protection	Ventilate area completely after discharge. Do not enter area prior to complete venting of enclosure. Use filter mask as necessary during clean-up.
Hand Protection	Wear gloves if handling generators prior to cooling.
Eye Protection	Safety glasses are advisable.
Skin Protection	N/A

9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance:	Steel Cylinder up to 175 mm in length

10. STABILITY AND REACTIVITY

These devices are extremely stable below 125°C. They should be protected from fire, sources of electrical power, shock, and high temperatures.

11. TOXOCOLOGICAL INFORMATION

Toxic by-products of combustion are extremely low. Main by-products are listed below with 15-minute TWA values for a maximum 100g/m^3 concentration in a hermetically sealed volume.

Gas	15 minute Time Weighted Average in parts per million
NO_2	1.08
NO	0.97
CO	84.20

12. ECOLOGICAL INFORMATION

These devices are sealed and present no ecological hazards. The aerosol produced upon ignition has no global warming potential and an ozone depletion potential = 0.

13. DISPOSAL CONSIDERATIONS

Comply with all local, state, and federal/international regulations.

14. TRANSPORT INFORMATION

UN Number: 0431	Shipping Limitations:	
UN Classification: 1.4G Articles, Pyrotechnic for Technical Purposes	Cargo Air	Max single packaging – 75 kgs.
Packaging Group: II	Passenger Air	None.
Division 1.4 G articles present no significant hazard as packaged for transport.		

15. REGULATORY INFORMATION

S15	Keep away from heat
S35	This material and its container must be disposed of in a safe way
S38	In case of insufficient ventilation wear suitable respiratory equipment
S39	Wear eye/face protection

16. OTHER INFORMATION

Comply with manufacturer's installation and maintenance procedures.

Disclaimer:

The information contained herein is accurate to the best knowledge and belief of Fireaway LLC, and is intended to describe the product for health, safety, and environmental requirements only. It is not intended and should not be construed as a warranty. Consult Fireaway LLC for further information.

Appendix C: UW Shipping Container Thermocouple Locations and Data File Names

The UW Shipping container burn room has 80 Type K thermocouples measuring gas temperatures across six vertical and four horizontal uni-strut rakes as shown in Figures C-1 and C-2 and described in Section 3.8. Each thermocouple has a geographical position within the burn room and also has a data file designator for the data acquisition system to differentiate between. The designators become headings in the comma separated data file exported to MS Excel. This appendix outlines the thermocouple locations within the UW burn room and the respective data file headings given to each.

Table C-1 Shows the thermocouple locations and data file heading for the vertical rakes, while Tables C-2 and C-3 represent the same for the horizontal rakes.

