ABSTRACT

Title of thesis: TRANSIENT FIRE LOAD ON ALUMINUM FERRIES

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The transient fire load aboard aluminum passenger ferries is studied to determine the contribution that baggage has on increasing the temperature of the compartment overhead, which serves as the deck for passenger rendevous during fire emergencies on many large vessels. Single-point and average temperature maximums are compared for a variety of baggage fire scenarios to determine if critical temperatures are reached that would compromise the structural integrity of the aluminum.

A survey of passenger ferry vessels has been performed to determine the extent and type of baggage loading present in passenger compartments. The baggage type, carriage rate, and baggage weight were recorded to determine the overall fire load as well as the average weight of luggage brought on board. Ferry vessels were examined for problem locations and potential sources of elevated flame lengths that may cause the flame to impinge directly on the aluminum structure overhead.

The Fire Dynamics Simulator (FDS) by the National institute of Standards and Technology (NIST) is used to model a representative large passenger ferry com-

partment. Multiple scenarios are simulated with baggage and seat burning along with consideration of flame spread based on a critical heat flux and collected survey results.

Based on the results of the survey, it was determined that the majority of aluminum ferries, when fully loaded, attain higher fuel loads than allowed by current Coast Guard requirements. Subsequent simulations also revealed that the current level of loading compromises the structural integrity of the aluminum superstructure on an average ferry. Additional scenarios tested, such as a stroller parked in the corner of a passenger compartment, would raise the temperature of the aluminum superstructure to a level that would compromise safety. It is recommended that regulatory changes be made to ensure that these severe scenarios are avoided to protect life and property.

TRANSIENT FIRE LOAD ON ALUMINUM FERRIES

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
2014

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Acknowledgments

I would like to thank my wife and family for their support and for being so flexible for the last two years with my constantly shifting schedule.

I would like to thank my adviser Dr. Michael J. Gollner for his guidance and support throughout this research endeavor. He has been instrumental in ensuring that I am on track with my research.

I would also like to extend my gratitude to Rick Nolan of Boston Harbor Cruises, Christian Myers and William McCombe of Interstate Navigation, Greg Gifford of Interstate Navigation, and the captains and crews of the surveyed vessels. Everyone went out of their way to ensure that I had full access to the vessels and was able to collect all of the information needed for this study. In addition, John Duclos, of Gladding-Hearn Shipbuilding, was instrumental in providing me with builder information on aluminum vessels to ensure accuracy of my research.

Finally I would like to thank Carl Moberg, Tom Woodford, LT Noel Shriner, LCDR John Miller, and all the other Coast Guard personnel who assisted me and provided me with insight into this research topic.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

PFM	Policy Fire Memorandum
MTN	Marine Safety Center Technical Note
FDS	Fire Dynamics Simulator
USCG	United States Coast Guard
MSC	Maringe Safety Center
NVIC	Navigation and Vessel Inspection Circular
CFR	Code of Federal Regulations
CFD	Computational Fluid Dynamics
FDS	Fire Dynamics Simulator
NIST	National Institute of Standards and Technology
PVA	Passenger Vessel Association
HRRPUA	Heat-Release Rate Per Unit Area
NTSB	National Transportation Safety Board

Chapter 1: Introduction

1.1 Regulatory History

Federal requirements governing the amount of flammable material brought aboard commercial passenger vessels have been in place for many years. These requirements are based loosely on information that dates back to the time of the first cruise ship type passenger vessels. A number of studies in the last 20 years have provided data and information on the appropriateness of current regulatory requirements, but this data is not complete. Although the interior furnishings such as tables, seats, carpeting, and veneers have been studied closely, the transient fire load from baggage has been largely ignored with the exception of somewhat arbitrary regulations restricting the weight based solely on the area of the passenger deck.

The prevalent use of aluminum as a building material beginning in the 1980s led the United States Coast Guard to enact special requirements for structural fire protection of aluminum vessels, but may place burdensome roles on vessel operators. Data is needed to ensure that Coast Guard requirements are appropriate and that vessel operators have a clear understanding of how to enforce regulations aboard their vessels.

1.2 Approach

The first step in order to address this problem is to determine whether or not current regulations are being met with regard to weight of transient fire load combustibles brought on board vessels. If the current regulation is not being met, the total extent of transient fire load being brought on board must be determined. Aluminum ferry vessels will be selected for audit and the baggage taken aboard will be recorded. The number of bags brought aboard, along with the baggage type will be recorded. This data will allow the formation of an overall carriage rate as well as determine what types of bags are most prevalent for carriage. Next the baggage brought aboard will be weighed to determine its contribution to the transient fire load. The weights will also be recorded based on baggage type to determine if certain bags are on average too heavy to be brought aboard. This will also allow for an average weight to be calculated for the purpose of knowing the average transient fuel load passengers bring aboard.

The next step is to create a computer simulation of the main passenger compartment of the ferry. The computational fluid dynamics (CFD) program Fire Dynamics Simulator (FDS) created by the National Institute of Standards and Technology (NIST) will be used to model the compartment and the fire to determine the heating of the aluminum overhead. A generic passenger compartment is created using overall dimensions of an in-service ferry vessel in Massachusetts. The seats will be modeled as rectangular objects with a prescribed heat release rate per unit area based on extensive full scale seat burning tests completed in 2012. This testing also revealed that seats are the only significant contributors to the fixed fire load within very low fire load passenger compartments. Data collected on the carriage and weight of the baggage will be coupled with baggage burn data from tests completed in 2010. Multiple scenarios will be considered, including the effect of baggage placed in corners and along walls, as well as multiple bags on a seat bank and bags placed on a table top. From the considered scenarios three will be selected for full scale simulation using FDS.

Simulations will be repeated multiple times to predict the spread of the fire between seats, seat banks, and baggage. The focus will be on creating conservative scenarios, meaning that each scenario will focus on a potentially dangerous configurations given the initial circumstances of the scenario. The scenarios will serve as an aid in determining if the specific placement of baggage, or the sheer volume of baggage in and around seats can possibly create an atmosphere within the compartment that will raise the temperature of the aluminum overhead to a temperature at which the structural integrity is compromised.

1.3 Objective

The goal of this study is twofold: first, to ascertain the current state of regulations regarding the carriage of baggage, referred to as the transient fire load, on aluminum ferry vessels; second, to provide a comparative analysis of the addition of transient fire loads in order to assist in measuring the risk associated with the current rate of carriage.

The current requirements in place for vessel operators allow for a fixed weight of baggage to be brought aboard for each square meter of passenger space. Although this figure is useful from a calculation perspective, it does not provide a tangible metric for use in regulating what passengers bring aboard the vessel. There is a lack of data regarding what amount and type of baggage constitutes the required maximum load of 2.5 kg/m^2 (0.5 lb/ft^2).

1.4 Past Fires

Although there have not been any significant fires in passenger compartments on day ferries, it is obvious from past experience that the unexpected often occurs. In today's social climate, with the threat of terrorist activities constant, and with the ever-present possibility of electronic and mechanical failure, the potential for a fire ignition in a passenger compartment cannot be ignored. It is the intent of this study to ensure that the conditions aboard these heavily-used day ferries be studied and modeled to the extent that the risk of a fire event that has a high casualty rate be minimized to the greatest extent possible. This will be done by ensuring that realistic fire loads are maintained aboard ferries, and by examining a range of probable fire and compartment layout scenarios.

Table 1.1 shows a sample of fires that have occurred on ferries within the last quarter century. Although the majority of fires have resulted in a zero death toll, one fire in 2006 resulted in the deaths of more than 1,000 people. This highlights the very real fire risk that is still present in modern day ferry vessels. The list of fires

Table 1.1: Sampling of ferry fires in the last 25 years.

Vessel	**Date**	**No. of Deaths**	**Fire Origin**
CATALINA ISLAND FERRY	25-Jan-89	0	Engine Room
SCANDANAVIAN STAR	07-Apr-90	159	Passageway
PRINCESS RAGNHILD	08-Jul-99	0	Machine Room
SUPERFERRY 14	26-Feb-04	1	Engine Room
AL SALAM BOCCACCIO	03-Feb-06	1,031	Car Deck
LEVINA I	22-Feb-07	41	Car Deck
LADY MARTHA	18-Sep-08	0	Engine Room
LISCO GLORIA	09-Oct-10	0	Upper Deck
PELLA	03-Nov-11	1	Car Deck
ANGELINA LAURA	09-Apr-79	0	Galley

that resulted in zero deaths appear to be somewhat passive events because of this statistic, but injuries and smoke inhalation are not reported and may be significant in some of these scenarios. It is important to note that many of these fires occurred overseas and not domestically. The United States is certainly a leading country in terms of the safety of its seafaring community, but until fire has been all but eliminated as a waterborne transportation risk it bears further study to approach the most efficient and cost effective mitigation methods.

1.4.1 Scandanavian Star

The first vessel fire relevant to this study is a blaze that occurred on board the M/V SCANDANAVIAN STAR. The SCANDANVIAN STAR was a 141 meter roll on roll off ferry that was capable of carrying 1152 passengers and 100 crew members along with a full load of cars and trucks. On the night of April 7, 1990 the ferry was making an overnight crossing from Denmark to Norway carrying 383 passengers and 99 crew members [9]. At 1:55 am a fire was started outside cabin 416 by an arsonist, but was quickly discovered and extinguished. At 2:00 am another fire was started by an arsonist outside cabin 219. This fire spread up through the ladder well of the ship and pushed smoke out into the passageways on decks 4 and 5. A number of open fire doors allowed the smoke to travel quickly and the fire to spread rapidly. In addition, the ventilation system was adjusted to a maximum flow which fed the fire a supply of fresh air and increased its spread rate. Over the course of the day a total of 4 more fires were started, but none with the significance and impact of the second fire. The rapid spread of the fire and large amounts of smoke hindered evacuation and a total of 159 people perished in the fire [9].

The fire on the SCANDANAVIAN STAR shows that human factors such as leaving open fire doors or making negative adjustments to the ventilation system, whether by ill intent or accident, can have a significant effect on the spread of a potential fire and tenability of compartments. In addition, it is a reminder that even in the absence of a high ignition risk equipment, fires can sometimes be started by people in unexpected areas and quickly get out of control. The risk of fire from arson or a terrorist attack is a real danger in the modern world and cannot be ruled out as a possibility when considering fire protection engineering for mass-transit systems such as ferries.

1.4.2 Al Salam Boccaccio 98

The second fire of importance for this study is the fire that resulted in the sinking of the M/V AL SALAM BOCCACCIO 98. The AL SALAM BOCCACCIO 98 was a 131 meter roll on roll off ferry that was capable of carrying more than 1,300 passengers, 100 crew and a full load of vehicles. On the evening of February 2, 2006 the AL SALAM BOCCACCIO 98 was making an overnight crossing from Saudi Arabia to Egypt carrying $1,321$ passengers, 97 crew members, 22 cars, 14 trucks, and 7 trailers [10]. At 7:09 pm the fire alarm on the AL SALAM BOCCACCIO 98 activated and one minute later the watchmen from the car deck arrived at the bridge to report that the car deck was full of black smoke and he believed the fire was coming from the engine room. The master ordered the activation of the water spray system in the car deck and ordered that fire hoses and teams be sent down to combat the fire. Several other reports of smoke and fire came in to the bridge and the master ordered water to mitigate the smoke in the cabin areas. At 7:36 pm the location of the fire was finally identified as the luggage trailer in the forward port side car deck. The master of the vessel continued to send hose teams to spray water anywhere that smoke was detected, even if no fire was present. The fire was fought for about 30 minutes before pumping of the fire water began to clear the car deck, however the list of the ship, caused by mostly unnecessary suppression efforts, was causing water being pumped out to return to the starboard side. The list of the vessel increased despite efforts to de-water and by 11:30 pm the list was at 25 degrees; 3 minutes later the vessel sank [10].

The fire on the AL SALAM BOCCACCIO 98 demonstrates that even with detection and suppression systems in place, sometimes conditions quickly get to a point beyond control. The AL SALAM BOCCACCIO 98 was not a day ferry as are the ferries that are the focus of this study, but it is an example of how a fire even in a supposedly well controlled space can quickly overcome installed systems and create insurmountable problems.

1.4.3 Lady Martha

The final fire of importance for this discussion was an incident aboard the LADY MARTHA. This vessel is a ferry that takes passengers from Cape Cod, MA to the island of Nantucket, MA. The fire started in the starboard engine room of this vessel just prior to arrival in port [11]. The fire could easily have spread to the passenger compartment if it had gotten out of control. The fire fighting system in the engine room activated, knocking down the fire, and the vessel was able to dock at the pier despite the smoke coming out of the vessel. The ferry only had about 6 people on board, so these people quickly disembarked and the swift notification from the harbor master ensured that shore-side firefighting personnel were on there way. The shore-side firefighting teams entered the vessel and completed extinguishment of the fire [12].

1.4.4 Summary

In all cases reviewed, incidents occurred on passenger ferries where overnight accommodations were available or did not involve passenger areas. Despite a lack of recorded incidents, the risk exists for a costly fire to occur in the passenger compartment of a day ferry. Several close calls, such as the LADY MARTHA fire, support the potential risk of more intense fires with greater casualties.

Many times regulatory changes and policy adjustments are made as a reactionary step following a disaster, however the purpose of this study is to ensure that information is provided that allows changes to be made prior to a disaster in a effort to prevent a loss. The fire on the AL SALAM BOCCACCIO showed that even with modern day suppression systems in place fires can quickly overwhelm systems. The fire on the LADY MARTHA shows that high speed ferries, which are

Figure 1.1: Burned remains of the LEVINA I ferry, a disaster that resulted in the deaths of more than 40 passengers [4].

the focus of this study, are also susceptible to fires and even with proper action of the suppression system the shore-side fire department was required to provide final extinguishment of the fire. Finally, the SCANDANAVIAN STAR tragedy shows us that even when mechanical or accidental means are ruled out, there is still the possibility of fire ignition. In today's unstable world where terrorism and crime are constant threats, the possibility of arson or a terrorist attack leading to a fire are very real. It must be ensured that should a fire begin in a passenger compartment or spread to a passenger compartment from another space, the the outfitting and luggage carriage of the vessel will not allow the passenger compartment fire to reach a critical level that would prevent passengers and crew from evacuating the vessel.

Chapter 2: Literature Review

2.1 Vessel Inspection History

The Federal Government has been involved in the regulation of commercial vessel safety since 1838 when Congress passed a law requiring better security of the lives of passengers aboard steam vessels. The primary safety concern in the beginning was explosions and fire caused by vessel machinery. Despite the passage of several laws over the years, steamboat disasters continued to be such a large problem that, in 1871 the Steamboat Inspection Service was created to regulate the safety of these vessels. This service was later shifted to the control of the US Coast Guard (USCG) and regulations have continued to adapt with time and technology. Current safety requirements are set out in the Code of Federal Regulations (CFR) as specified by United States law. Policy documents such as Navigation and Vessel Inspection Circulars (NVIC) and Marine Safety Center Technical Notes (MTN) clarify the regulations and offer guidance on acceptable ways to meet the regulations.

Shipboard fire scenarios are extremely dangerous because immediate evacuation is not possible and fire fighting options are severely limited. Unlike a building, evacuation is not a simple process of walking out a door or down some steps; to evacuate a vessel at sea you must first locate and don a life preserver, wait while the crew launches lifesaving devices, and carefully embark the lifesaving device, often times by climbing down a ladder or net in order to board the raft or lifeboat. In addition, because ships must maintain stability and buoyancy, the amount of water used to combat fires must be carefully limited, and pumping operations create additional tasks for the crew when battling a large blaze. All of these factors in combination mean that in order to ensure the safety of passengers during a fire, there must be a safe and secure location where the passengers can muster, don their life preservers, and embark lifesaving devices.

In addition to detailed regulations regarding detection and suppression, current regulations also require that large vessels must have refuge areas adequately protected from smoke, fire, and heat for a time period adequate for the evacuation of passengers and crew. Structural insulation has long been a heavily utilized method of fire protection that allows for the containment of fire, smoke, and heat for a period of time sufficient for evacuation of the vessel to occur. Insulation can contain the fire to the compartment of origin, retard the spread to other compartments, and provide protection for refuge areas. Adequate fire insulation along with noncombustible materials with large thermal inertia has long been the preferred method to ensure adequate evacuation time. Steel has also long been the material of choice for shipbuilders, and a great many vessels are constructed with this material. Consequently the regulations were written primarily with steel in mind. However, in the 1980's aluminum was becoming an increasingly popular building material for commercial vessels because its light weight meant higher speeds and lower fuel costs compared with similar steel vessels.

The level and degree of insulation required for a space is based on the use and location of the space. Spaces with an increased risk of ignition, such as machinery spaces, are required to have a high degree of insulation. Compartments bordering these high risk spaces must also have adequate boundary insulation. Compartments with very low risk of ignition are required minimal insulation, with uninsulated steel potentially being an adequate barrier surrounding the compartment. The regulations were written with the thermal properties of steel in mind, but a growing interest in aluminum vessels would eventually necessitate a change to the requirements.

2.1.1 Aluminum Vessels

In the early 1980's shipyards and naval architects began pushing to create a new kind of passenger ferry. In order to increase the number of passengers moved, builders and owners wanted to create high-speed ferries that could complete traditional ferry runs in as little as half the time. Aluminum was the material of choice for the design of this new type of vessel because the reduced weight of the hull and superstructure allowed the vessels to maintain a dead-weight low enough to be able to achieve high speeds without the need for massive engines. When it came to structural fire protection the designers and engineers ran into a problem, the difference in thermal properties between aluminum and steel meant that the aluminum bulkheads in these new vessels would have to be heavily insulated in order to meet the minimum requirements. This additional insulation would effectively negate the weight savings of using aluminum and eliminate the advantages of the design. The high density and low thermal conductivity of steel meant that it had a greater thermal capacity to absorb heat than an equal thickness of aluminum and the steel would not transfer the heat to the non-fire side of the bulkhead as quickly. Table 2.1 shows the differences in properties between aluminum and steel.

Table 2.1: Comparison of density and thermal conductivity of common steel and aluminum alloys [1, 2].

Material	**Density (kg/m^3)**	**Thermal Conductivity (W/mK)**
Aluminum, 6082	2700	180
0.4% Carbon Steel	7850	48

USCG regulations promulgated in Title 46 of the Code of Federal Regulations (CFR) specify the requirements for insulation of decks, bulkheads, and overheads. These requirements are based on insulating to a level that will prevent a temperature rise on the unexposed side over 121°C (250°F) during the hour-long standard fire test. The standard fire test is defined in 46 CFR 114.400 as an exposure based on a curve that should pass through five specified temperature points in time. The requirement for insulation is based on the location and use of the space. When considering space usage as a risk factor, both ignition probability and fire load are contributors to the risk level a space presents. Fire load is a term used to describe the weight of all combustibles in the space normalized by the area of the space.

In order to alleviate the problem created by the difference in thermal properties between steel and aluminum, designers appealed to the argument of low fire load. In 46 CFR 116.427 the regulations specify that low risk accommodation spaces must have fire load calculations completed. Fire load calculations are done to ensure that the density of combustible material is below a prescribed value. The calculations consist of taking the weight of every combustible item in the accommodation space and dividing this number by the area of the deck. The maximum fire load for a low risk accommodation space has been defined as 15 kg/m^2 (3 lbs/ft^2).

Several shipbuilders teamed up to create a plan whereby they would eliminate structural fire protection insulation in passenger compartments of large aluminum vessels while concurrently reducing the fire load to lower the risk of fire and reduce the hazard should a fire start. The proposal centered around the idea that, should a fire start in one of these low fire load spaces, the lack of available fuel in the space would keep temperatures low enough that the criteria for temperature rise would be met by aluminum bulkheads and decks without the need for fire protective insulation. Since this plan did not adhere to the current regulations, the ship builders had to appeal directly to the USCG Marine Safety Center (MSC) in Washington, D.C. to get approval for this equivalent safety design. The USCG MSC decided that the plan presented by designers and shipbuilders did achieve an equivalent level of safety to that of the current regulations and approval of designs was granted on a case by case basis for several high speed aluminum vessels.

In the early 1990's other shipbuilders began taking a serious interest in building aluminum high-speed vessels in order to take advantage of the same equivalent safety design utilized by the few that had pioneered the design. At the time the USCG

MSC was still only approving this equivalent safety design on a case by case basis. As industry pressure began to mount, the USCG sought to codify the equivalencies presented in the equivalent safety design cases, and in 1994 they published Policy Fire Memorandum (PFM) 1-94. PFM 1-94 created a policy whereby any shipbuilder could eliminate the structural fire protection insulation requirement by ensuring that the vessels had an appropriately low fire load in the passenger compartment, and met stricter requirements for interior materials and fire detection [13].

PFM 1-94 officially created the concept of very low fire load accommodation spaces and designated these spaces as Type 5A. Previous exemptions were given on a case by case basis, but this policy memorandum synchronized all of the requirements to ensure that all vessels using the structural fire protection insulation exemption met certain conditions. PFM 1-94 limited Type 5A spaces to vessels carrying not more than 600 passengers, with no overnight accommodations, and with predominately open public spaces with a uniformly distributed fire load. The fire load for these spaces was limited to 5.0 kg/m^2 (1.0 lb/ft^2), and they were required to be constructed with noncombustible trim and veneers and fire resistant furnishings [13].

PFM 1-94 allowed a C-Class, smoke-tight structural boundary of aluminum (without insulation) to be used where a refuge area was located adjacent to the 5A space. This meant that even if a refuge area was designated for the bow or upper deck, bare aluminum could be used as long as the fire load was low. This allowed designers and builders to create vessels with significantly reduced weight, particularly in the superstructure of the vessel.

2.1.2 Coast Guard Research

With the number of aluminum vessels rapidly increasing the USCG decided to validate the assumption that type 5A spaces had sufficiently low fire load in order to maintain temperatures low enough to meet the criteria for temperature rise on the unexposed side. The primary tool for evaluating this assumption would be a test to ascertain whether or not a compartment with low fire load would flashover prior to the evacuation of all persons. The full-scale tests were conducted by USCG Research and Development Center personnel aboard the vessel STATE OF MAINE. The test compartment had dimensions of 4.6 m wide, by 5.0 m deep, by 2.5 m high and was constructed of steel. A 6 mm thick aluminum drop ceiling was positioned 0.1 m below the overhead. The test utilized seats that provided a fire load of 5.0 kg/m^2 (1.0 lb/ft^2) arranged in 3 rows of 9 chairs and one row of 8 chairs. The seats were ignited using a 15 cm or 10 cm diameter pan of heptane that was 3 cm deep. Tests were done with different seat configurations and with the addition of wood cribs for one test to increase the fire load. The combustible weight of the seats alone, spread out over the entire 23 m^2 deck area only equated to a total fire load of 1.52 kg/m^2 (0.31 lb/ft^2), well short of the 5.0 kg/m^2 (1.0 lb/ft^2) fire load limit given by the regulations. With the addition of 24 wood cribs, each weighing 5.0 kg, the fire load in the space was raised to 6.74 kg/m^2 (1.38 lb/ft^2), which easily exceeds the requirement [5].

Heat-release rates for the tests were measured using oxygen consumption calorimetry with concentrations and flow rate measurements being taken at the doorway and integrated over the area above or below the neutral plane, dependent on whether inflow or outflow was being used. The flow to be used was determined by comparing the flow rate based on a heat of combustion for the seats of 21,000 kJ/kg and 13,000 kJ/kg for the wood cribs. The two tests that utilized the wood cribs, and thereby achieved the correct fire load density, achieved peak heat-release rates of 560 kW and 370 kW dependent on the arrangement of the seating. In addition to heat-release rates, the temperature on the interior and exterior of the aluminum panel ceiling were measured. The measurements were taken with 5 Type-K thermocouples sheathed with Inconel and peened into the aluminum panel at five different locations. The peak ceiling temperature for the test completed with the additional wood cribs was 385°C on the interior and 247°C on the exterior of the aluminum panel [5].

The final test done as part of the USCG full scale testing series was to place the seat cushions from all 35 seats in one massive pile in the center of the room. Although this still equated to a relatively low fire load over the whole space (still only 1.52 kg/m^2), the proximity of the cushions to one another created a large fire. This fire had a peak heat release rate of 2200 kW and achieved ceiling temperatures of 657°C [5]. The purpose of this test was to investigate the effect that fuel loading and configuration had on the heat-release rate and to determine whether a worst-case scenario, such as the stacking of the seat cushions in the center, was sufficient to cause flashover in the compartment.

In addition the test investigated the temperature that aluminum panels would reach when exposed to different fire scenarios. The aluminum temperatures mea-

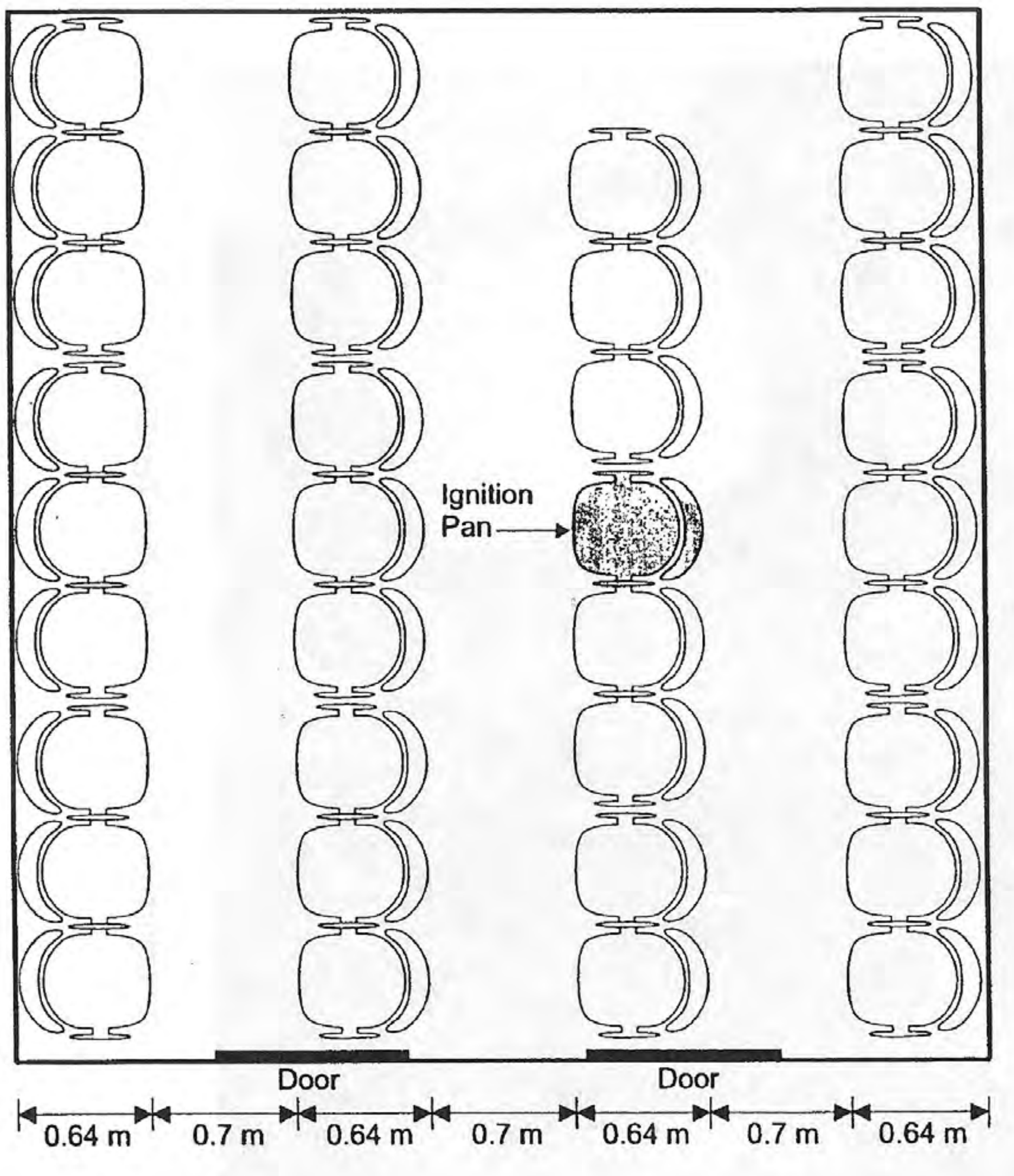


Figure 2.1: Setup of the test compartment aboard the STATE OF MAINE [5].

sured did not conclusively reach the melting temperature of aluminum, but far exceeded the 232°C temperature which corresponds to a 50% loss of structural integrity for aluminum. In order to investigate the impact of flame impingement on the ceiling of the bulkhead of an aluminum compartment, a series of tests were done with a 61 cm by 61 cm section of the 6 mm thick aluminum ceiling panel. The tests showed that a heat-release rate of 25 kW caused a panel temperature of 300°C and 60 kW caused a temperature of 400°C. Using this test data, along with the START*CD CFD program and correlations for fires against a wall, the authors of the test concluded that an estimated fire size of 180 kW positioned next to a bulkhead would cause the aluminum to reach its melting point after 10 minutes. The remainder of the test was a comparison of the full scale experiments with the USCG fire modeling program SAFE. The results of this test could prove significant in that, baggage placed against a bulkhead could easily create a fire of 180 kW and thereby compromise the structure of an aluminum bulkhead within 10 minutes.

Following the full scale testing and verification of current assumptions aboard the STATE OF MAINE, the USCG promulgated NVIC 9-97 on Structural Fire Protection, including chapter 4 which dealt with aluminum vessels. Chapter 4 of NVIC 9-97 concerns the structural fire protection guidelines for aluminum vessels, and section 4.2 speaks specifically to very low fire load spaces of concern for this research. In order to qualify as a very low fire load (Type 5A) space it must be a large open public space with uniformly distributed fire load not to exceed 5.0 kg/m^2 (1.0 lb/ft^2), must have fire resistant furnishings and finishes, must have an approved fire detection and manual fire alarm system, and an A-II portable fire extinguisher

Table 2.2: Comparison of USCG Fire Load Requirements from oldest to most recent. The CFR restricts fire load based on a low fire load accommodation space. With the introduction of PFM 1-94 the remaining requirements are related to the newly created Type 5A space with very low fire load.

USCG Requirement	**Year**	**Fire Load (kg/m^2)**	**Transient Fire Load (kg/m^2)**
PFM 1-94	1994	5.0	N/A
CFR	1996	15.0	N/A
NVIC 9-97	1997	5.0	N/A
NVIC 9-97 Change 1	2010	5.0	0.75
MTN No. 01-13	2013	5.0	2.5

must be provided for every 45 m^2 of deck area. The fire load for passenger effects is not to exceed 0.75 kg/m^2 (0.15 lb/ft^2) [14]. There are several other requirements detailing the construction materials and special conditions that can be found in NVIC 9-97 4.2.1. The requirement for passenger effects was new, and introduced a further variable in maintaining a low fire load, one that must be carefully managed by vessel operators. Table 2.2 shows the progression of the regulations from the first policy in 1994 to the most recent policy given in Marine Technical Note (MTN) 01-13.

2.1.3 Regulatory Changes

In the late 2000's the fire load issue was again re-examined to ensure the policy provided an equivalent level of safety to the full regulations. Advances in computer technology since the testing done in 1997 made it possible to conduct Computational Fluid Dynamics (CFD) modeling. The modeling conducted in conjunction with this project showed that the safety of the area of refuge, when no insulation was present, was highly dependent on the type and distribution of the seating and other combustible materials within the space as well as the ventilation conditions. The dependency of fire size and severity on the configuration of combustible materials had been clearly shown by the compartment testing completed by the USCG in 1997, but the new modeling work suggested that the dependency on fuel load and configuration was more severe than previously thought. Unfortunately, an official report was not published for this work, and specific details on the modeling are not currently available. The conclusions drawn from this modeling effort presented a large dilemma because there were numerous vessels in service taking advantage of the type 5A insulation exemption. These vessels all had sufficiently low fire load to meet NVIC 9-97, but the new research suggested that some of these vessels may be at much higher risk due to the configuration of combustibles on board and the status of ventilation.

The only way to know which vessels were truly low risk and which were in potential danger, was for vessel operators to evaluate fire load and configurations for each vessel. In 2010 the Coast Guard promulgated Change 1 to NVIC 9-97 which now required that boundaries between Type 5A spaces and areas of refuge be insulated to achieve a fire rating of A-60. This meant that the boundary must be capable of preventing the passage of smoke and flame for one hour as well as prevent the temperature of the unexposed side from rising by more than 131°C (250°F) on average or 181°C (325°F) at any point after 60 minutes. Meeting these requirements for an aluminum vessel meant following prescriptive insulation requirements which, in addition to costing thousands of dollars per vessel, would cripple the speed of the vessels by adding a massive amount of weight. If a vessel wanted to keep its current construction without any insulation it must submit a full engineering analysis to the Coast Guard to prove that the area of refuge would be safe for the full evacuation time.

Aluminum vessel builders as well as owner/operators who had been taking advantage of the Type 5A policy given in NVIC 9-97 were now in the position of paying thousands of dollars for each of their vessels to either install insulation or have an engineering analysis performed. Several industry representatives got together along with the Passenger Vessel Association (PVA) and asked the Coast Guard to create a method for compliance that would allow vessel builders and owner/operators to comply with the new policy without spending thousands of dollars per vessel. In response to this request the Coast Guard worked with a University of Maryland (UMD) graduate student to study the problem and create a potential solution for vessel owners. The result of the research and interaction between industry and the Coast Guard was the 5A Space Performance Guidelines which are published in MTN 01-13.

Table 2.3: Summary of the relevant aspects of NVIC 9-97 Change 1 requirements for compartments to utilize a type 5A very low fire load exemption.

1	Large open public space with a uniformly distributed fire load.
2	Fire load calculations showing 5.0 kg/m^2 fire loading.
3	Interior finishes must meet 46 CFR 164.012 or .112.
4	Furniture, draperies, and carpets must be fire resistant.
5	Fire detection and manual fire alarm system must be installed.
6	One type A-II portable fire extinguisher for every 45 m^2.

2.2 Recent Work

The Coast Guard utilized its graduate student program to study the issue of the fire load in aluminum ferries, in order to try and create a pre-approval system whereby vessel builders would be able to follow a simple set of rules in the layout and construction of type 5A spaces in order to make full use of insulation exemptions. Creating a simple set of rules would allow vessels to continue to operate effectively without structural insulation in the superstructure, while maintaining an approriate level of safety.

2.2.1 Coast Guard FDS Modeling

The Coast Guard, PVA, Nichols Brothers Boat Builders, and Gladding-Hearn Shipbuilding worked together utilizing a study done by UMD student Noel Shriner to refine the policy put out through NVIC 9-97 Change 1 regarding fire loads in very low risk accommodation spaces. The purpose of the study and subsequent policy document was to identify a pre-approved arrangement that could be accepted in lieu of a full engineering analysis. This would allow operators to take advantage of the exemption policy without spending large amounts of money insulating passenger spaces or conducting individual studies for each vessel.

This study was conducted with the purpose of validating current regulations related to the maximum fire load in very low risk accommodation spaces, and creating seating configuration rules that could be utilized by industry to take advantage of the insulation exemption without doing a full engineering analysis. The structural

Figure 2.2: Picture of the M/V IYANOUGH the subject vessel of the 2012 study [6].

integrity of the overhead above a burning compartment was evaluated to ensure that the temperature of the aluminum overhead did not exceed a certain level deemed critical. At 232°C aluminum is considered to have lost half of its structural integrity, therefore a value of 232°C was used as a threshold temperature; any values greater than this would be of serious concern.

The 2012 study built on past research by using current CFD modeling tools to evaluate a modern aluminum ferry passenger compartment. The study was modeled after the M/V IYANOUGH, representative of a typical vessel with Type 5A spaces. The layout of the vessel's lower passenger compartment was modeled using Fire Dynamics Simulator (FDS) Version 5, a large eddy simulation (LES) computer model developed by the National Institute of Standards and Technology (NIST) [15]. The study considered flame spread between seats, the influence of the spacing of seats,

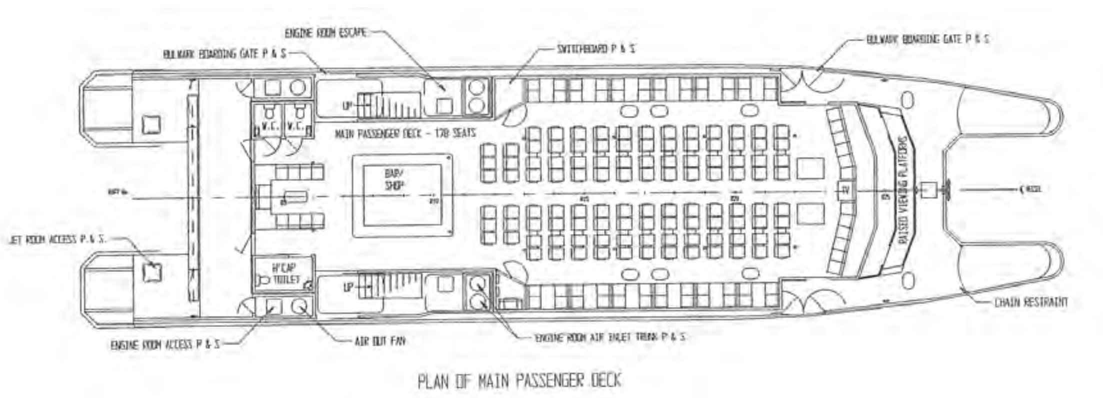


Figure 2.3: Top-view showing the general arrangement of a vessel with a similiar layout to the M/V IYANOUGH [7].

and the overall heat release from an estimated worst case scenario. Performance criteria included requirements that the deck above not reach an average temperature of 200°C over any square meter and that no point on the deck reach 400°C.

In order to ensure that the fire was represented appropriately all possible combustible materials had to be considered. These included tables, chairs, and carpet. The tables in the study, however were considered noncombustible and were thus ruled out as a contributor to the fire load.

The carpet was tested to determine ignition and flame spread properties. Installed carpet must meet the ASTM E84 (116.423). The carpet was tested with a simple butane lighter, but failed to sustain a flame. Next the carpet was subjected to flame tests after having a portion soaked with heptane fuel. The carpet was not able to sustain flaming combustion even with a section soaked in 150 mL of heptane. The section of carpet that had the heptane burning was damaged, but the carpet itself did not sustain a flame and did not spread the flame laterally. The carpeting was therefore ruled out as a contributor to the fire load in the space.

Next the seats were tested for their flammability properties. The seats were required to meet the fire resistance standard UL 1056 in order to be approved for type 5A spaces. The seats have a combustible weight of 1.6 kg and a plan view area of 0.2 m^2. This creates a localized fire load of 7.0 kg/m^2 (1.43 lb/ft^2), but distributed over the entire space studied this equates to a fire load of 1.27 kg/m^2 (0.26 lb/ft^2). The foam used in the seats varies between the seat cushion, seat back, and other foams to add stiffness. The most predominant foam, however is EN 38-200 which has a density of 38 kg/m^3. This foam was assumed to account for the entire 1.6 kg of combustible weight.

Initial testing on the seat cushions showed that the fabric was capable of sustaining a flame long enough to melt the foam and establish a small pool fire on the melted foam. Samples of the seat cushion were then burned in the cone calorimeter to determine the critical heat flux, time to ignition, and heat of combustion. The critical heat flux was 10 kW/m^2 and the heat of combustion of the seat cushion was found to be 17.3 MJ/kg. Next, the seats were tested for their overall heat-release rates. Two ignition scenarios were tested, ignition underneath the middle of the seat, and side ignition from an adjacent seat. The peak heat-release rate measured from both of the ignition scenarios was 100 kW $\pm$3kW.

The area under the heat-release rate curves was calculated and linear trend lines were used to represent the curves in a more simple fashion. Ensuring that the area under the trend line curve was equal to that of the measured heat-release rate curve ensured that the total heat released was conserved. The total heat released for the burning chairs was 22.7 MJ for the middle ignition scenario and 21.8 MJ for the side ignition scenario.

The chair was then modeled as a burner within FDS, using a specified burning rate according to the trend-line heat-release rate curve from the testing. The burner was placed at a height of 0.5 m, representing the bottom seat cushion because the burning of the seat was assumed to mostly occur on the bottom cushion. The main passenger compartment of the M/V IYANOUGH was modeled in FDS with each seat representing a burner. The burners were programmed to begin releasing heat at a prescribed time based on the time to ignition for side ignition of the seat. Several adjustments and corrections were made to the model, inter alia, changing the radiative fraction to correspond with the values measured during full-scale testing.

Once all the corrections and adjustments were made, the model was run to determine the temperature of the aluminum overhead for bare aluminum and for aluminum covered by carpet (for the case where another passenger space is above the main deck). The aluminum overhead was found to reach a maximum temperature of 55°C.

In order to determine the spread of fire to adjacent seats a series of FDS simulations were run with adjacent seats instrumented within the model to determine the heat flux to the adjacent seats. If the heat flux seen by the adjacent seat was greater than the the critical heat flux a theoretical time to ignition was calculated. The simulation was then run again with the ignition of this adjacent seats programmed into the model, and the next adjacent seat instrumented for heat flux. This process continued until the heat flux was not above the critical heat flux for the

Table 2.4: Comparison of USCG seat cushion data from testing performed in 1998 and 2012.

Property	1998 Fire Test	2012 Fire Test
Heat of Combustion	21000 kJ/kg	17300 kJ/kg
Combustible Weight	1.0 kg	1.6 kg
Foam Density	45 kg/m^3	38 kg/m^3
Heat Released Per Seat	21000 kJ	27680 kJ

next adjacent seat. Using this method, a fire starting in a single seat was assumed to spread to a maximum of 10 seats based on the limitation that the longest row of seats will be 5. Two rows of 5 that are back to back are therefore assumed to ignite in the fire scenario while rows facing each other or facing the same direction would not spread as long as certain spacing is maintained. The study assumed that a fire starting in a single seat will then spread only to a maximum of 10 seats. Based on the study, performance guidelines were created to direct builders and operators.

These performance guidelines were published in Marine Safety Center Technical Note (MTN) NO. 01-13. The transient fire load is limited to 2.5 kg/m^2 (0.5 lb/ft^2) in order to prevent escape path obstruction and prevent the spread of the fire to other seats. The construction and outfitting fire load is limited to 5.0 kg/m^2 (1.0 lb/ft^2). The gaps between rows of seats is also strictly set at a minimum of

76.2 cm (30 inches) for rows facing the same direction, and 45.7 cm (18 inches) for rows facing one another. No more than 5 seats can be placed in a row and no more than 10 seats can be arranged in an back-to-back formation. The total combustible weight of each seat must not exceed 1.75 kg (3.86 lbs). In addition Vessels that follow these guidelines are currently allowed to maintain their configuration without adding structural fire protection insulation or completing a costly full engineering analysis.

2.2.2 Swedish Baggage Testing

In 2010 a Swedish study was completed on the carried fire load of mass transit vehicles in an underground railroad system [3]. The increased need for safety in transport systems, the general lack of available data on burning bags, and the dangers of underground fires motivated the study.

Several rail fires were reviewed from catastrophic events in Sweden, Azerbaijan, and South Korea. A study of these fires showed that passenger baggage was a factor in the size of the fire and tenability conditions in the rail coaches and the tunnel. The pictures in Figure 2.4 from the Baku metro fire in Azerbaijan clearly showed a significant amount of passenger baggage and effects left in the unburned coaches after evacuation [3]. The actual weight and composition of the baggage left behind was not measured, but the amount shown in the picture clearly indicates that these transient loads do have some effect on a potential fire.

Following a review of recent railroad fires throughout the world, the author

Figure 2.4: Picture of unburned rail-cars that were abandoned during the Baku metro fire [3].

conducted a survey of metro and commuter trains in Sweden. The bags carried by passengers at different times of the day and times of the week were recorded along with the weight and general contents of the bag. A total of 622 bags were examined during the study. The average weight of a bag on the commuter train was 4.4 kg during weekdays and 4.9 kg during weekends. The average weight of a bag on the metro was 3.5 kg during weekdays and 4.5 kg during weekends. On the commuter train 87% of the people carried bags, while on the metro 82% carried bags.

Bags studied included: laptop, sports, tourist, school-university, school-high school, handbag, suitcase, cabin bag, shopping bag, rucksack, pram (baby stroller), trolley, and paper shopping bags. Representative bags were created and burned in the laboratory to find the heat release rates. The ignition source for the test was a pilot flame of 25 kW for 90 seconds.

The testing showed that the carried fire load in a metro train could be as much as 50% of the fire load of the train itself. In addition, prams alone could possibly be enough to cause flashover inside the train.