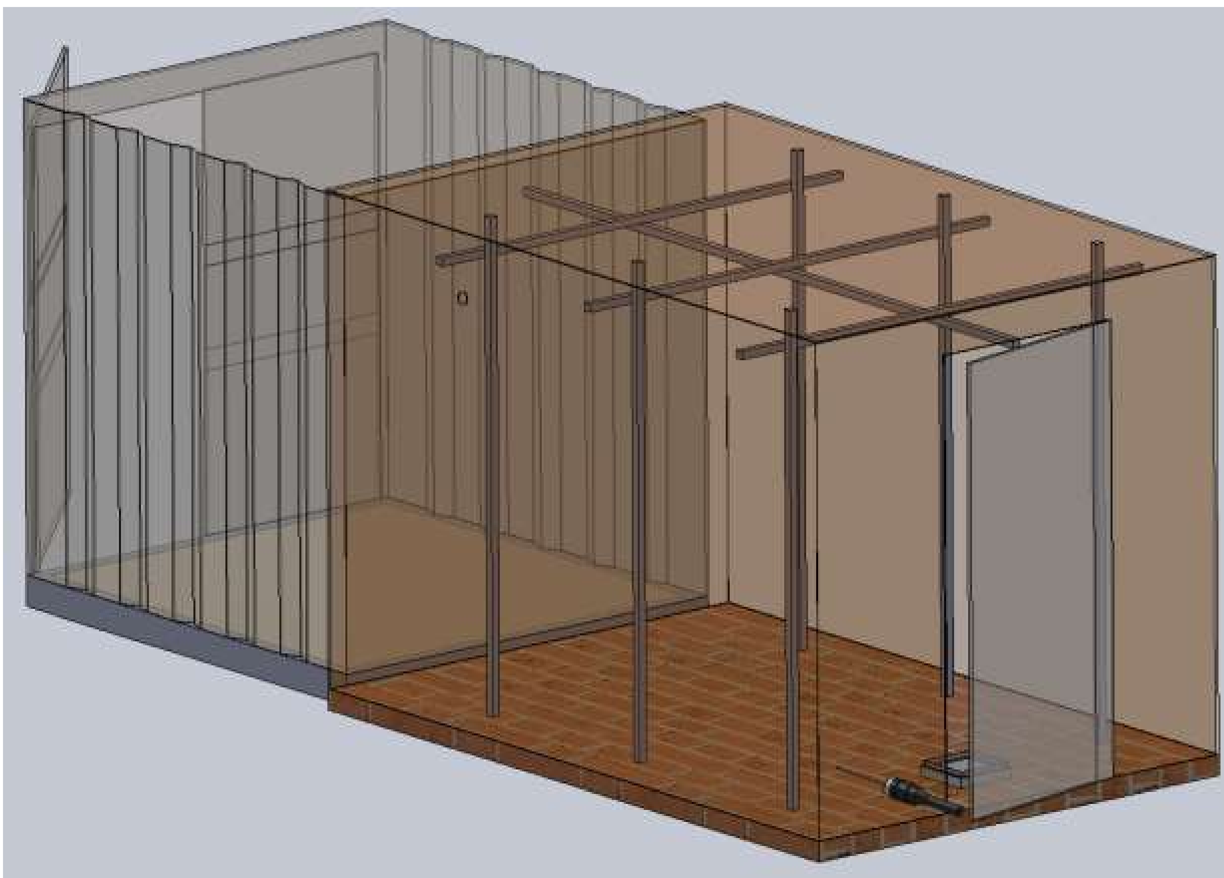

Figure C-1. 3D Computer Aided Rendering of the UW Shipping Container Burn Room

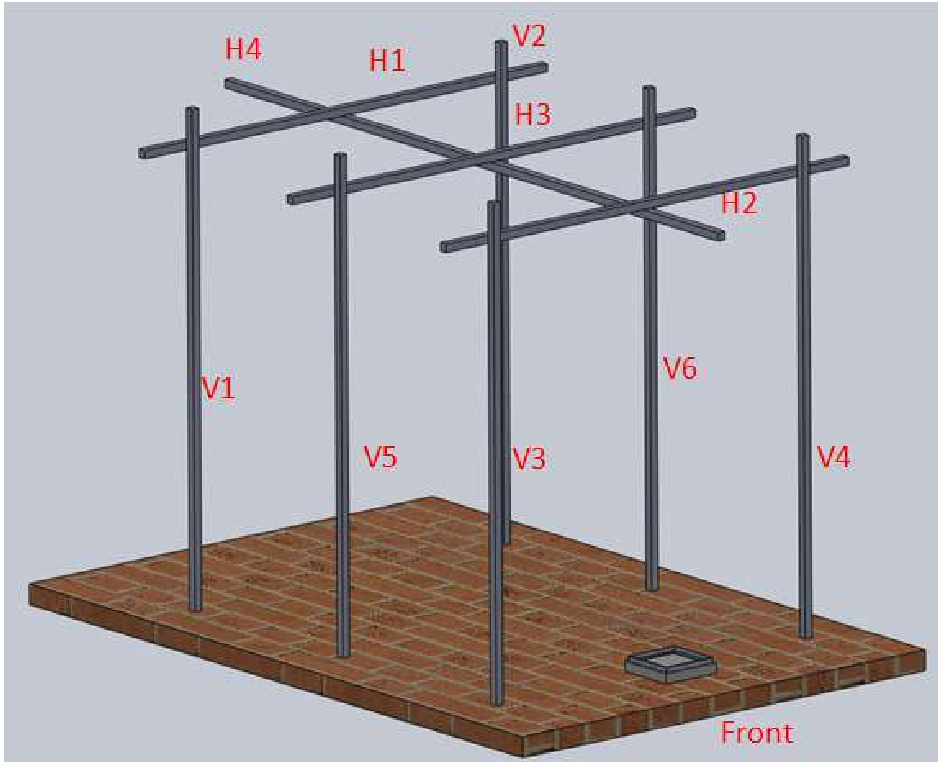

Figure C-2. 3D Rendering of the Vertical and Horizontal Thermocouple Rakes Within the UW Shipping Container

Table C-1. Thermocouple Locations on Six Vertical Rakes Located in the Fire Compartment with the Corresponding Column Headings Used in the Excel Files.