The weights of each of the bags, along with a weight breakdown for components was recorded both before and after the test to determine what burned. The heat release rate from each bag was measured during the testing and varied from 30 kW for the trolley bag to more than 800 kW for the pram. In addition the total energy released for each type of bag was calculated and compared to the theoretical total energy of the bag before and after that fire. The heats of combustion used were 26.1 kJ/g for electronics, 19.0 kJ/g for textiles, 17.0 kJ/g for paper, and 47.0 kJ/g for plastics. The data from the test is summarized in Table 2.5.

Commuter and metro trains were considered in the study. The average weight per bag was calculated for both of the trains. The percentage of passengers that carried bags was also calculated. Based on this, the average weight of the baggage per person can be calculated. The floor area of the train car was not listed in the study, but based on the per-person weight and the number of seats in a ferry the weight of the baggage can be calculated in total and divided by the total deck area to get the fire load density. The weight of each bag was broken up into electronics, metal, textile, paper, plastic, and wood with the weight of each of these recorded before and after the burn test to determine the contribution to the heat released. The total weights were also recorded for each type of bag, as well as the heat released. The handbag and suitcase both had sharp heat-release rate peaks corresponding to

Table 2.5: Relevant test dat from Swedish Bag Tests [3]. (*Peak heat-release rates due to explosion of pressurized can of hairspray are momentary and have been excluded from line fit data.)

Bag Type	**Peak Heat Release Rate (kW)**	**Total Energy Released (kJ)**
Computer Bag	110	45.2
Sports Bag	80	33.1
Tourist Bag	120	15.3
University Bag	85	15.5
High School Bag	65	7.9
Hand Bag	190*	14.7
Suitcase	720*	123.2
Cabin Bag	160	97.0
Shopping Bag	55	8.5
Rucksack	285	144.6
Stroller	830	179.1

the explosion of a pressurized can of hairspray. The peak was momentary and can be largely ignored. The pram, which is the European name for a stroller, has by far the highest heat release rate, reaching over 800 kW within 5 minutes. The possibility of parking prams must be carefully considered, especially whether or not the pram could be parked in the corner.

Chapter 3: Carriage Rates

3.1 Allowed Carriage

The allowed carriage rate for vessels currently stands at 2.5 kg/m^2 (0.5 lb/ft^2) as laid out in MTN No. 01-13 for aluminum passenger vessels type 5A spaces [19]. This transient fire load requirement has very little real world meaning for a vessel operator that would much prefer to know how large or heavy a bag may be carried aboard by each person. It would be more straightforward for operators and regulators alike if there existed a policy or regulation similar to the airline industry in which the size and/or weight of the baggage is limited by each carrier [20, 21]. Given the small administrative size of some ferry operators it would be difficult to obtain good standard practices across the industry without a consistent policy for operators to follow. The current policy and regulator requirements require some calculation to interpret. Since the weight allowed per person aboard the vessel would vary based on the passenger loading (because the deck area remains the same for the calculation, the number of passengers would dictate the weight) the operator could in theory use the following equation to find the answer:

$$\text{Weight per Person} = \frac{\text{Main Deck Area}}{\text{No. of Passengers Scheduled}} \times 2.5 \text{ kg/m}^2 \tag{3.1}$$

However, this only works if the operator knows ahead of time how many people will be present on the trip. If true, this would still leave the logistical problem of informing passengers ahead of time of the weight allowed per person, and ensuring that they knew it meant baggage would be stored separately or left behind.

The calculation above may be easy for an ocean excursion vessel, or an airline trip where booking is required well ahead of time, but for most ferry vessels booking is not necessarily required in advance. Many operations allow tickets to be purchased immediately preceding a trip, running on a schedule much like that of a bus. This is a major part of the business plan and must be taken into consideration. Thus, for these operators it is impossible to run a calculation ahead of time, and the logical assumption from a conservative safety perspective, is to complete the calculation assuming a full load of passengers. This equation looks exactly like the previous equation with the number of scheduled passengers being replaced by the total number of seats, which results in a full load assumption.

$$\text{Weight per Person} = \frac{\text{Main Deck Area}}{\text{No. of Seats}} \times 2.5 \text{ kg/m}^2 \tag{3.2}$$

The weight of baggage allowed for each person then depends upon the number of seats and the deck area. These two figures can be combined into the seat density, which is a measure of the quotient of these values. Given the required maximum transient fire load of 2.5 kg/m^2 (0.5 lb/ft^2), and the seat density of the vessel, the

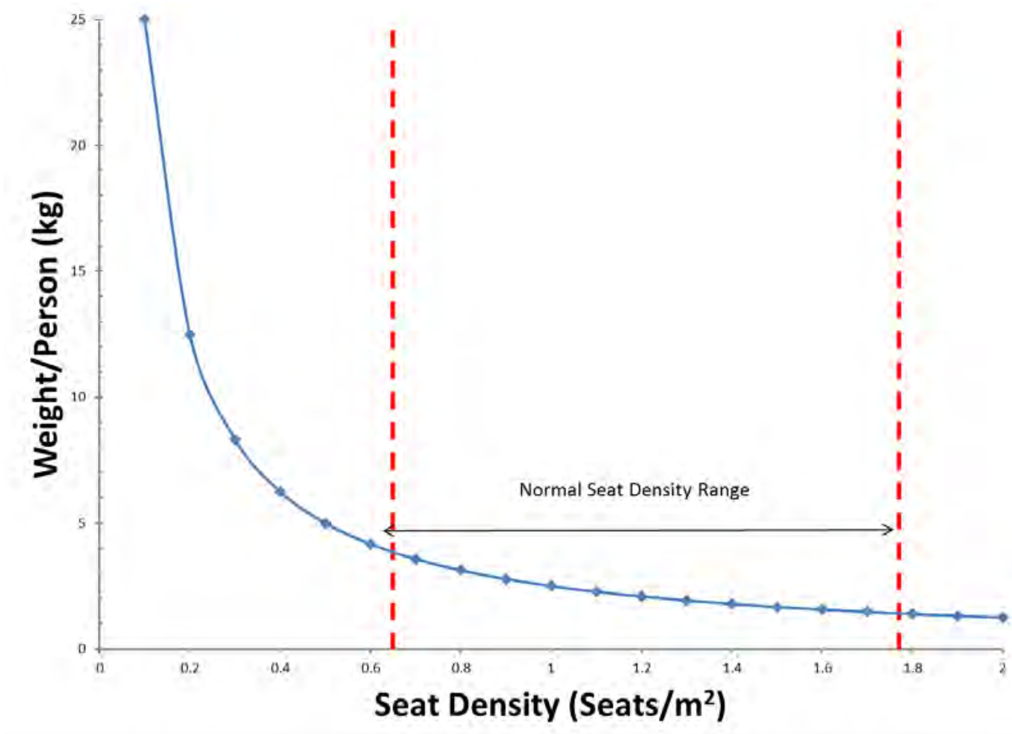


Figure 3.1: Allowed weight per passenger based on seat density and using a conservative full load assumption. The red dashed lines bound the normal range of seat densities found in currently operating ferry vessels.

weight of baggage per person can be calculated for each vessel at the assumed full load condition. Figure 3.1 shows the allowed weight per person based on varying ferry seat densities. The normal range of seat densities shown between the red dashed lines corresponds to a normal range of allowed weight per person of 1.4 to 3.8 kg (3.1 to 8.5 lbs).

This figure will be compared with the findings to see if vessels are currently falling within the requirements by way of ferry company policies, or if these policies are inadequate to the task of enforcing a somewhat abstract regulatory requirement.

The normal range of allowed weight per person as seen in Figure 3.1 is a realistic value when considering the average weight of a bag, but is quite restrictive in limiting every bag to a maximum of only 3.8 kg (8.5 lbs) or less depending on seat density.

3.2 Data Collection

In order to ascertain the current state of the carriage of baggage aboard aluminum ferry vessels, data was collected from these vessels. Although the weight of baggage brought aboard per square meter of space was the ultimate desire, the carriage rate, baggage type distribution, and weight of individual bags was of interest as well. A total of three vessels were surveyed in the southern New England area, and a total of 12 runs on these ferries was considered. The ferry vessels were divided into two types, commuter and non-commuter ferries. Commuter ferries are considered as usually short-run vessels which carry primarily passengers that are utilizing the ferry as a means of traveling to and from their place of work. It is suspected that these vessels may have a lower weight of baggage brought aboard as passengers will typically not be carrying clothing, toiletries, or long-term items. The non-commuter ferry vessels include all other ferry vessels including those that take day trip passengers, weekenders, and even passengers that may be travelling for extended vacation periods. The data was collected on a Thursday through Sunday during the summer (August 22,23, and 24); which is important to ensure that the non-commuter ferries are taking a large number of vacationers and beach-goers indicative of a worst case loading condition.

Two data sets were collected for each ferry vessel run. The first data set was collected by obtaining data points at the boarding location of the ferry vessel. Every bag that was brought aboard the vessel was classified as one of the following: tote, purse, small duffel, carry-on suitcase, large duffel, large suitcase, backpack, or briefcase as shown in Figure 3.2. In addition there was a data collection column for no bag, which was included in order to ascertain the overall carriage rate. The second data set was collected during the transit of the ferry by weighing and photographing a sampling of baggage of each type aboard the vessel. Passengers were solicited at random and were given the option of volunteering to have their baggage weighed and photographed. The bags were once again classified by type in order to obtain a weight distribution for each baggage classification.

Although data collection was completed on large suitcases and duffel bags, both non-commuter ferry operators had company policies in place whereby these larger bags were separated from the passenger and placed in special luggage storage compartments. Although several data points were taken on the weight of these larger baggage items, the carriage of these bags was eliminated from the carriage rate and average weight data since the bags were not present in the compartment of interest.

3.2.1 Commuter Ferry

A ferry that completes commuter runs from Hingmham, MA to Boston, MA was studied for two early morning commuter runs at 7:15am and 8:45am as well as a 8:00am return trip between the runs. At 7:15am there were a total of 193 people surveyed boarding the vessel, 81.6% carried bags of some kind. Of those carrying bags 43.6% carried briefcases, 28.8% carried purses, 22.1% carried backpacks, and the remaining 5.5% carried some form of duffel bag or suitcase. At 8:45am 148 people were surveyed, with 81.1% carrying bags of some kind. Of those carrying bags 37.5% carried briefcases, 35.0% carried purses, 24.2% carried backpacks, and the remaining 3.3% carried some form of duffel bag or suitcase. This data follows the expected trend for a commuter vessel as backpacks and briefcases are preferred methods of carrying work requisites, and purses are commonly carried on a daily basis.

The average weights of a backpack and briefcase brought aboard the vessel were 4.8 kg (10.5 lbs) and 4.8 kg (10.6 lbs) respectively. This average value exceeds the normal limiting value of 3.8 kg (8.5 lbs), with some briefcases and backpacks weighing in at more than 6.8 kg (15 lbs). The average weight of a purse for the commuter run was only 2.5 kg (5.4 lbs), which falls within the range of allowed weight, but only if the seat density remains at or below 1.0 seats per square meter. Additional data collected from the survey is presented in Appendix A.

3.2.2 Non-Commuter Ferry

Two different non-commuter ferry vessels were studied; one that takes passengers from Point Judith, RI to Block Island, RI, and one that takes passengers from Hyannis, MA to Nantucket Island, MA. These two islands are common summer destinations for day-trippers, beach-goers, and passengers going on vacation for several days up to a few weeks. As a result, the luggage carried by the passengers, particularly during the summer months, can be quite significant and the ferries are usually filled to capacity on the weekend days. Data was collected from Point Judith, RI to Block Island, RI on a Friday from midday through early afternoon, and the data from Hyannis, MA to Nantucket, MA was taken on a Saturday from late morning through mid-afternoon. The date, day of the week, and time are critical to ensuring that the data collected is indicative of the greatest passenger and baggage loading conditions seen by the ferry vessels throughout the year. Non-commuter data was collected for more than 1000 passengers with a carriage rate of 88.5% over all ferry runs. Of the passengers carrying baggage 32.2% carried a tote bag, 30.4% carried a backpack, 18.1% carried a purse, and the remaining 19.3% carried small suitcases, duffel bags, coolers, or briefcases. These results are very similar to the commuter ferry results in terms of type percentage, with the exception that the carriage rate of briefcases in the commuter ferry has been replaced by the tote bag for the non-commuter run. Since more passengers are using this vessel for overnight and long-term travel the percentage of suitcases and duffel bags is significantly higher for the non-commuter ferry as expected.

The average weight of the tote bag and backpack were 4.2 kg (9.3 lbs) and 5.0 kg (11.1 lbs) respectively. As with many bags carried aboard the commuter ferry, these values exceed the normal limiting value of 3.8 kg (8.5 lbs) from Figure 3.1. The average weight of a purse for the non-commuter run was 2.5 kg (5.6 lbs), which is consistent with data taken from the commuter ferry vessel. This weight falls within the allowed weight range of baggage per person assuming full load, but only if the seat density remains at or below 1.0 seats per square meter.

3.3 Results

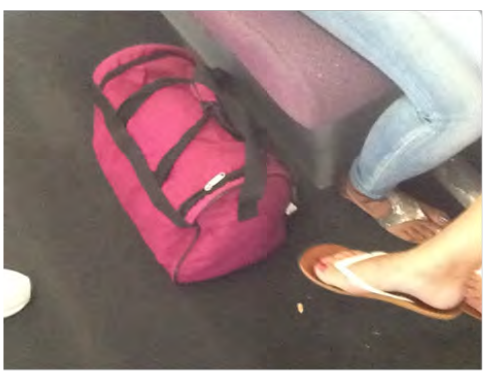
The focus of the baggage data collection was to ascertain the current baggage carriage aboard ferry vessels and determine if this level of carriage falls within the current regulatory requirement of 2.5 kg/m^2 for transient fire load. The average weight per bag carried aboard each type of ferry was multiplied by the carriage rate to determine an average baggage weight per person boarding the ferry. The average baggage weight for the commuter ferry was 3.4 kg (7.4 lbs); giving an average weight per person of 2.8 kg (6.2 lbs). The average baggage weight for the non-commuter ferry was 4.2 kg (9.2 lbs); giving an average weight per person of 3.7 kg (8.1 lbs). These numbers are in close agreement with the average weight per person calculated by Kumm [3] for carriage on trains. The average weight per person on a metro train on a weekday, comparable to the commuter ferry on a weekday, was 2.9 kg per person as compared to 2.8 kg per person for the ferry. The average weight per person on a commuter train on a weekend, comparable to the non-commuter ferry on a weekend, was 4.3 kg per person as compared to 3.7 kg per person for the non-commuter ferry.

The vast majority of baggage carried, 79%, weighed less than 6.8 kg (15 lbs) with approximately half (54%) weighing less than 4.5 kg (10 lbs) as seen in Figure 3.3. The frequency of the baggage weights measured shows that the average value calculated is consistent with the greatest frequency of baggage weight carried. The

1. Briefcase – 11.4 lbs

2. Purse 3.6 lbs

3. Small Duffel Bag – 10.6 lbs



4. Backpack – 12.1 lbs

5. Tote Bag – 14.2 lbs

6. Carry-On Suitcase – 24.6 lbs

Figure 3.2: Representative samples of baggage that were weighed on commuter and non-commuter ferries.

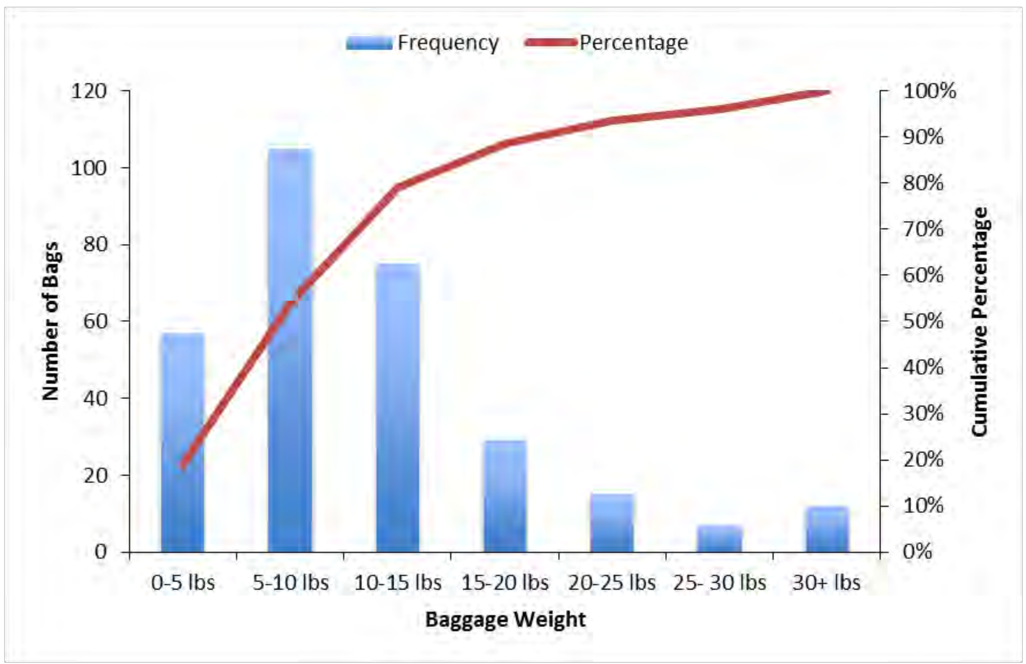


Figure 3.3: Histogram showing the weight of baggage and cumulative percentage carried aboard ferry vessels.

largest group percentage of 35% for the 5 to 10 lb range, easily encompasses both the average values calculated. The weight distributions of each bag type, along with additional survey results are shown in Figures A.1 through A.13.

Next the average weight per person must be compared with the seat density of the vessels studied to determine if the requirements of the regulations are being met. The calculated weight along with seat density information obtained from the builders of the vessels will be inserted into Equation 3.3 to calculate the currently carried weight per square meter.

$$\text{Weight per Person} \times \text{Seat Density} = \text{Weight per Square Meter} \tag{3.3}$$

Table 3.1 shows the results of the calculations for all three of the ferry vessels surveyed. All three vessels, as loaded at the time of the data collection, exceed the transient fire load requirement of 2.5 kg/m^2 (0.5 lb/ft^2). Using the transient fire load requirement and the average weight per person taken from data collection, the cutoff seat density can be calculated to get an intimation of how much of the current aluminum ferry fleet is exceeding the requirements on a busy day with a full load of passengers.

Given the commuter ferry average weight per person of 2.8 kg, the seat density would have to be equal to or less than 0.89 $seats/m^2$ in order to meet the regulatory requirement. Data on seat densities for vessels with Type 5A spaces indicates that only 28.8% of currently operating vessels have a seat density of less than or equal to 0.89 $seats/m^2$. Given the non-commuter ferry average weight per person of 3.7

Table 3.1: Seat density and transient fire load for three ferry vessels from which carriage data was collected.

Ferry Vessel	**Seat Density (Seats/m^2)**	**Transient Fire Load (kg/m^2)**
Commuter Ferry	0.99	2.77
Non-Commuter Ferry 1	0.79	3.08
Non-Commuter Ferry 2	1.07	4.17

kg, the seat density would have to be equal to or less than 0.68 seats/m^2 in order to meet the regulatory requirement. Only 3.4% of vessels meet this seat density requirement, indicating that almost any ferry vessel operating as a non-commuter ferry could be exceeding the requirements on its busiest days. In order to ensure that all vessels and seat densities were operating within the requirements, the allowed baggage weight per person would have to be limited to 3.1 lbs, an unreasonable number when considering that of the baggage surveyed 95.7% exceeded 3.1 lbs. Excluding more than 95% of currently carried bags would be excessive, particularly during off-peak times.

The carriage rate of the different bags will be used to weight a heat-release rate curve using data from Kumm, with an adjustment made for the average weight difference. This will allow simulations to be conducted to test if the current level of carriage will cause sufficient heat transfer to compromise the structural integrity of the aluminum superstructure.

Chapter 4: FDS Model

4.1 Verifying the Mechanism

In order to create results that are useful to policy making bodies within the Coast Guard, the mechanism used to create and track the progress of the fire in the simulated space must closely match the mechanism used in previous research by Shriner [8]. The overall physical dimensions of the space are known, along with the basic type layout of the seat banks. Measurements for the seat area will be used to create the physical model of the seats, but since FDS will not be used to model the spread (hand calculations will be used) the precise properties of the seats are relatively unimportant. The seats will be modeled as non-combustible so that spread does not occur within the simulation. Heat flux gauges will be used to measure the incident heat flux at the seat cushions adjacent to the seat on fire, and this flux will be used to predict the time of spread, which will be programmed into a subsequent FDS simulation. In this way each fire scenario will be run in a series of steps as the spread is calculated and then modeled into the next simulation step in the scenario.

The two most important parameters to be matched between this model and the model used by Shriner are the specification of the fire and the placement of the heat flux gauge. The fire is specified using the HRRPUA (Heat Release Rate per

Unit Area) command in FDS with a ramp function used to control the growth and decay of the fire for each individual seat [15]. The ramp function within FDS allows the user to specify independent and dependent variables so that quantities such as the heat-release rate can be ramped up according to a set of simple linear equations. Full scale testing from Shriner [8] provides a ramp function for the heat-release rate for middle ignition and side ignition of the seats, as shown in Figure 4.1. The area of the seat is known, along with the size of the fire and the progression of the heat release rate, so that the fire is fully specified and matched with the work of Shriner. The next task is to match the heat flux gauge measurements that were recorded during the simulation and used to calculate the spread of the fire between adjacent seats. The exact mechanism used by Shriner for measuring the heat flux in FDS is not known. The location of the heat flux measurement point was specified as 7 cm from the fire and will be assumed to be a straight horizontal measurement from seat cushion to seat cushion. The vertical placement of the point was not specified, nor was the orientation, except to say that the gauge faced the fire. A total of 3 vertical placement and 3 orientations were used to record the heat flux at the next adjacent seat to the seat on fire. The mechanism that gave a result most closely matching the work of Shriner was the radiative heat flux gas quantity placed at a 90 degree orientation to the seat on fire at a distance of 7 cm and a height of 0.5 meters, which corresponds to the height of the top of the modeled seat cushion. The quantity called "radiative heat flux gas" within FDS acts to place a radiometer at the specified location and integrates the incoming radiative flux over a solid angle of 2π, centered around the specified orientation vector [15].

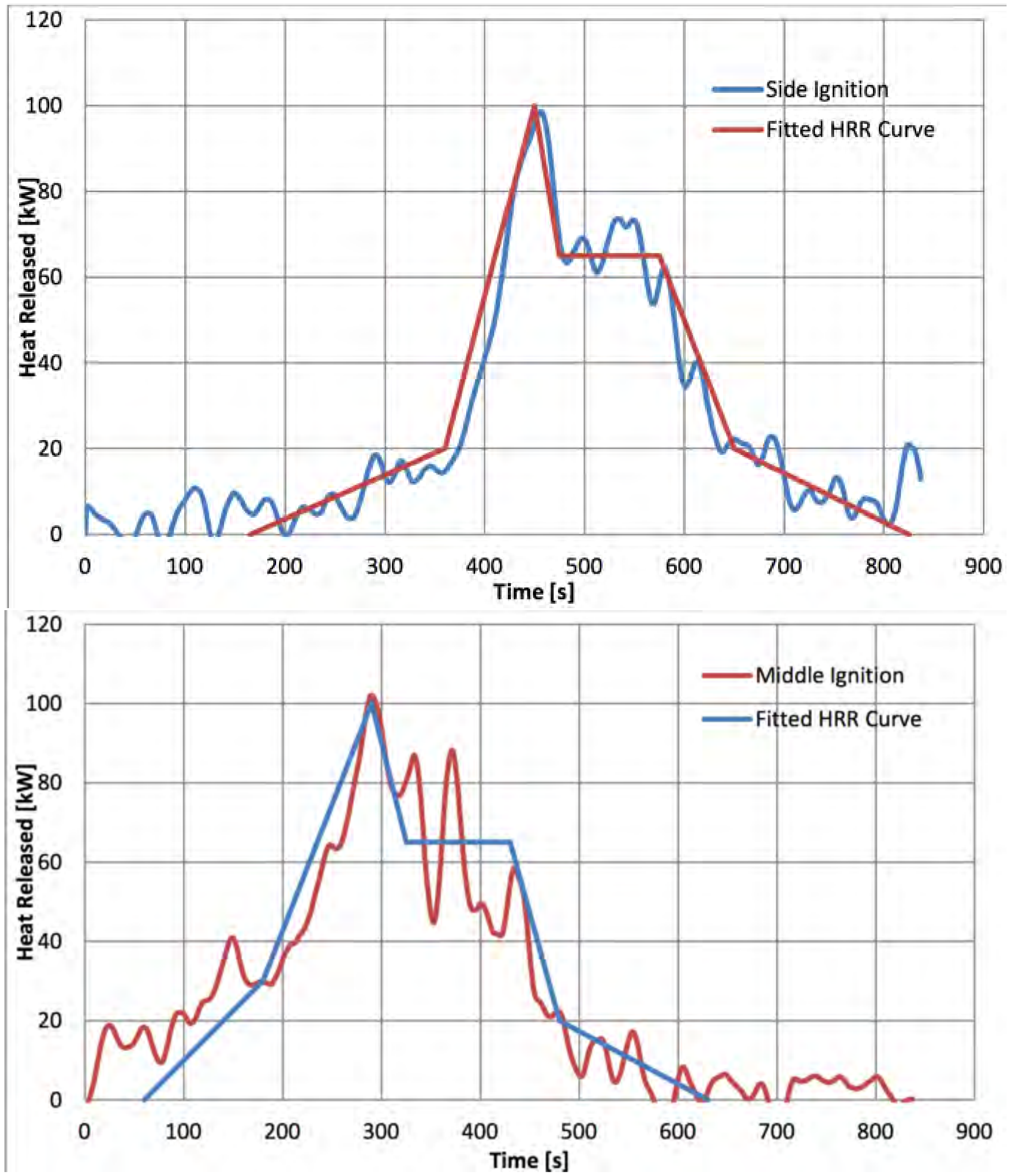


Figure 4.1: Experimental measurements and ramp functions for middle and side ignition of seats given by Shriner [8].

Although Shriner's data on heat flux gauge measurements was unavailable for direct comparison, the ignition curve and calculated ignition time for adjacent seats provided a method of comparison. The specified ignition curve from Shriner, showed a relationship between the inverse of the square root of the ignition time, t_{ig} and the natural log of the heat flux, HF and was used to calculate an ignition time for the adjacent seats of 200 seconds for Shriner's work [8]. By eliminating heat flux values below the critical heat flux of 10 kW/m^2 and taking an average heat flux value over time for use in the ignition equation, the ignition time can be recalculated using heat flux gauge measurements from current simulations with the radiative heat flux gas quantity. The calculated ignition time for adjacent seats from the simulation data is 190 seconds, giving an error of 5% for the ignition time.

$$t_{ig}^{-1/2} = 0.21 \ln HF - 0.46 \tag{4.1}$$

One of the reasons for this error is the difference in the FDS grid resolution between the present work and the work of Shriner. Additional time available for the present work allowed for a finer grid resolution, which in turn creates small differences in data as the calculations are refined and improved. The error is small (4.5%), and because the calculated ignition time is shorter than that shown by Shriner, this calculation will give a more conservative result, which is often desired when making life safety decisions. Additionally, the increased grid resolution suggests a further degree of accuracy in the current measurements.

4.2 Grid Resolution Study

An important aspect of setting up a CFD simulation is to ensure that the simulation has the proper grid resolution. The grid resolution is a measure of how well resolved the problem is; meaning how many grid cells are present for a characteristic length scale. The more grid cells that are present for a given length scale, the finer the mesh and the greater the resolution of the problem. Although greater resolution means theoretically greater accuracy of the problem, the computational costs and potential numerical errors increase rapidly with increased grid resolution. Doubling the grid resolution, for instance, will result in roughly 16 times the computational time, so increases in resolution must be carefully considered and sensitivity must be studied to ensure adequate resolution without wasted computational cost. The FDS User Guide suggests using Equation 4.2 to calculate the characteristic diameter of the fire. This characteristic diameter is used as the characteristic length scale for the problem and is divided by the cell size in order to obtain a grid resolution value.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \tag{4.2}$$

D* = characteristic fire diameter

$\dot{Q}$ = heat-release rate (kW)

ρ_∞ = density of air (kg/m^3)

c_p = specific heat capacity of air (J/kgK)

T_∞ = ambient temperature (K)

g = acceleration due to gravity (9.81 m/s^2)

The characteristic fire diameter was calculated using 700 kW as the peak value, as this is the peak sustained heat-release rate from the burning of a stroller, the highest single item heat flux. Using the properties of air and the peak heat-release of 700 kW yields a characteristic fire diameter of 0.831. Using a course grid resolution value of 4 would yield a mesh of 135×60×20 with a total of 162,000 cells; while a finer grid resolution value of 10 would yield a mesh of 324×150×48 with a total of 2,332,800 cells. A grid resolution value of 10 is preferable to ensure better accuracy, but the resolution must be carefully checked to compare the level of accuracy increase and the increase in computational cost. Given that supercomputers and multi-computer banks are not available for this work, the computational cost will be a significant limiting factor in deciding on the final grid resolution.

For the characteristic fire diameter of 0.831 the grid resolution value was tested at 8.3, 10, and 11.5 to check for grid convergence. Since the quantity of interest in this testing is the ceiling temperature, the average ceiling temperature was compared between the three different mesh resolution values. This comparison can be seen in Figure 4.2. The grid resolution value of 10.0 differed from the grid resolution value of 8.3 by 2.6% when considering the peak average ceiling temperature. The grid resolution value of 11.5 differed from the grid resolution value of 10.0 by 0.5% when considering the peak average ceiling temperature. Although there is some advantage in increasing from a grid resolution value of 8.3 up to 10.0, the advantage when raising the value above 10.0 decreases rapidly. A greater increase above 10.0 to a value of 15 or higher may have a very slight advantage, but the computational cost of running a simulation at this resolution is not possible due to time constraints.

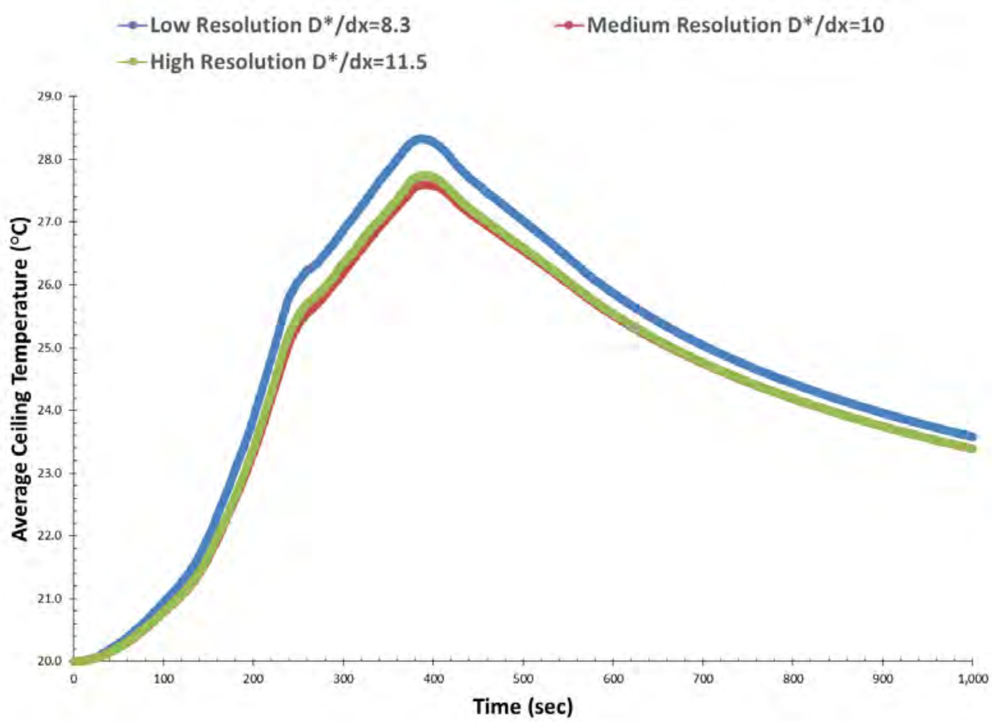


Figure 4.2: Grid resolution comparison showing the average ceiling temperature across the passenger compartment for three different grid resolution values. The ceiling temperature (the important parameter for this study) converges at a grid resolution value of 10.

The grid resolution value of 10 will be used yielding a final mesh of 324×150×48 with a total of 2,332,800 cells.

4.3 Creating an Average Bag

One goal of this research is to determine a single number value that depicts the allowed carriage of bags on a ferry. Even with only 6 bag types and a seat bank that includes 10 seats, the number of permutation for baggage arrangement is in the millions and far greater than is possible to test completely for this work. It is desired therefore to create an average scenario in terms of baggage placement. In order to do this there must be a single average bag with a specified heat release rate curve that can be placed in conjunction with the heat release rate curve of the seat. In order to create this average bag the carriage percentage for ferry vessels will be used in conjunction with the average weight of a bag to determine the average heat-release rate.

Baggage heat-release rate data was taken from the Kumm study [3] and used to create linear heat-release rate curves that specify the heat-release rate using between four and eight lines described by a series of time and heat-release rate coordinates. The area under these created curves was compared with the total heat released during testing of the baggage to ensure that the area under the curve matched the area under that data points given. Since each curve was specified using different points the time coordinates used to describe each curve were also different. Linear interpolation was used to ensure that for each unique time coordinate present for any bag, all bags had an interpolated data point for heat-release rate at that time. The heat-release rate approximation curves for all baggage are shown in Figure B.1 through B.6. The result was a heat-release rate value for every baggage type at each possible time coordinate. These heat-release rate values were then weighted based on the carriage rate of the particular bag type to get a single heat-release rate value for each time coordinate that describes the average heat released. The resulting average heat-release rate curve can be seen in Figure 4.3.

Now a correction must be made to the data based on the differences in measured weight of baggage between the Kumm study and the data taken from ferry

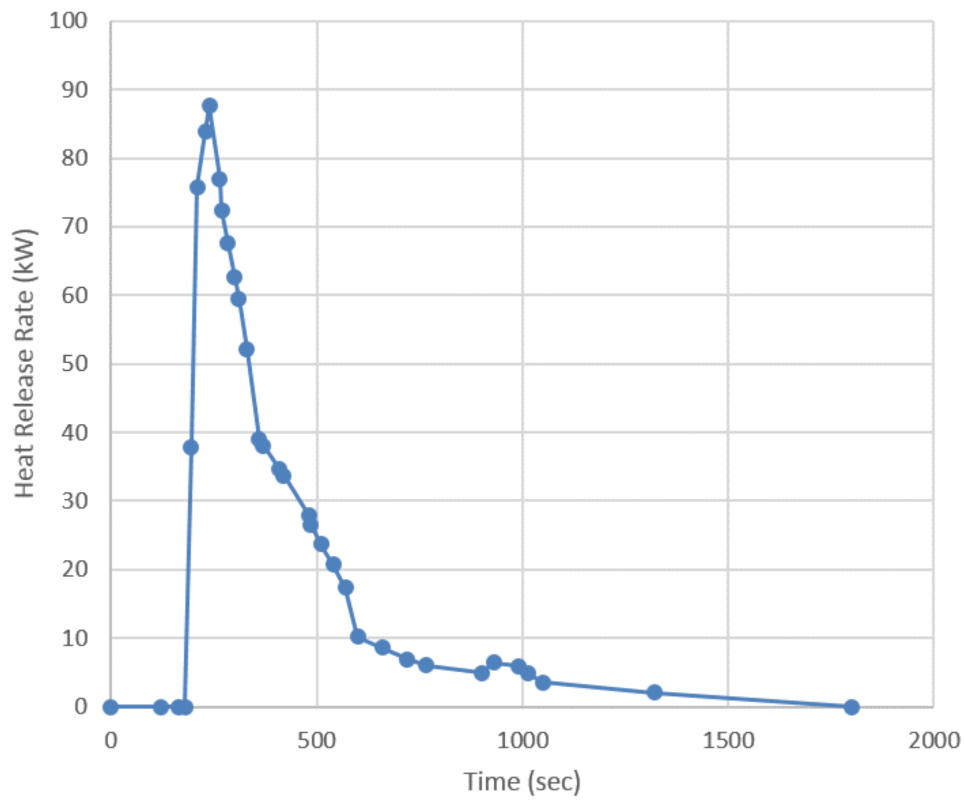


Figure 4.3: Weighted heat release rate curve for an average bag carried aboard a ferry.

vessels. The average weight of each baggage type is taken from Kumm and weighted based on the carriage rate from vessel surveys. The summation of these values gives the average weight based on the baggage weight given from the Kumm data of 2.4 kg (5.3 lbs). This compares to an average baggage weight of 3.7 kg (8.1 lbs) from vessel surveys. The heat-release rate at each time coordinate is then multiplied by the quotient of the average weight from vessel surveys and the average weight based on the Kumm study. This gives a curve that represents the heat-release rate curve of an average bag brought aboard a ferry vessel. This heat-release rate curve can be used alone to simulate a bag placed on the deck of a ferry or it can be added to the heat-release rate curve for a burning seat to create the scenario of baggage left behind on top of seat cushions.

4.4 Scenarios

A total of three scenarios were considered for this research. The first two configurations are scenarios which use an average bag heat-release rate combined with a particularly concerning baggage placement location to present dangerous, but not necessarily worst possible case scenarios. Due to the restricted entrainment into the fire plume caused by the corner configuration, a corner fire can have a significantly greater impact on overhead heating than a fire that occurs in the open due to the increased flame height and potential direct impingement on the overhead. To test this dangerous placement scenario, a stroller was parked in the corner, as had been seen during vessel surveys (seen in Appendix B), to determine if corner storage of baggage has the potential to compromise the structural integrity of the aluminum. Next the normally clear escape aisle between seat banks was occupied by a carry-on type bag to determine if the possible ignition of multiple seat banks, filled with average bags, would create a large enough fire to raise the aluminum overhead temperature above prescribed safe limits.

Finally a more common scenario was created that involved the burning of one seat bank consisting of ten total seats arranged in two back to back rows of five seats each. This scenario represents the current seat bank size limitation imposed on builders who wish to use the Coast Guard exemptions from structural fire protection insulation. This scenario will include the addition of the average bag on top of each seat within the seat bank. This scenario will be tested to determine the extent of heating of the aluminum overhead, and to ascertain whether the addition of bags on the seats creates a fire big enough to ignite additional seats banks around the initial fire.

4.4.1 Stroller in the Corner

It was observed during ferry vessel surveys that strollers were present on nearly every non-commuter ferry run. The placement of these stroller was concerning as in some cases they were placed in escape aisles, against walls, or even in compartment corners. The study by Kumm gave a peak heat-release rate of a stroller (called a Pram in that study) of 830 kW, with a total energy released of 179.1 MJ [3]. This energy content is greater than any of the other single items of baggage and is therefor a significant concern. Although a stroller parked within an escape aisle could potentially spread the fire to several adjacent seat banks, this scenario is seen as not occurring frequently as most strollers are stored elsewhere and due to the large size of a stroller relative to a bag it could not be stepped over during escape and would have to be pushed or otherwise moved out of the aisle during vessel evacuation. The dang common scenario is for a stroller to be parked in the corner of the space as seen in Figure 4.4. The stroller was set up as a simple box in FDS with a prescribed heat-release rate according to an accompanying ramp function, done to maintain consistency between the method of modeling the seats and the baggage. The stroller box was given dimensions of 1.0 meters (39.4 inches) long by 0.5 meters (19.7 inches) wide by 1.0 meters (39.4 inches) high, and was placed against each wall of the corner to simulate being parked in the corner. Temperature measurement devices were placed on both of the corner walls as well as the ceiling above the burning stroller.

4.4.2 Burning of Two Seat Banks

Although bags are normally restricted from being placed in escape aisles, it is possible that baggage could be placed there or left there during evacuation, leading to the potential ignition of seat banks on either side of the escape aisle. To test this scenario a carry-on bag was modeled in FDS as a 0.56 meter (22 inches) by 0.36 meter (14 inches) carry-on type bag placed on the deck at the exact midpoint between two seat banks as shown in Figure 4.5. A carry-on type bag was selected

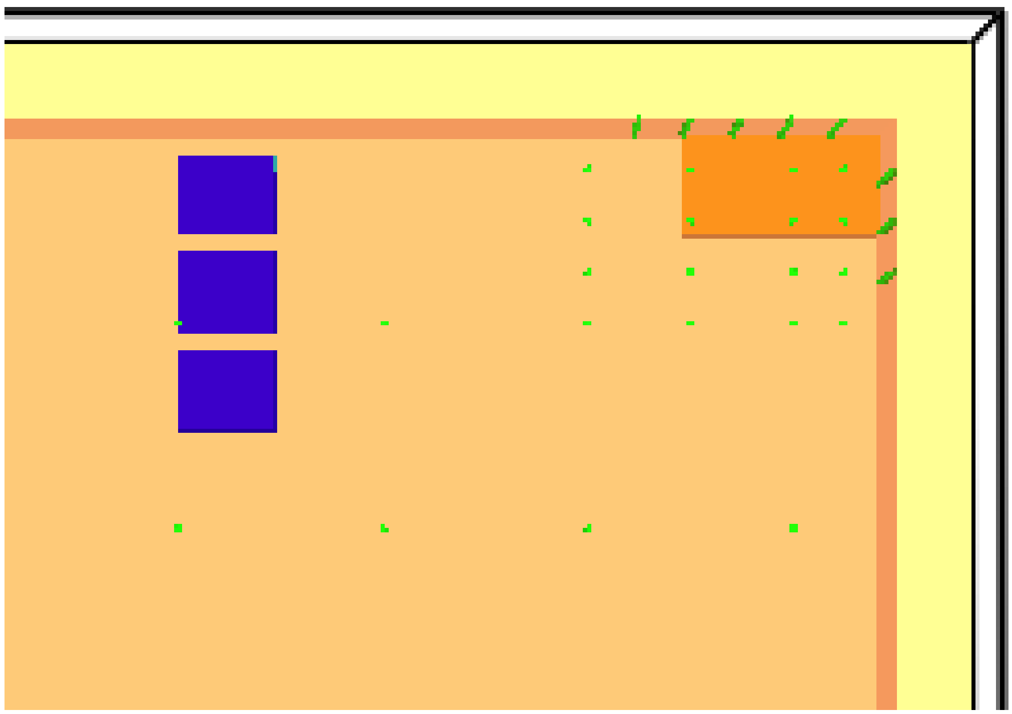


Figure 4.4: FDS setup for burning of the stroller in the corner.

because it has the highest heat-release rate of any bag (stroller excluded) that may be carried into a passenger compartment. The width of the aisle was made to be 0.76 meters (30 inches), which is the maximum aisle width allowed by Coast Guard regulations. The maximum possible aisle width was used for this simulation because if this aisle width allows the ignition of adjacent seat banks, a smaller aisle width will also certainly cause ignition. The adjacent seat banks each consist of ten total seats with each bank being arranged in two rows of five seats placed back to back. This creates the tightest concentration of seats possible within the current requirements.

Radiative heat flux gas gauges were placed on each of the four seats closest to the burning carry-on bag, with the placement being as near center line of the seat bank as possible. The heat flux gauges can be seen in Figure 4.5 on the left hand side as green dots. If the heat flux is recorded at any time as exceeding the critical heat flux value of 10 kW/m^2 than the ignition equation will be utilized to determine if the seats ignite. If the seats ignite, the simulation will be reprogrammed with burning seats and the heat flux gauges would be moved to the next adjacent seat. This process will continue until all seats are burning, until the fire no longer causes ignition of the next seat, or until critical temperatures are reached for the aluminum structure. The average bag heat-release rate will be added to any seats that are determined to ignite so that this scenario will consider a fully loaded ferry vessel.

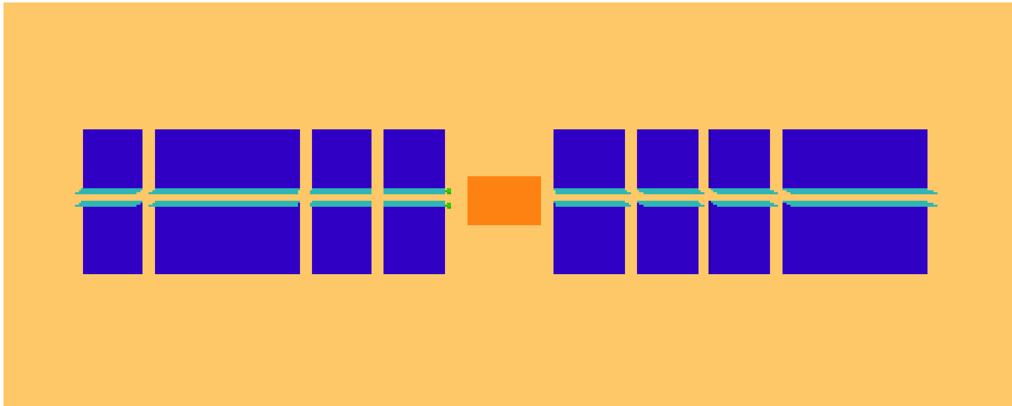


Figure 4.5: FDS setup for burning of two seat banks. The burning carry-on bag is shown by the orange box in the middle, with the seat cushions shown in blue. Heat flux gauges for the left hand seats are visible as two green dots, which are oriented to face the fire.