Dist. From Floor (m)	**Heading Used in Excel File**					
	Rake 1	**Rake 2**	**Rake 3**	**Rake 4**	**Rake 5**	**Rake 6**
0.00	V1 000	V2 000	V3 000	V4 000	V5 000	V6 000
0.50	V1 050	V2 050	V3 050	V4 050	V5 050	V6 050
0.80	V1 080	V2 080	V3 080	V4 080	V5 080	V6 080
1.10	V1 110	V2 110	V3 110	V4 110	V5 110	V6 110
1.40	V1 140	V2 140	V3 140	V4 140	V5 140	V6 140
1.70	V1 180	V2 180	V3 180	V4 180	V5 180	V6 180
2.00	V1 200	V2 200	V3 200	V4 200	V5 200	V6 200
2.30	V1 230	V2 230	V3 230	V4 230	V5 230	V6 230

- Vertical Rake 1: -0.9 m from fire compartment centreline and 0.4 m from bulkhead;
- Vertical Rake 2: +0.9 m from fire compartment centreline and 0.4 m from bulkhead;
- Vertical Rake 3: -0.9 m from fire compartment centreline and 2.95 m from bulkhead;
- Vertical Rake 4: +0.9 m from fire compartment centreline and 2.95 m from bulkhead;
- Vertical Rake 5: -0.9 m from fire compartment centreline and 1.8 m from bulkhead; and

- Vertical Rake 6: +0.9 m from fire compartment centreline and 1.8 m from bulkhead.

Table C-2: Thermocouple Locations on Three Horizontal Rakes Located in the Fire Compartment with the Corresponding Column Headings Used in the Excel Files.

Dist. From Centre (m)	**Heading Used in Excel File**		
	Rake 1	**Rake 2**	**Rake 3**
-1.05	H1 -105	H2 -105	H3 -105
-0.75	H1 -075	H2 -075	H3 -075
-0.45	H1 -045	H2 -045	H3 -045
-0.15	H1 -015	H2 -015	H3 -015
0.15	H1 015	H2 015	H3 015
0.45	H1 045	H2 045	H3 045
0.75	H1 075	H2 075	H3 075
1.05	H1 105	H2 105	H3 105

- Horizontal Rake 1: E/W above fire, 2.15 m above the floor and 0.4 m from bulkhead;
- Horizontal Rake 2: E/W at compartment entrance, 2.15 m above the floor and 2.95 m from bulkhead; and
- Horizontal Rake 3: E/W at compartment entrance, 2.15 m above the floor and 1.8 m from bulkhead.

Table C-3. Thermocouple Locations on Longitudinal Horizontal Rake Located in the Fire Compartment with the Corresponding Headings Used in the Excel Files.

Dist. From Bulkhead (m)	**Heading Used in Excel File**
	Rake 4
0.2	H4 020
0.6	H4 060
0.9	H4 090
1.2	H4 120
1.5	H4 150
2.2	H4 220
2.55	H4 255
3.2	H4 320

- Horizontal Rake 4: N/S Longitudinal from compartment entrance to bulkhead, 2.15 m above the floor at the centreline

Appendix D: Purpose Built Safe Storage and Incendiary Potential Test Rig Thermocouple Locations and Data File Names

The UW test rig for conducting safe storage and incendiary potential test of handheld aerosol extinguishers has 16 Type K thermocouples measuring gas temperatures across two horizontal uni-strut rakes as shown in Figures D-1 and described in Section 7.2. It also has two data channels for thermocouples installed inside the storage containers (CaseN and CaseS) and two data channels for thermocouples measuring gas temperatures at the sides of each storage case (SealN and SealS). Each thermocouple has a geographical position and a data file designator for the data acquisition system to differentiate between. The designators become headings in the comma separated data file exported to MS Excel. This appendix outlines the thermocouple locations on the test rig and the respective data file headings given to each, which are listed in Table D-1.

Figure D-1. Safe Storage and Incendiary Potential Test Rig

Table D-1 Safe Storage and Incendiary Potential Test Rig TC Locations and Headings

Dist. From Centre (m)	Heading Used in Excel File	
	Rake 1 EW	Rake 2 NS
0.787	EW+31	NS+31
0.635	EW+25	NS+25
0.381	EW+15	NS+15
0.127	EW+5	NS+5
-0.127	EW-5	NS-5
-0.381	EW-15	NS-15
-0.635	EW-25	NS-25
-0.787	EW-31	NS-31