4.4.3 Burning of a Single Seat Bank

The final scenario to be tested is the burning of a single bank of ten seats with the addition of an average bag on each seat. The ten seat bank consists of two rows of five seats each, placed back to back. This is the largest single seat bank allowed by the current exemption policy requirement given in MTN 01-13. A ten seat bank of the same size was tested by Shriner without any baggage or additional loading and found to raise the ceiling temperature to 55°C. The addition of the bags to the seats will determine what temperature the ceiling will reach with the additional heat released from an average bag. This will aid in determining if the carriage of baggage at its current level, as measured during vessel surveys, is sufficient to raise the ceiling temperature over any square meter to a critical value of 200°C. In addition heat flux gauges were placed on each of the seats across aisles and across

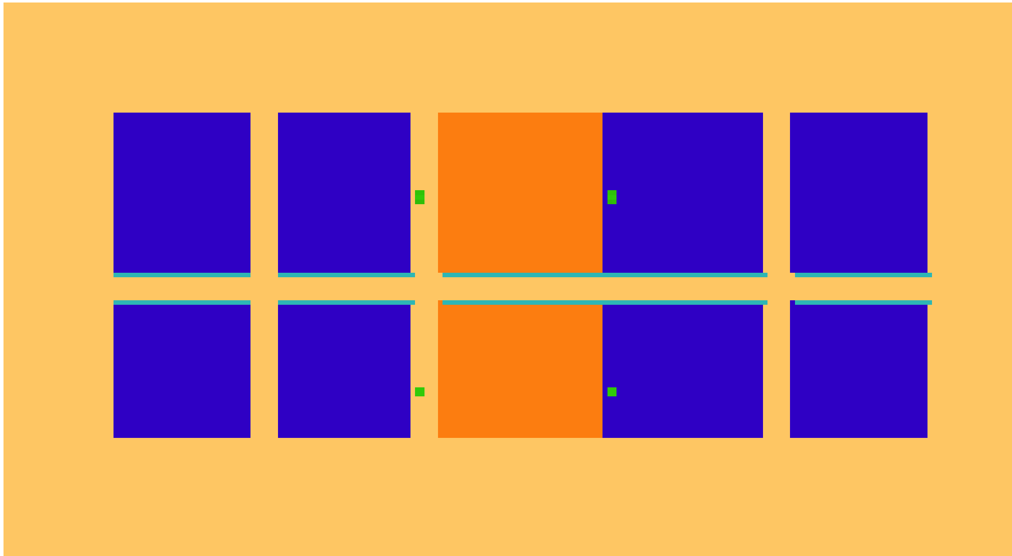


Figure 4.6: FDS setup for burning of a single seat bank. The initial seats set on fire are indicated as orange seats, with heat flux gauges shown as green dots.

knee gaps to determine if any adjacent seat banks will ignite now that the seat bank fire is larger with the addition of bags. Heat flux gauges were placed on the closest edge of each seat oriented to face the fire and located as shown in Figure 4.6.

Chapter 5: Results & Analysis

5.1 Simulation Results

5.1.1 Stroller in the Corner

The simulation of the stroller placed in the corner of the space reached its peak heat release rate 120 seconds into the simulation and maintained this heat release rate until 240 seconds, at which point the heat release rate began to decline sharply. The peak ceiling temperature closest to the corner was 821°C, a value sharply in excess of the 555°C melting temperature of the 6082 Aluminum alloy commonly used in ship superstructures [1].

Figure 5.1 shows the ceiling temperature measured above the burning stroller in the corner of the space. The melting point of the material is also shown, along with the temperature at which the aluminum has lost approximately 50% of its structural integrity [22]. The aluminum ceiling maintains a temperature above the melting temperature for a period of 156 seconds and maintains a temperature above the 50% loss of structural integrity for a period of 367 seconds. According to MTN 01-13 no single point of the aluminum deck shall reach 400°C and the temperature over any square meter must no reach 200°C. Both of these limitations are exceeded

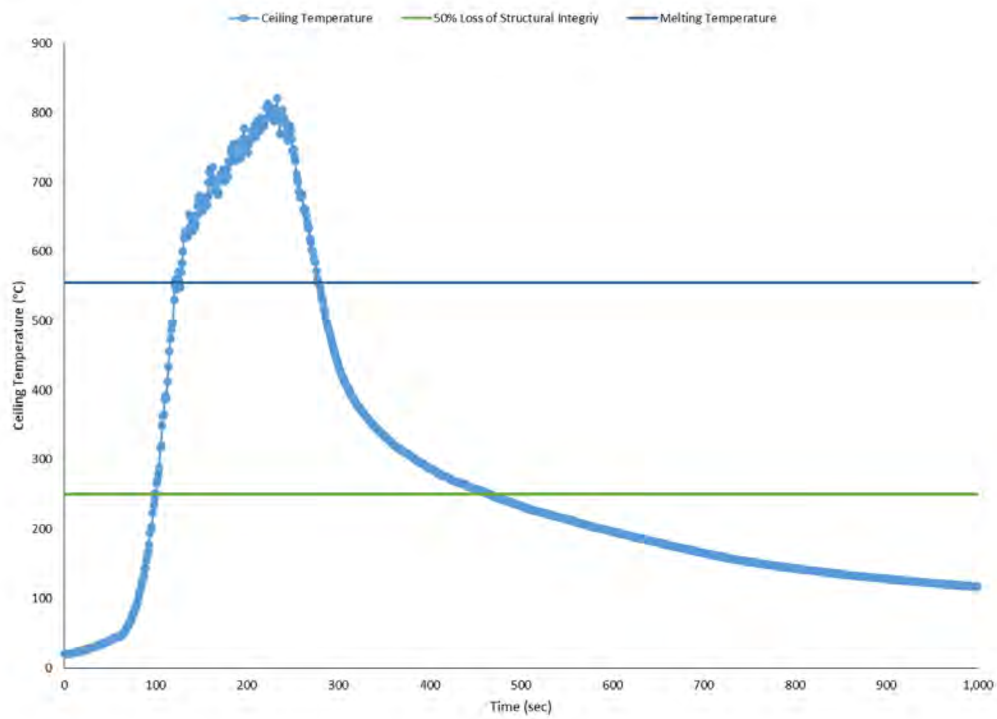


Figure 5.1: Corner ceiling temperature above burning stroller.

in the ceiling of the passenger compartment in which the stroller fire takes place in a corner.

In examining the results of the stroller fire it is important to consider the size and type of the stroller that is modeled in the space. The study that provided the heat-release rate data used to model the stroller fire was conducted in Sweden, meaning that the type of stroller may be different than those used in the United States. The weight of the stroller used for the full-scale testing in Sweden was 15.1 kg, while strollers in the United States are often as lightweight as 5.0 kg. Although strollers used in the United States can weigh as much as 20.0 kg, using data from a 15.1 kg stroller means that the simulation conducted leans towards a worst case scenario with a heavy stroller. The stroller used in the Swedish study was also constructed with a metal frame weighing 5.4 kg; which contributes nothing to the heat-release rate, while a plastic frame frequently used in today's strollers in the United States may contribute significantly to the heat-release rate of the stroller. In addition to the stroller itself, there could be notable weight increases depending on the blankets, pillows, and diaper content of the stroller or the bags that could be attached or stored underneath in stroller storage bins. Observations of a stroller, filled with goods adjacent to a pile of newspapers and waste basket in the corner of a surveyed vessels raises concerns that the modeled heat-release rate could be reached in a real passenger compartment.

5.1.2 Burning Bag In Aisle

For the second scenario, the carry-on bag placed in the center of the escape aisle caused the nearest seats to exceed the critical heat flux of 10 kW/m^2 at 234 seconds. The heat flux continued to increase and at 306 seconds the heat release rate per unit area reached 19.7 kW/m^2, creating an average over 72 seconds of 15.8 kW/m^2. Using Equation 4.1 from Shriner, an average heat flux of 15.8 kW/m^2 will cause ignition in 69.9 seconds, indicating that all four seats adjacent to the carry-on bag will ignite from the side at 306 seconds.

Following this same process, the next four seats ignite at 515 seconds, the following four seats at 725 seconds, and the last four seats in the two seat bank ignite at 1148 seconds. Figure 5.2 shows the heat-release rate from the fire with the ignition point of each subsequent "set" of four seats indicated. Although there are several peaks, the highest heat-release rate peak of 1255.5 kW occurs 966 seconds into the simulation. The peak is reached at this time because it corresponds to the time at which the first four burning seats decrease to a heat-release rate of only 60.1 kW/m^2 from their peak at over 200 kW/m^2. At this point the first set of four seats is effectively burned out, and the second set of four seats has dropped below half of its peak heat-release rate. The average temperature of the aluminum overhead in the area of the fire at this time is 161°C, and continues to increase.

The two criteria for the aluminum ceiling temperature are that the aluminum not reach a temperature of 400°C at any point, and that the average over any square meter not reach a temperature of 200°C. These values are taken from the

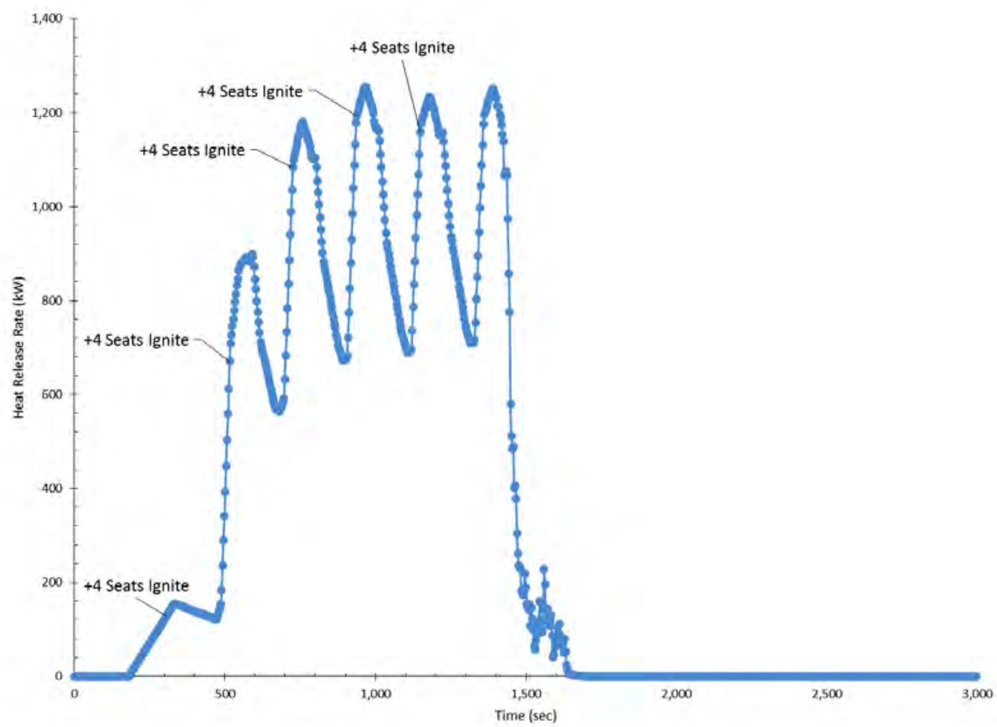


Figure 5.2: Heat-release rate from a simulation of burning of two seat banks.

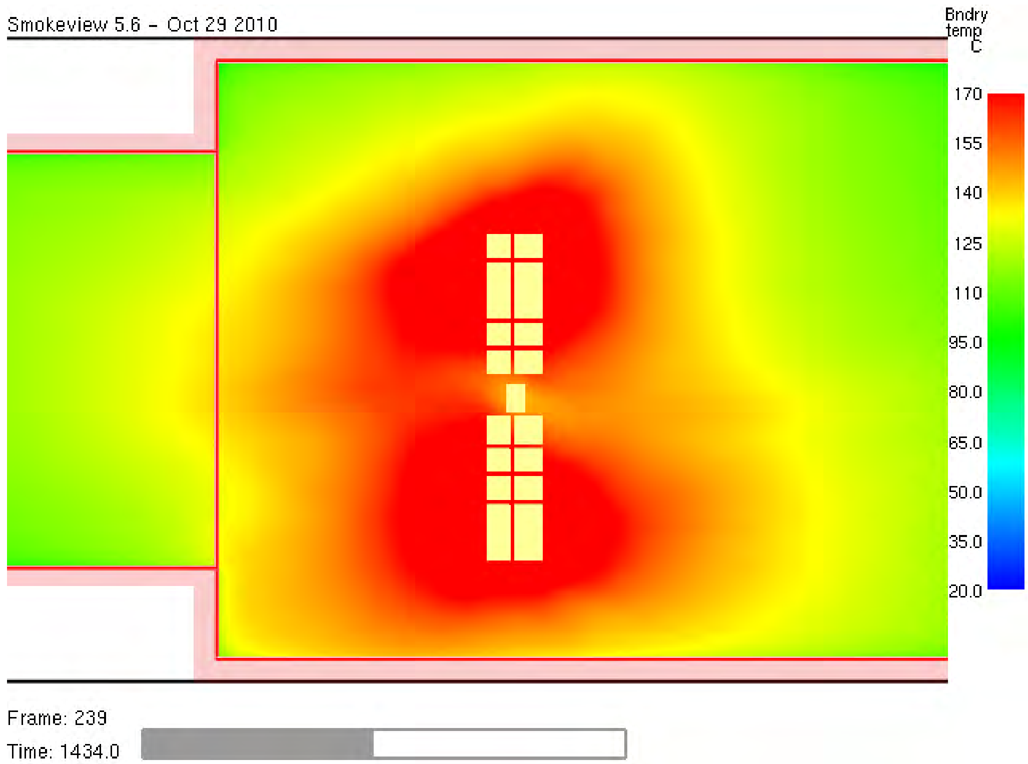


Figure 5.3: Ceiling temperature profile above two burning seat banks at 1434 seconds after ignition of the carry-on bag.

policy requirements published in MTN 01-13. The maximum single point ceiling temperature reached during the simulation is 363°C, a highly elevated temperature, but still within the requirements.

The average temperature over a square meter was not considered in the center above the carry-on bag, but rather centered above the outer four seats to burn on the lower end in Figure 5.3. Since the carry-on baggage burns out first, the ceiling directly above it does not reach the highest temperature. Also the relatively low density of fire load in the area of the bag, particularly given the openness of the aisle and the low height of the fire due to the bag being on the floor, means that

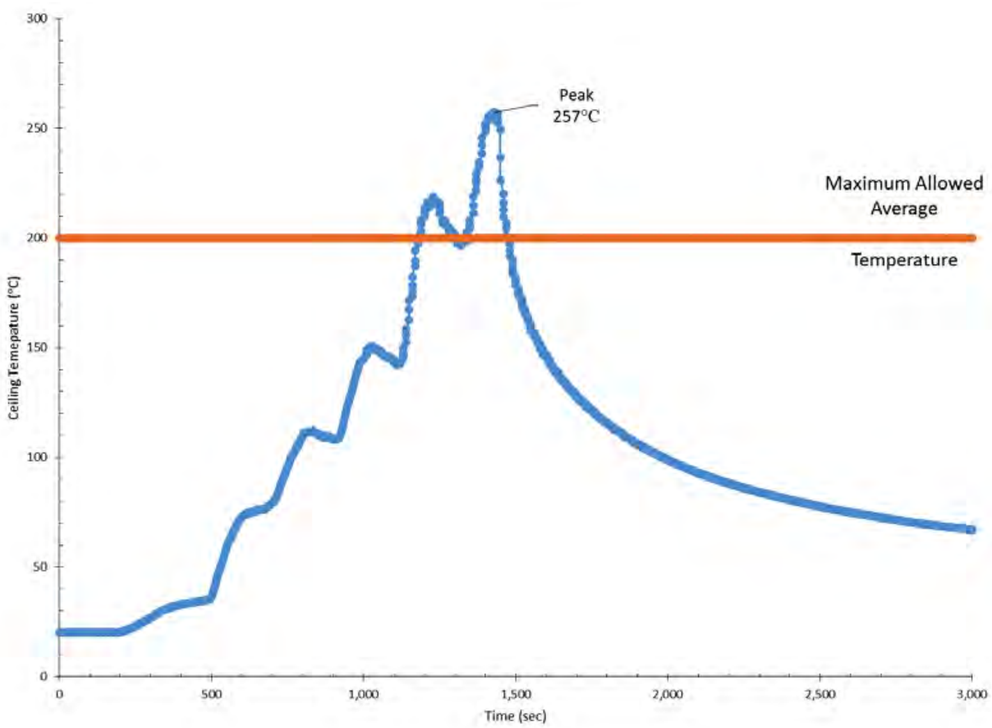


Figure 5.4: Average temperature over the square meter of ceiling above the lower four burning seats.

the fire does not heat the ceiling to critical temperatures at that point. The ceiling above the lower and upper four seats at either end of the seat banks is essentially preheated by the carry-on and first six seats, after which the temperature peaks when the last seats are ignited. This shapr increase can be seen in Figure 5.4, which shows the average temperature of the ceiling above the lower four seats of the two seat banks. The average temperature of the square meter above these seats reaches a maximum value of 257°C at a time of 1420 seconds, just under 24 minutes into the simulated fire. This value clearly exceeds the maximum of 200°C over a square meter, and also exceeds the temperature at which there is a 50% loss of structural integrity for 6082 Aluminum.

5.1.3 Single Burning Seat Bank

The single seat bank simulation was conducted assuming that a burning bag or other heat source tucked underneath the seat causes middle ignition of the two back to back seats at the center of the 10 seat bank. The heat flux measured at the adjacent seats reached 10 kW/m^2, a critical value, 116 seconds into the simulation and had an average heat flux of 16.1 kW/m^2 over the next 65 seconds leading to ignition of the next seats at 181 seconds. With a total of six seats now burning, the remaining four adjacent seats in the current bank ignite at 385 seconds. The ignition times were calculated using Equation 4.1 as before.

Even with all 10 seats and their associated baggage burning, the ceiling temperature above the single seat bank does not reach critical levels; therefore, the

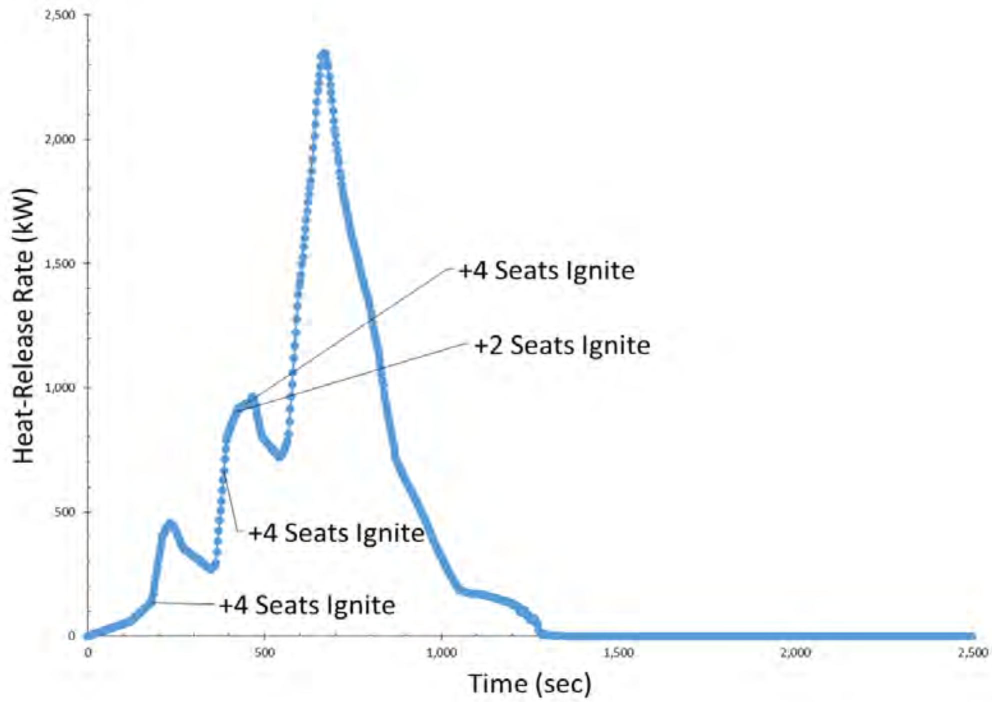


Figure 5.5: Heat release rate from a single bank of burning seats with baggage.

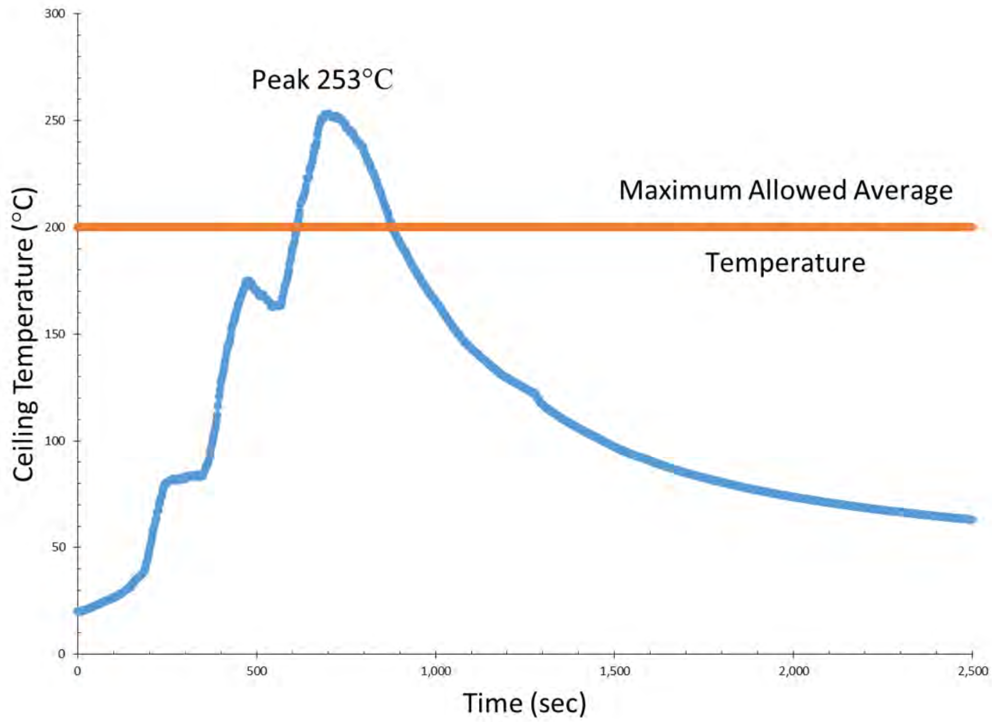


Figure 5.6: Average ceiling temperature over one square meter above burning single seat bank.

potential for spread across the knee gap on either side must now be considered. Heat flux gauges were placed on the leading edge at the middle of seats across the knee gap on either side of the burning seat bank. The middle seats across the knee gap receive critical heat flux starting at 348 seconds, and ignite at 419 seconds. The next four seats across the knee gap ignite a mere 30 seconds later at 449 seconds into the simulation. The quick succession of ignitions is seen in Figure 5.5 and causes an ensuing spike in the heat-release rate and ceiling temperature of the compartment.

The two criteria for the aluminum ceiling temperature are again that the aluminum not reach a temperature of 400°C at any point and that the average over any square meter not reach a temperature of 200°C. The maximum single point ceiling temperature reached during the simulation is 291°C at 725 seconds, safely below the maximum allowed temperature of 400°C. The average temperature over any square meter was considered in the center directly above the middle seats in the single bank of seats. The average temperature of the square meter above these seat, as shown in Figure 5.6, reaches a maximum value of 253°C at a time of 700 seconds, only 11.7 minutes into the simulated fire. This critical temperature is reached quickly for the single seat bank simulation because of the quick succession of seat ignitions across the knee gap between seat banks.

5.2 Analysis of Results

5.2.1 Evacuation Carriage

An important consideration in determining the contribution of baggage to a fire in a passenger compartment is how many bags are removed from the space by passengers during evacuation. The size and openness of a ferry vessel passenger compartment, in comparison to an airplane, provides little motivation to study the carriage of baggage during evacuation; and it has not been exhaustively studied. In the commercial airline industry the carriage of baggage during evacuation is of significant concern. Flight attendants are trained to instruct passengers to leave behind baggage during evacuations and in some cases are trained to take baggage from passengers as they are leaving to ensure that bags do not cause evacuation delays. In addition, airplane evacuation tests include piles of carry on luggage in the aisle to simulate the delays caused by baggage. Although the present research is not concerned specifically with evacuation time, there is an undeniable connection between the carriage of baggage during evacuation and the transient fire load in the passenger compartment that is the subject of this research.

The current simulations were completed with the assumption that all of the baggage brought aboard the ferry vessel remains in place in the passenger compartment during the evacuation of the passengers. This would be the worst possible situation in terms of the transient fire load, and thereby gives a conservative estimate which is often desired when making life safety decisions. However, if a large percentage of people take baggage with them during evacuation, this may have a potentially huge impact on the size of the fire in the compartment and the potential for spread between seat banks.

An airline survey conducted by the National Transportation Safety Board (NTSB) in 2000 indicated that 46.8% of respondents who had been involved in an airplane evacuation attempted to retrieve baggage prior to evacuating the airplane [23]. In the airplane environment it is harder to carry a bag because of tight aisles, and retrieval can be difficult and time consuming due to overhead compartments; thus there are a number of factors to discourage people from taking baggage with them during a plane evacuation. These same discouragements are not present on a ferry vessel, and the carriage rate during evacuation could potentially be even greater. If baggage is stored at people's feet or in the seat next to them it is second nature to retrieve the bag while getting up to begin evacuation. Passengers that retrieved baggage during an airline evacuation reported that they needed to retrieve bags because of medicines, job items, keys, wallets, and credit cards. These same motivations will be present during a ferry evacuation and will provide incentive for people to take bags with them during evacuation.

Ship evacuation studies typically focus on larger vessel such as cruise ships and are more concerned with response and evacuation time rather than carriage of baggage or purses, so very little data exists on carriage for ferry vessels [24–26]. However, given the natural desire of people to take bags with them, particularly if they have money, wallets, medicine, or important papers in the bags, it can be surmised that at least some people will try to take baggage with them during evacuation. That means that although the exact amount cannot be pinpointed without further research, it is known that some percentage of people will attempt to take baggage with them during evacuation. Given that airline studies indicate almost half of people carry bags with them, means that a factor of safety as high as two may be built in to the simulations given the assumption of all bags remain within the space.

5.2.2 Extent of Simulations

The single seat bank burning has a peak average temperature over a square meter of 253°C, a temperature equal to that created by the burning of two seat banks. In addition the heat-release rate for the single bank of seats is significantly greater than that of the two seats banks. The reason for this is the methodology used to calculate the spread of the fire along the seat banks. The procedure used was to first consider the burning of the seat bank or banks in question, determine if the ceiling temperature reached critical values, and then consider ignition of seats across the knee gap only if the initial seat bank(s) did not reach critical temperatures. The single seat bank fire did not reach critical temperatures and so the spread across the knee gap was considered. This knee gap spread led to the ignition of six additional seats within 30 seconds of simulation time, and thus created a quick peak temperature that easily exceeded critical values. The two burning seat banks on their own exceeded the critical value of 200°C and thus the knee gap spread was not considered. Were this type of spread considered the heat-release rate and temperature of the two seat banks should easily exceed that of the single seat banks. Since the goal of the research was to consider the pass/fail criteria of the critical values, and due to time constraints caused by long simulation times, the full extent of the fires was not considered past the critical average ceiling temperature. This means that the burning of two seat banks, with knee gap fire spread considered could potentially be significantly worse than indicated at later times.

5.2.3 Practical Considerations

Prior to drawing conclusions and making recommendations about the allowed carriage of baggage, it is important to determine what possibilities for policy change are realistic and which are unrealistic or impossible. The simplest method for measuring and meeting the current Coast Guard policy requirements would be to weigh each bag brought aboard the vessel and require that all baggage be less than the maximum weight per person calculated using the seat density of each particular vessel. This would place an unreasonable restriction on baggage, as very few bags are under the 1.4 kg (3.1 lb) weight restriction necessary for high seat density vessels. This measure would also be impossible for companies to enact as the time required to weigh each piece of baggage would prevent ferry vessels from running on a regular or predictable schedule.

If the weight of the baggage cannot be effectively managed, the number of bags brought aboard is another option. Limiting the number of bags carried by each person, or perhaps limiting the relative size of the baggage, would allow a reasonable and possible limitation on the transient fire load place in the compartment. This measure could only be effective and realistic if the ferry vessel was able to provide additional compartments specifically for the storage of baggage that is not allowed into the passenger compartment. As such, this measure would create additional burdens on the company, but is potentially realistic from an operations standpoint.

One final possibility is to alter the storage of the baggage within the compartment itself. Eliminating stowage of strollers or bulky items in compartment corners, and preventing storage of baggage on top of seats are two possible options. For the present study baggage was considered to be placed on top of seat cushions, the likeliest location based on vessel surveys. If however, the baggage were placed underneath seats, or in special storage compartments between aisles, the potential for fire size may be decreased. Baggage stored underneath the seat would limit the height of the fire plume, and thus result in lower ceiling temperatures. In addition the decreased height of the fire could have a positive impact in limiting the spread of the fire across knee gaps and aisles. However; this option would require major modifications to passenger compartments to ensure adequate stowage options, as well as additional training for crews and lengthy re-education of passengers who are accustomed to a high degree of behavioral freedom on ferry vessels as compared to an airplane.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

It is clear that the current level of carriage aboard aluminum passenger ferries with type 5A spaces presents a significant danger in terms of increasing the fire load within the space. It is relatively simple to calculate and control the fixed fire load within a space, but controlling the baggage and baggage content brought aboard by passengers is neither simple nor straightforward. Although some companies have strict baggage policies in place, these policies are not fully able to account for the weight of every piece of baggage brought aboard, and as a result Coast Guard policy requirements are not strictly met. Survey data indicates that the current average baggage weight of 3.7 kg exceeds that allowed by Coast Guard policy for 93% of vessels, with the remaining 7% falling within the policy requirements due to unusually low seat density in the main passenger compartment.

The weight of baggage brought aboard ferry vessels has the potential to raise the temperature of the aluminum ceiling above 200°C in less than 12 minutes when a fire occurs with baggage left on top of seats. The aluminum ceiling reaches a temperature of 253°C, corresponding to a loss of more than 50% of the structural integrity of the aluminum and creating the potential for a lethal structural failure.

This structural failure would endanger the lives of passengers that may be gathered on the deck above in preparation for abandoning ship. In addition there are at least two further scenarios, a stroller parked in the corner of the compartment and a carry-on bag in the middle of an escape aisle, that also create dangerous situations and exceed current temperature limitations. In the case of the stroller on fire in the corner of the compartment the danger is exceedingly great as the melting temperature of aluminum is exceeded for a period of two and a half minutes, which would assuredly result in significant damage to the vessel's superstructure.

6.2 Recommendations

A simple solution to the problem would be to limit the weight of baggage each person is allowed to bring aboard to 1.4 kg (3.1 lbs) per person, the value that corresponds to the weight limit per area of 2.5 kg/m^2 for the vessel with the greatest seat density. However, this would unnecessarily restrict vessels with low seat densities and would place an unreasonable restriction on baggage weight by eliminating the carriage of 96% of bags currently brought aboard vessels. In addition the effort and time of weighing each individual bag as it comes on board would severely impact the current business procedures of ferry companies who depend on a swift unloading and reloading in order to maintain tight schedules. It would also be unrealistic to expect to eliminate transient fire load altogether as passengers have a reasonable expectation that they will be able to carry at least some personal belongings with them, particularly those belongings that may be necessary for use during transits.

A more practical solution may be to limit baggage to one small size bag per person. Persons that attempt to bring aboard multiple bags or larger items such as suitcases (even carry-on size suitcases) could be limited to one small bag with which to carry valuables and important belongings, while having remaining baggage stored in a sprinkler protected luggage compartment. For items in contention, a weight limit of either 4.5 kg (10 lbs) or 6.8 kg (15 lbs) could instituted. The decrease in the weight of the average bag associated with imposing these weight limits would mean that 28.8% of vessels would be in full compliance with Coast Guard policy requirements with the limit set at 6.8 kg (15 lbs) and 62.7% of vessels would be in full compliance with Coast Guard policy with the limit set at 4.5 kg (10 lbs). In addition it would be necessary to make provisions for large bulky items such as strollers so that these items would not be placed in corners, along walls, and in escape aisles where they could inhibit evacuation and result in dangerous fire scenarios. Finally, storage of all items could be strictly eliminated in problem areas such as corners, against walls, and in escape aisles.

Appendices

Appendix A: Vessel Survey Data

Additional data from the vessel surveys is provided here; including histograms for individual bag types, weight data from measured bags, and carriage distribution graphics.

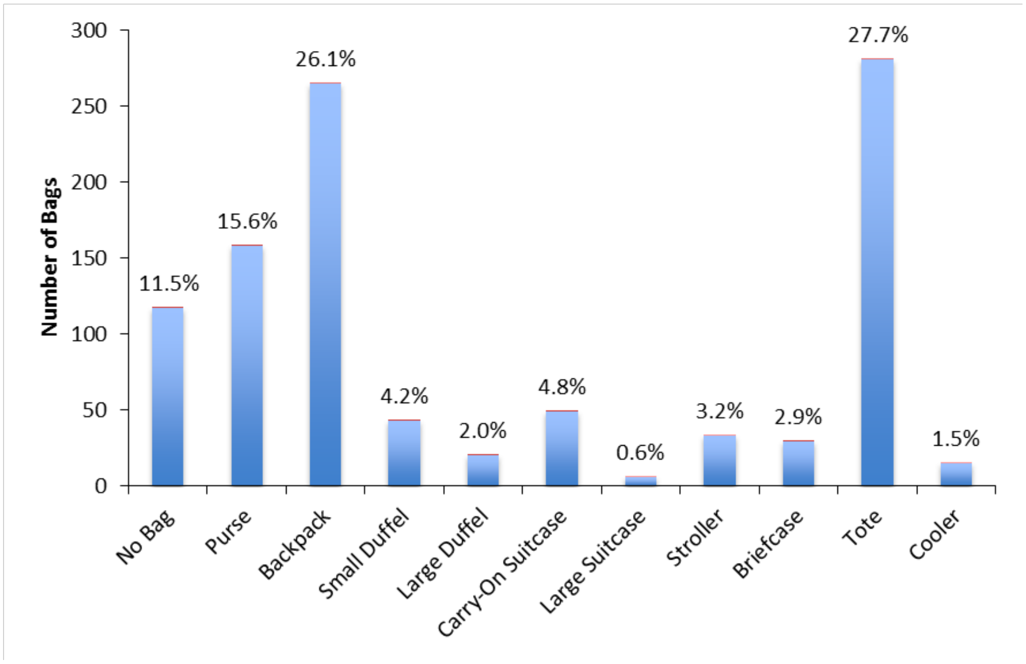


Figure A.1: Baggage carriage distribution for ferry vessels.

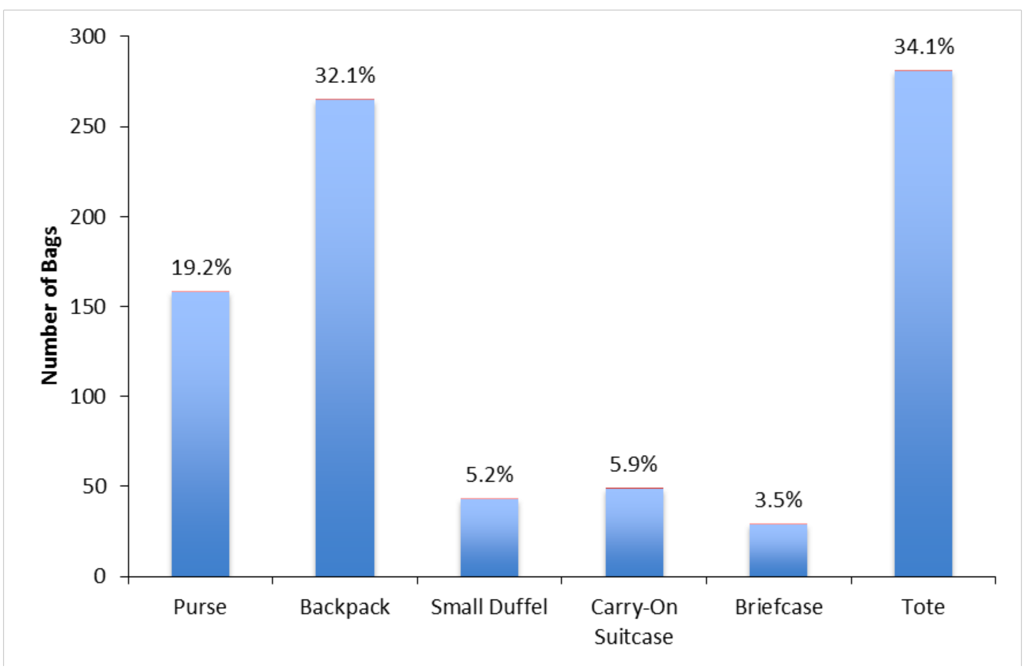


Figure A.2: Baggage carriage distribution including only small bags carried into the passenger compartment.

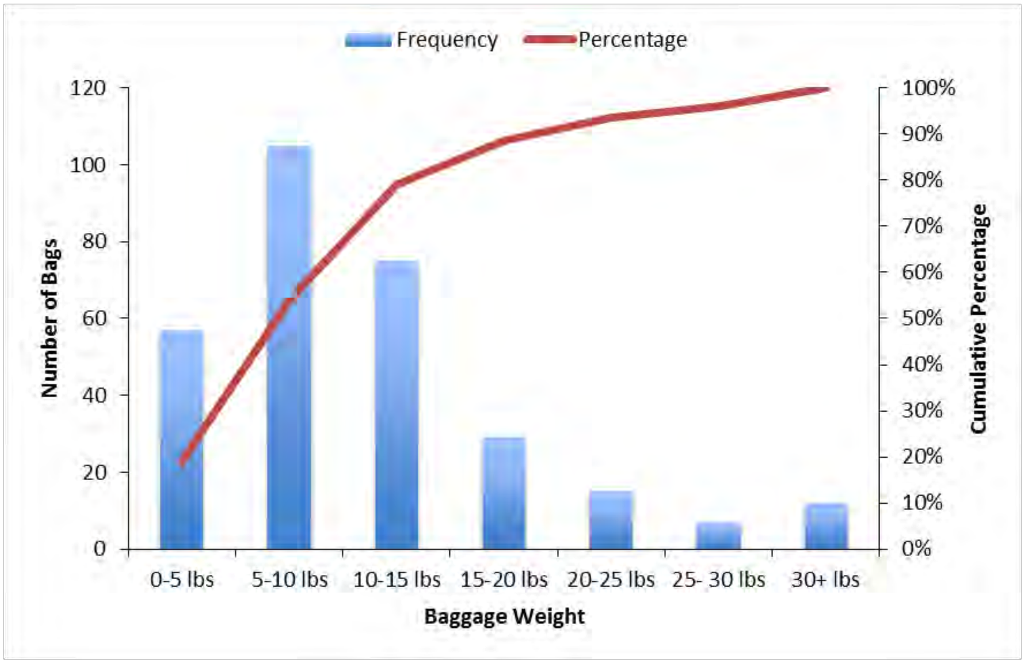


Figure A.3: Baggage weight histogram for all baggage combined.

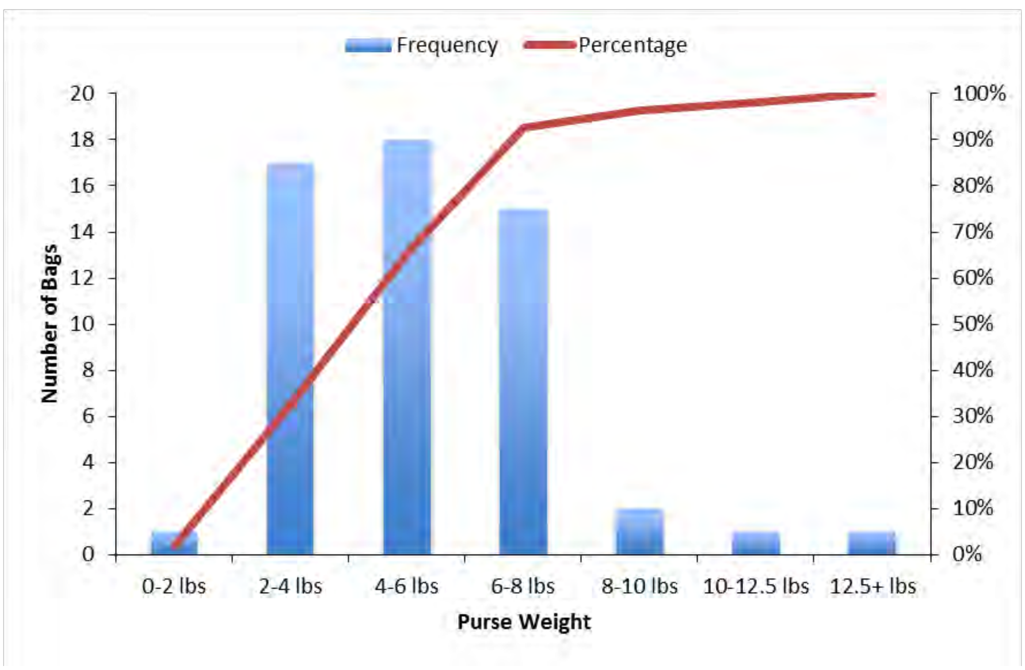


Figure A.4: Baggage weight histogram for purse.

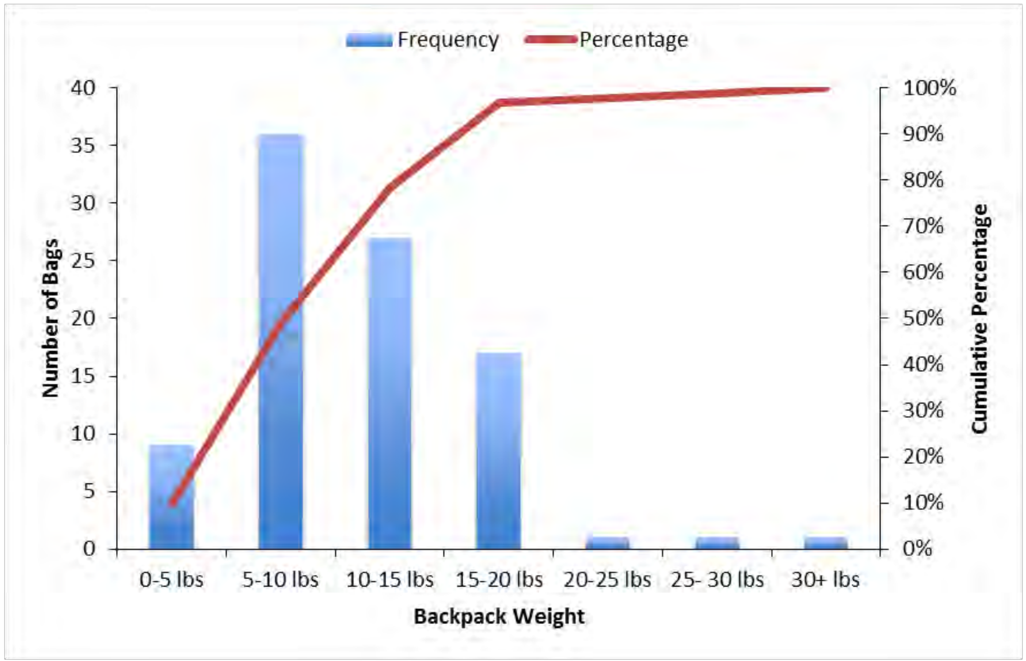


Figure A.5: Baggage weight histogram for backpack.

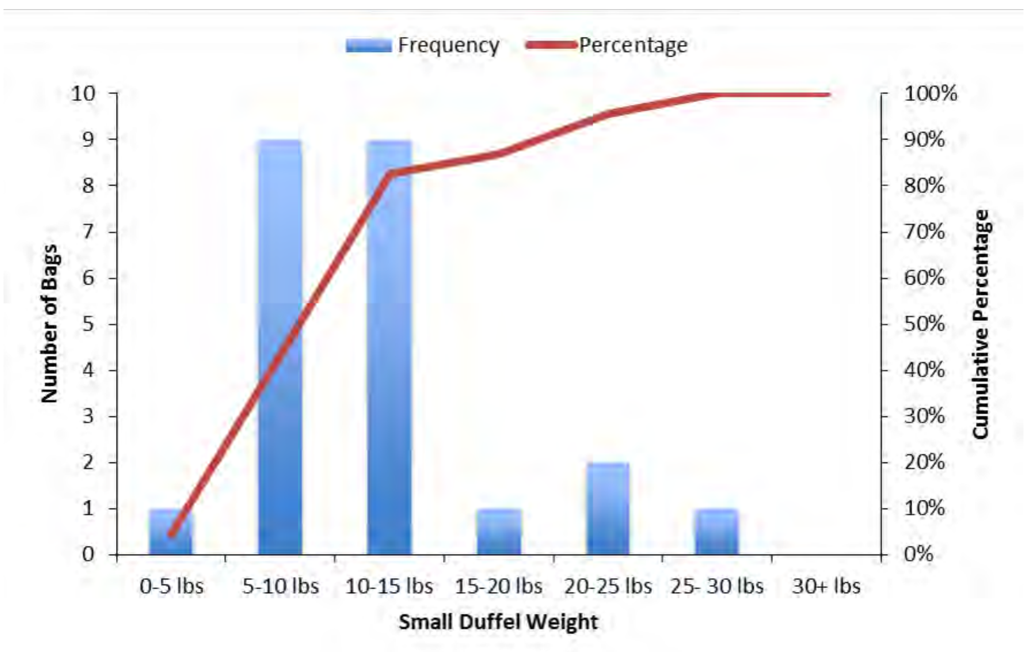


Figure A.6: Baggage weight histogram for small duffel bag.

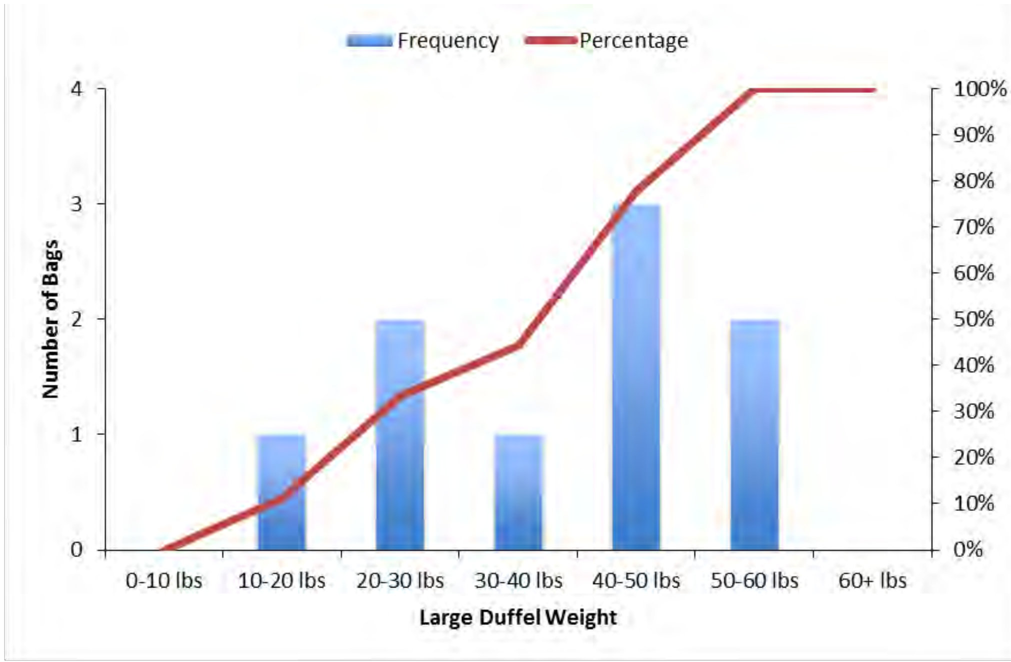


Figure A.7: Baggage weight histogram for large duffel bag.

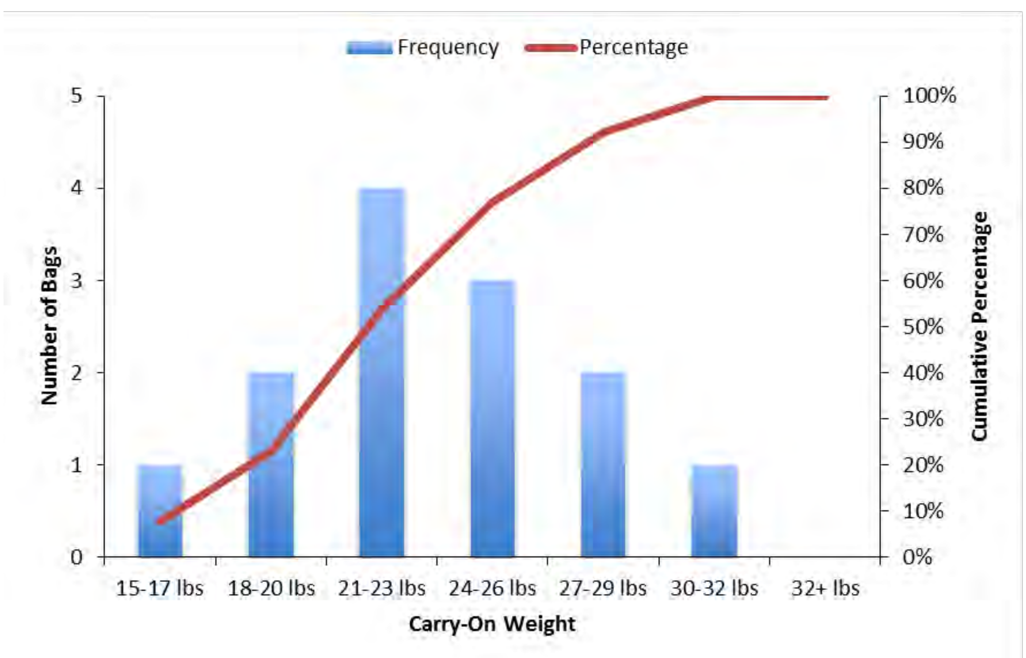


Figure A.8: Baggage weight histogram for carry-on size suitcase.

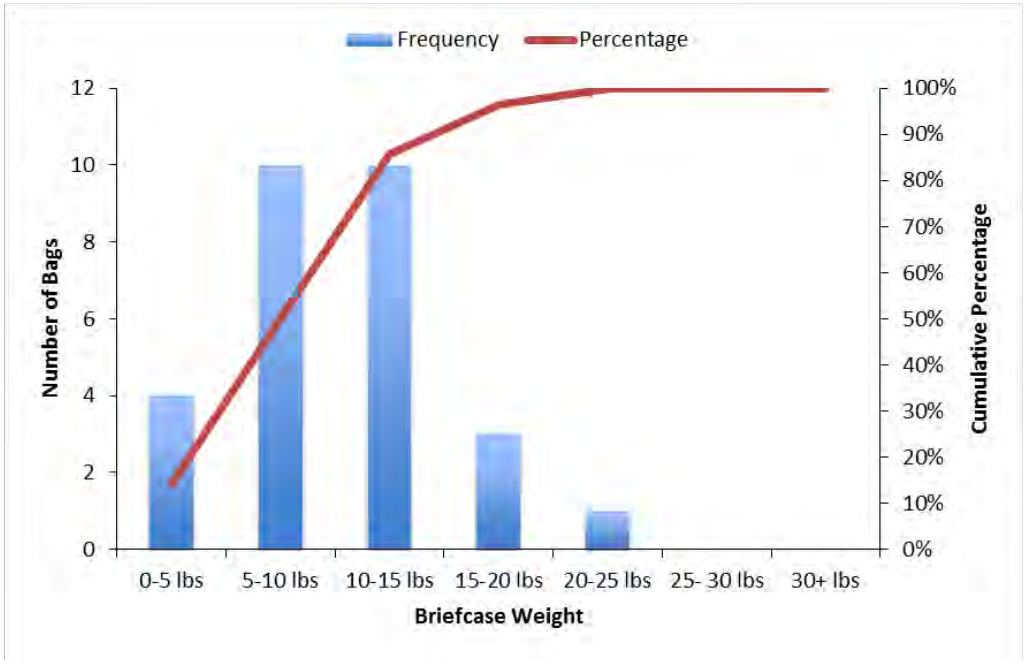


Figure A.9: Baggage weight histogram for briefcase.

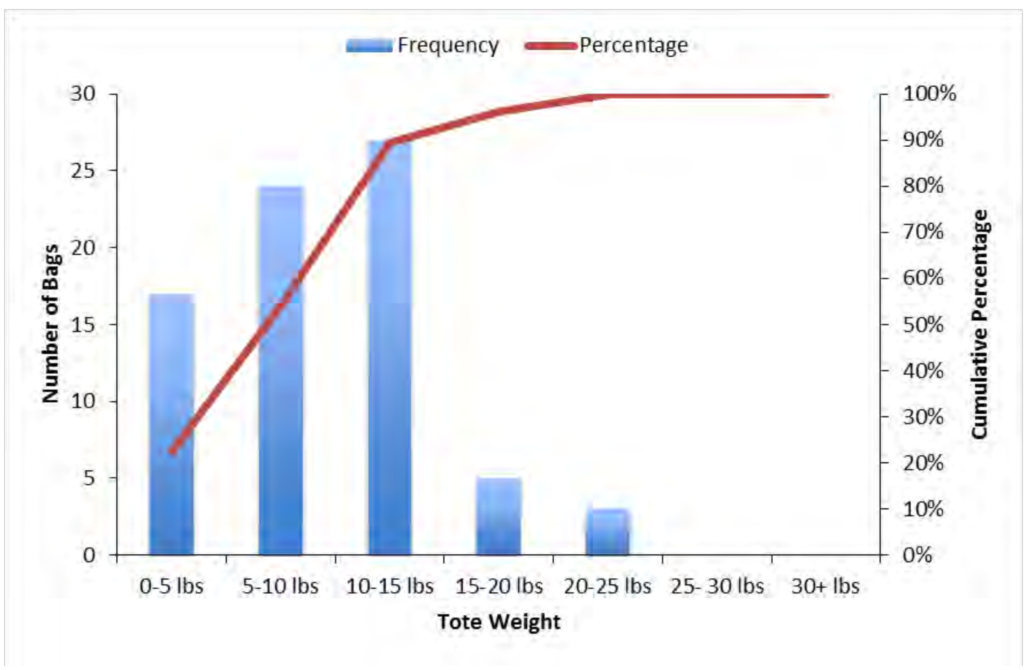


Figure A.10: Baggage weight histogram for tote bag.

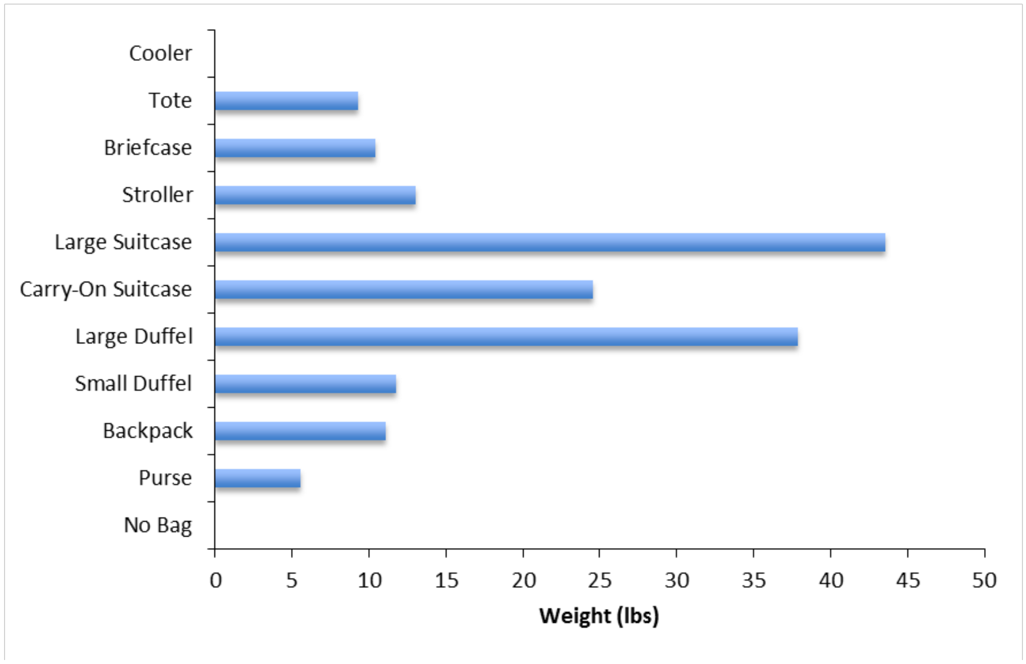


Figure A.11: Average weights of each specified baggage type.

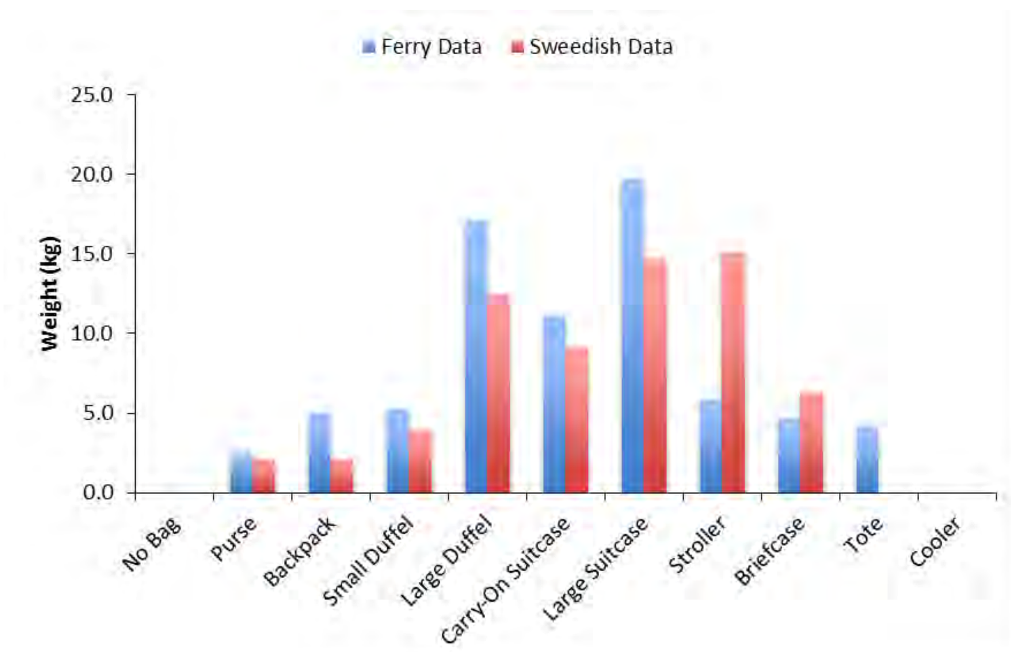


Figure A.12: Comparison between average weights from Swedish Study [3] and vessel survey data.

Backpack Weights (kg)		Briefcase Weights (kg)	Carry-On Weights (kg)	Large Duffel Weights (kg)	Suitcase Weights (kg)	Purse Weights (kg)	Small Duffel Weights (kg)	Tote Weights (kg)	
1.3	4.9	1.6	8.0	8.7	15.1	0.9	2.0	0.5	5.7
1.4	5.0	1.7	9.3	10.7	19.1	1.0	2.5	0.8	5.8
1.5	5.2	1.9	9.5	12.2	21.5	1.0	2.7	1.0	5.8
1.7	5.2	2.1	9.7	13.8	23.4	1.1	3.0	1.1	6.0
1.8	5.3	2.7	10.3	20.0		1.4	3.3	1.4	6.3
2.0	5.3	3.0	10.3	20.9		1.4	3.9	1.5	6.3
2.1	5.5	3.0	10.8	21.5		1.5	4.0	1.6	6.4
2.2	5.7	3.0	11.2	23.0		1.6	4.0	1.6	6.4
2.2	5.7	3.3	11.4	23.8		1.6	4.3	1.8	6.4
2.3	5.7	3.8	11.5			1.7	4.4	1.8	6.4
2.4	5.9	3.9	12.7			1.7	4.8	1.8	6.4
2.4	5.9	4.1	12.9			1.7	4.8	1.9	6.5
2.4	6.1	4.3	14.2			1.7	4.9	2.0	6.6
2.5	6.1	4.4				1.8	5.1	2.0	6.7
2.8	6.1	5.0				1.8	5.3	2.0	6.8
2.9	6.2	5.2				1.8	5.4	2.1	7.1
2.9	6.6	5.2				1.8	5.5	2.2	7.1
2.9	6.8	5.4				1.8	5.9	2.3	7.6
2.9	7.0	5.5				1.9	6.8	2.4	8.6
2.9	7.0	5.6				2.0	6.8	2.4	9.3
3.0	7.1	5.7				2.1	9.3	2.4	9.4
3.0	7.2	5.7				2.2	9.7	2.5	9.9
3.1	7.3	6.5				2.2	11.6	2.5	
3.2	7.4	6.8				2.2		2.6	
3.3	7.6	7.1				2.3		2.8	
3.5	7.6	8.8				2.3		2.8	
3.6	7.6	8.9				2.4		2.9	
3.6	7.7	9.3				2.4		2.9	
3.7	7.9					2.4		2.9	
3.8	8.1					2.5		3.1	
3.9	8.5					2.5		3.1	
4.0	8.7					2.5		3.1	
4.0	8.7					2.7		3.2	
4.0	8.8					2.7		3.3	
4.0	9.1					2.7		3.3	
4.2	9.3					2.8		3.4	
4.3	12.6					2.8		4.0	
4.3	15.8					2.9		4.1	
4.3						3.0		4.2	
4.4						3.0		4.2	
4.4						3.0		4.5	
4.4						3.1		4.6	
4.5						3.2		4.6	
4.5						3.4		4.6	
4.5						3.4		4.9	
4.6						3.5		4.9	
4.6						3.5		4.9	
4.6						3.5		5.0	
4.6						3.6		5.2	
4.7						3.6		5.3	
4.8						3.9		5.4	
4.8						3.9		5.4	
4.8						5.0		5.4	
4.8						7.5		5.4	

Figure A.13: Measured weight data from all baggage weighed during vessel surveys.

Appendix B: Baggage Heat-Release Rates

Linear heat-release rate curves were used to create an average heat-release rate curve for a piece of passenger baggage in FDS simulations. Figures B.1 - B.6 show the curve for a stroller, carry-on, briefcase, purse, small duffel, and backpack.

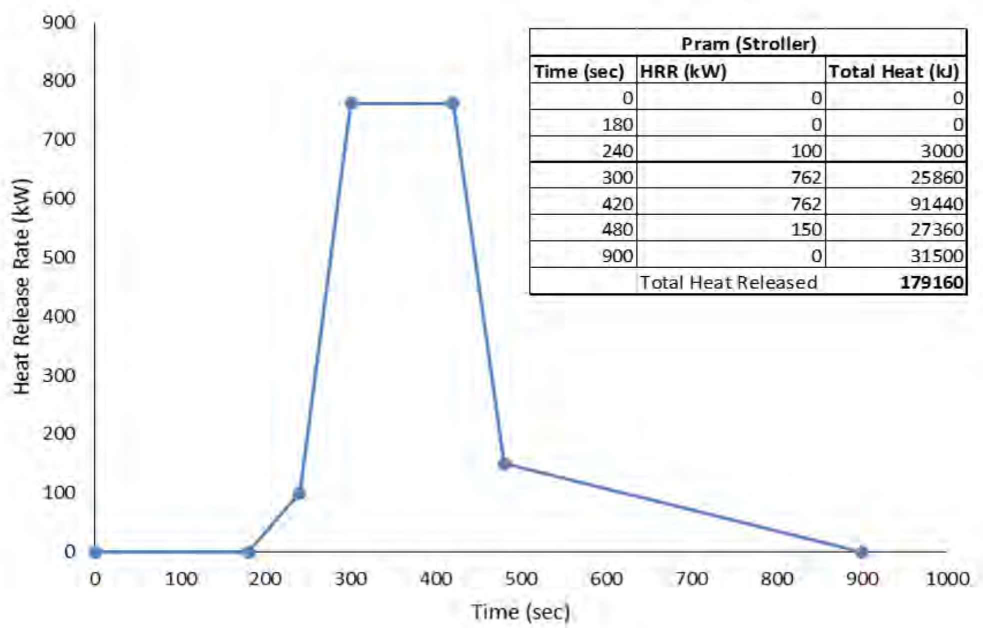


Figure B.1: Liner heat-release rate curve use for a stroller based on data from Kumm [3].

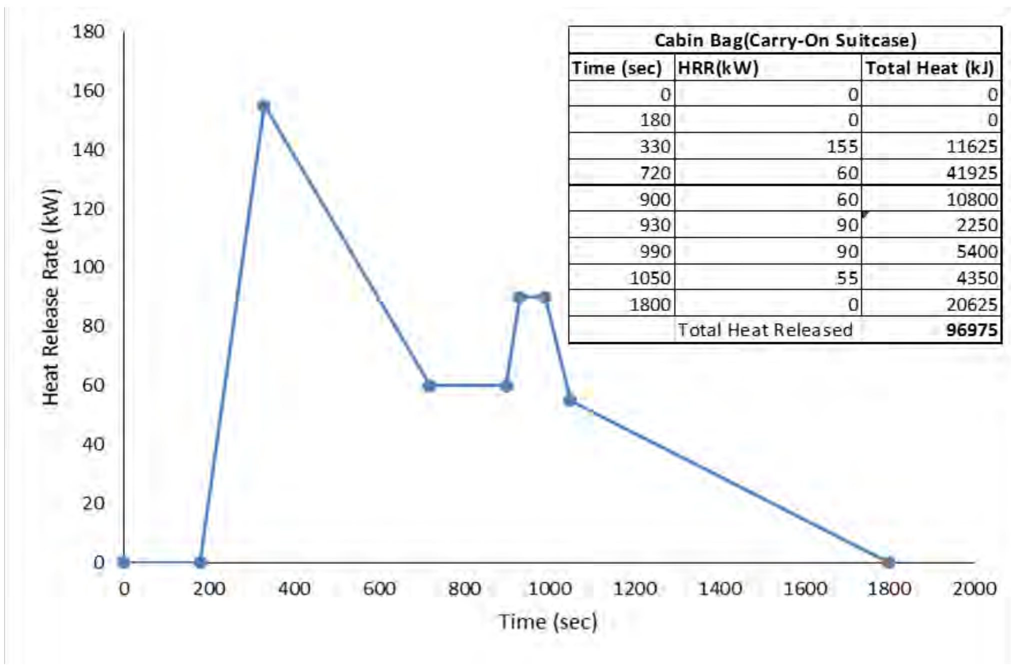
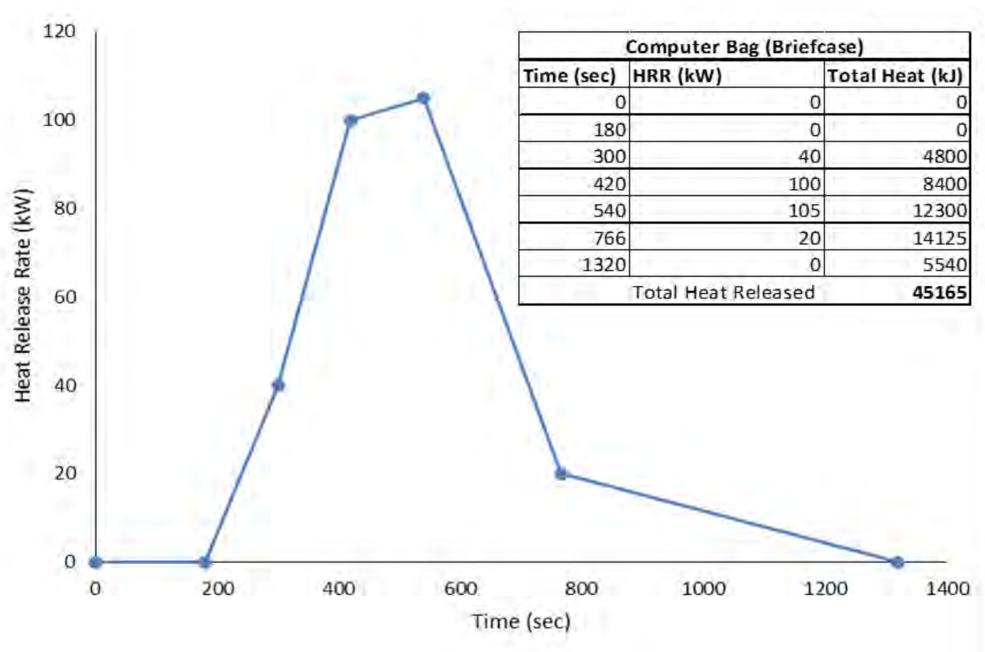
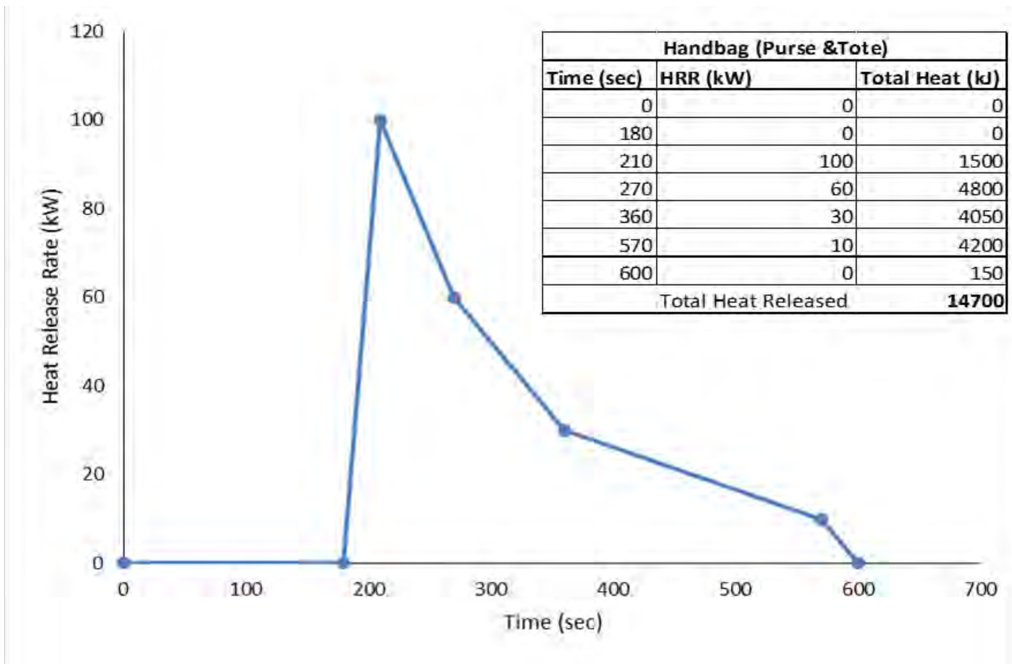


Figure B.2: Liner heat-release rate curve use for a carry-on bag based on data from Kumm [3].



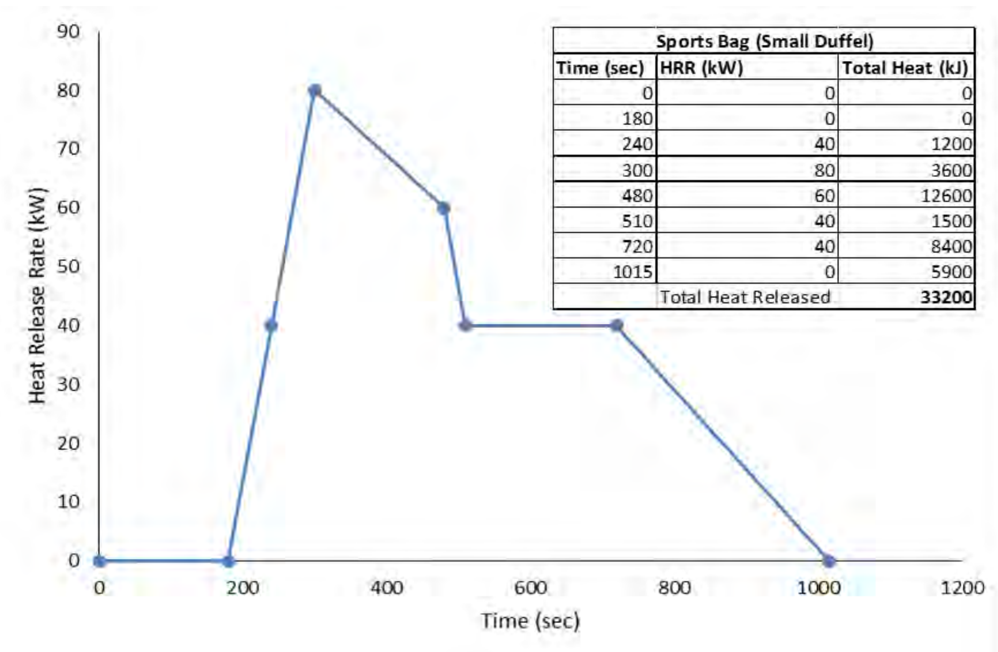
Computer Bag (Briefcase)		
Time (sec)	**HRR (kW)**	**Total Heat (kJ)**
0	0	0
180	0	0
300	40	4800
420	100	8400
540	105	12300
766	20	14125
1320	0	5540
	Total Heat Released	**45165**

Figure B.3: Liner heat-release rate curve use for a briefcase based on data from Kumm [3].



Handbag (Purse &Tote)		
Time (sec)	HRR (kW)	Total Heat (kJ)
0	0	0
180	0	0
210	100	1500
270	60	4800
360	30	4050
570	10	4200
600	0	150
	Total Heat Released	**14700**

Figure B.4: Liner heat-release rate curve use for a purse based on data from Kumm [3].



Sports Bag (Small Duffel)		
Time (sec)	**HRR (kW)**	**Total Heat (kJ)**
0	0	0
180	0	0
240	40	1200
300	80	3600
480	60	12600
510	40	1500
720	40	8400
1015	0	5900
	Total Heat Released	**33200**

Figure B.5: Liner heat-release rate curve use for a small duffel bag based on data from Kumm [3].

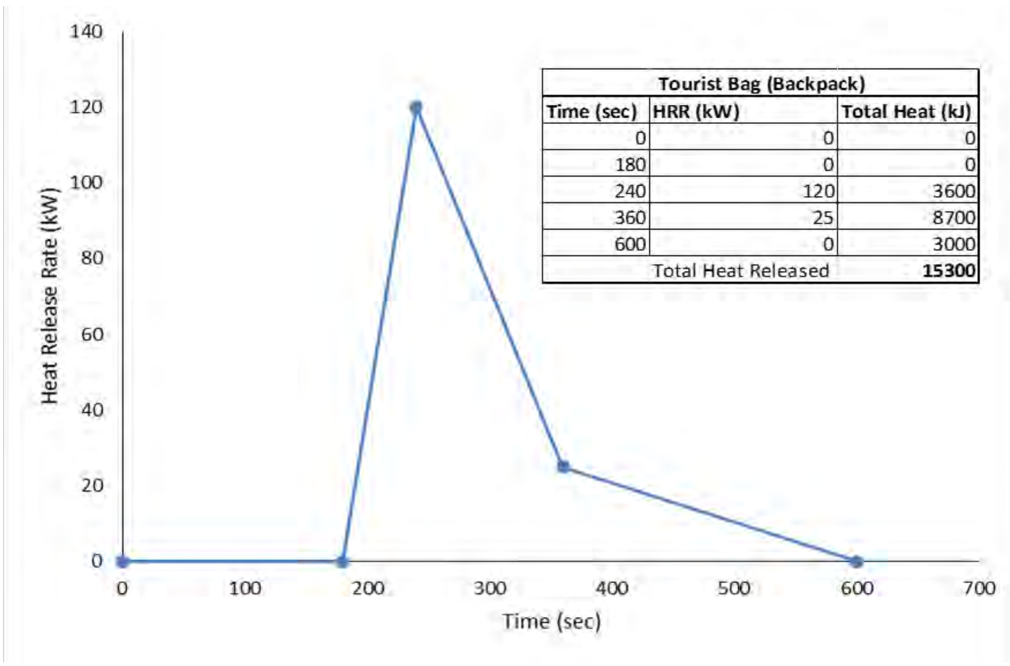


Figure B.6: Liner heat-release rate curve use for a backpack based on data from Kumm [3].

Appendix C: FDS Simulation Results

This appendix provides additional images and figures depicting the results from FDS simulations for the three tested scenarios.

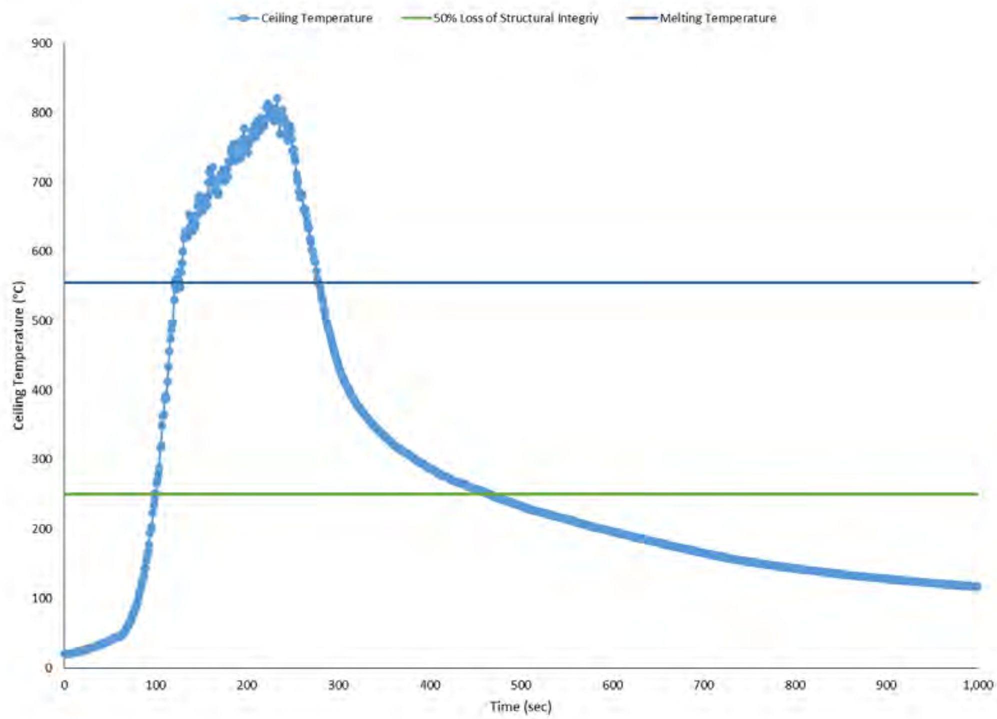


Figure C.1: Single point ceiling temperature above the burning stoller.

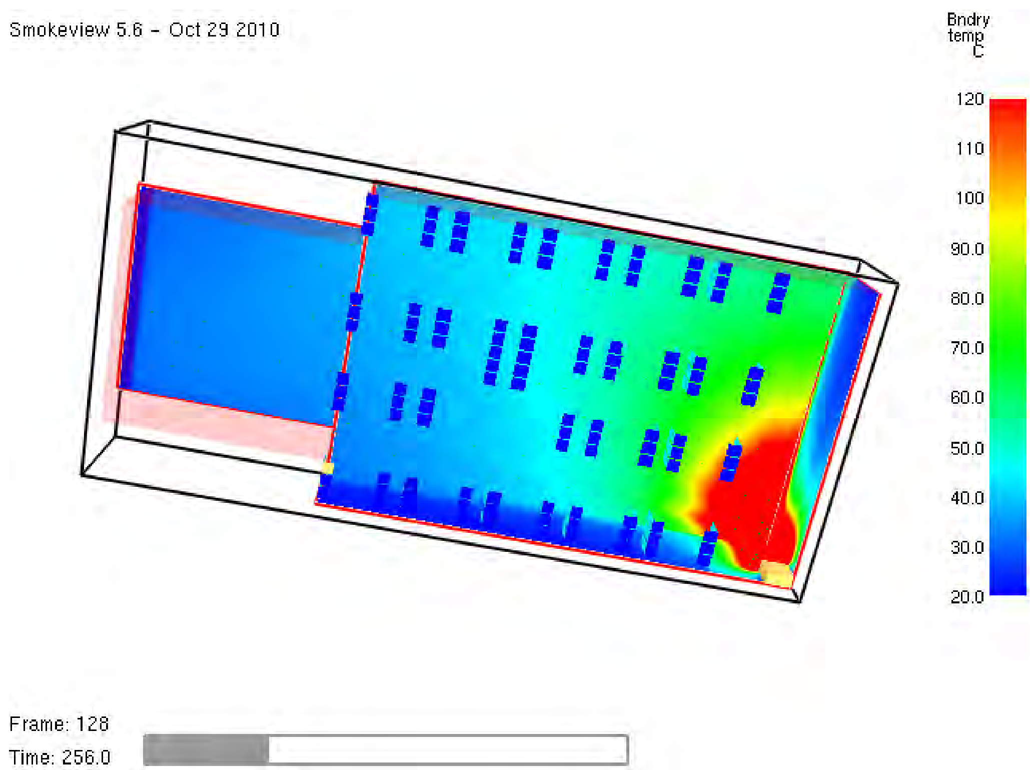


Figure C.2: Ceiling temperature above burning stroller in the corner of the compartment.

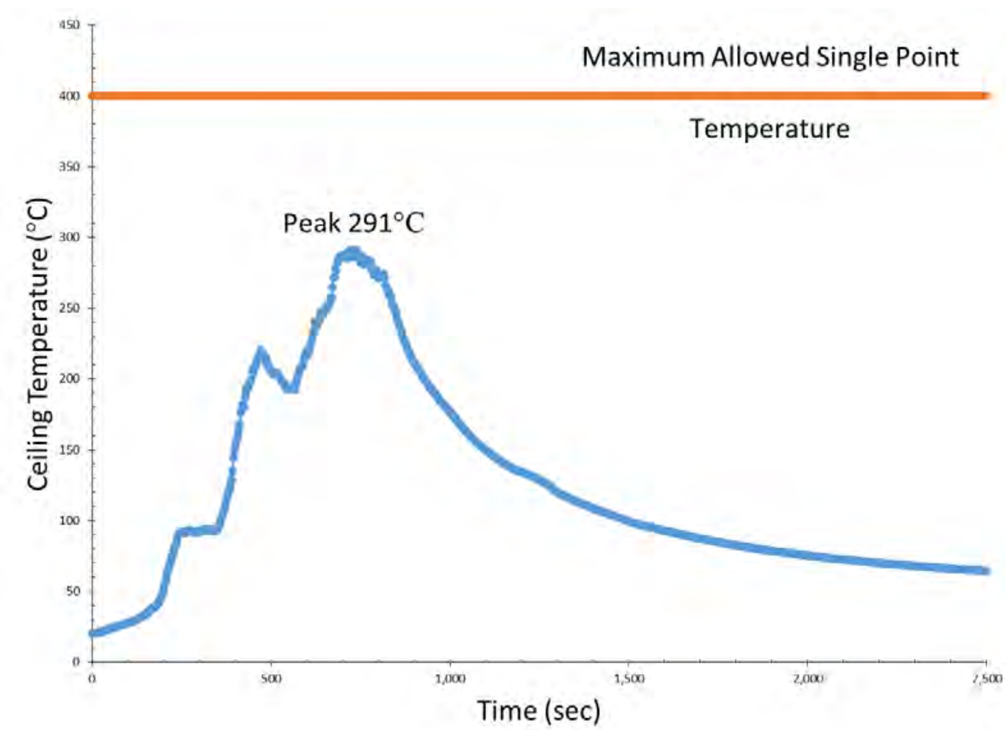


Figure C.3: Maximum single point ceiling temperature above a single bank of burning seats.

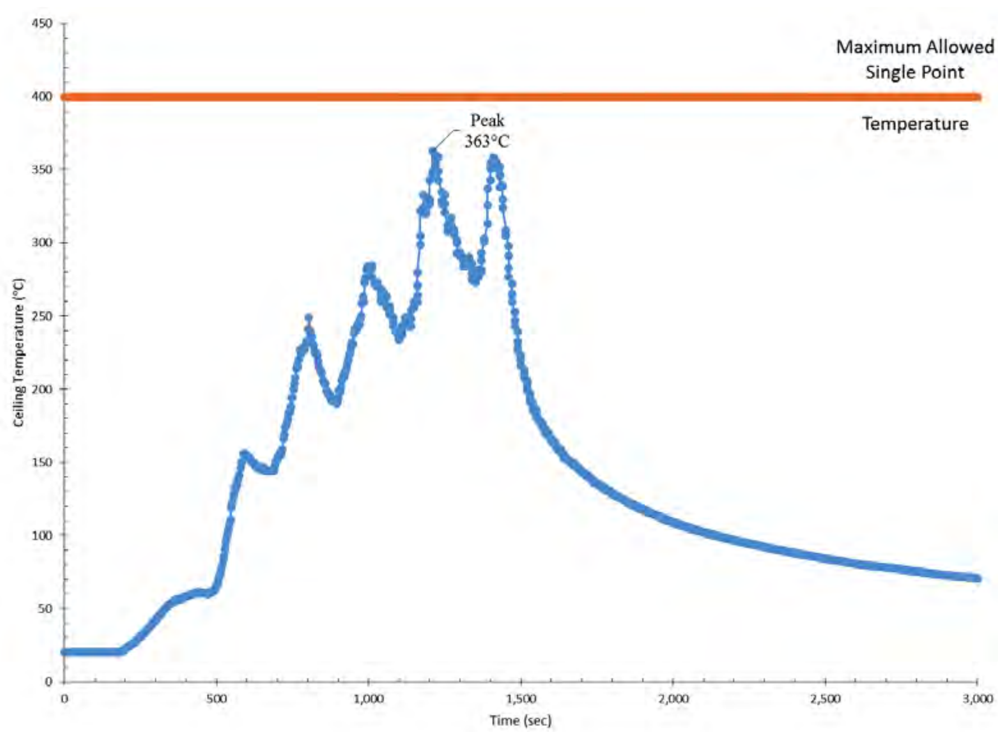


Figure C.4: Maximum single point ceiling temperature above two burning seat banks.

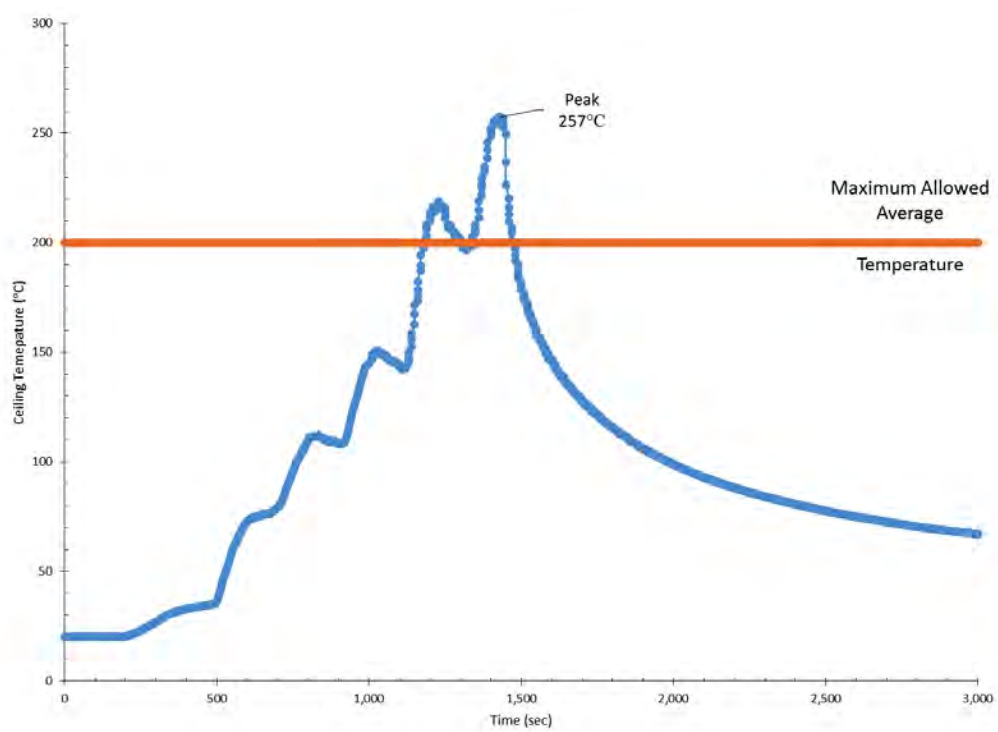


Figure C.5: Average ceiling temperature over one square meter above two burning seat banks.

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