Fire Environments Typical of Navy Ships

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Abstract

Current test methodologies used to evaluate the performance of protective clothing do not adequately determine the provided level of protection. The heat fluxes imposed by current evaluation methods are not specifically related to fire environments typical to those the clothing is designed provide protection against. The U.S. Navy is in the process of developing an improved process for testing the fire resistance of daily wear uniforms and protective gear. The first phase of this project involves evaluating currently used evaluation methods and identifying the severity of fire environments that would be expected aboard Navy ships. The examination of the test protocols currently in use identifies major weaknesses, providing the justification for a new test protocol.

The first step in developing an improved test protocol is to determine the types of fire scenarios that would be expected aboard Navy vessels. The nearly infinite number of possible fires are reduced to 6 typical cases involving spray fires, pool fires and furniture fires in both compartmented and unconfined cases. An analysis of the environments produced by these types of fires is presented. The effects of compartmentation parameters are also investigated to determine the critical factors that affect the expected fire environment. Expected heat fluxes for all scenarios are presented at a number of distances from the fire.

Executive Summary

The development of a comprehensive test protocol that will allow the comparison of the fire performance of equipment during typical navy fire scenarios will ultimately improve the safety provided by Navy issue uniforms. The primary objective of this project is to evaluate existing fabric performance tests in order to identify strengths and weaknesses and identify fire scenarios that would be typical of those found aboard Navy ships.

Current Test Methods

Tests currently in use by the Navy include:

ASTM F 1358-95 Standard Test Method for Effects of Flame Impingement on Materials Used in Protective Clothing Not Designated Primarily for Flame Resistance [1]

FTMS 5903.1 Standard Test Method for Flame Resistance of Cloth; Vertical [14]

Thermal Protective Performance (TPP) Test [6,7]

Instrumented Manikin Test [4,5,10]

The three bench top methods are very limited in that they can only test fabrics or layers of fabric. The performance of a garment can not be directly extrapolated from the information determined from this evaluation. Furthermore, the heat fluxes used in these tests are not related to heat fluxes that would be expected in a fire. The full size test is limited in the fire scenarios that are investigated. Only a small range of flash and pool fires, where there is direct flame impingement on the clothing are available.

Burn Injury Parameters

Before fire environments can be determined for a test protocol, it is important to specify the parameters that directly effect the extent of burn injuries to an individual. These factors can be divided into two major categories. Factors unrelated to the protective fabric, which include items such as the fire intensity and the ratio of convective to radiative heat flux. The second category is factors related to the fabric, which include parameters such as barrier and insulating properties.

Justification for Improved Test Method

None of the fabric evaluation methods currently available accurately investigates the performance of clothing designed to provide protection against heat and flames. Exposure times, heat fluxes and modes of heat transfer are difficult to predict in a real fire, but all the tests investigate very specific thermal environments. None of the test methods currently in use addresses the diversity of potential shipboard fires.

The bench top tests offer little value in testing behavior of a garment and are best suited for selecting an appropriate fabric when designing protective garments. Data collected from these types of tests can not be used to predict the performance of the completed garment in a real fire scenario. Perhaps the best test would incorporate the robotic manikin and a test chamber similar to the NCSU chamber that is set up to allow a wide range of fire scenarios, from pool fires to flash fires to simulated structure fires. A test sequence that involves a wide range of fire environments could then be developed.

Shipboard Fire Environments

The complete evaluation of existing test methods and the development of new ones require the characterization of the expected fire exposures. Judicious examination of typical ship fires allows careful selection of a smaller number of fire scenarios that cover the spectrum of reasonable survivable fires. In this study, efforts were made to select widely varying fire scenarios to cover all possible types of fires. One important factor to consider when developing fire scenarios for full scale testing is the survivability of the scenario assuming the fabric provides adequate levels of protection. The fire scenarios presented here do not consider these important factors. A test protocol that involves a wide range of fire scenarios will allow the characterization of the overall performance of new clothing. This will allow the best overall performers to be selected based on concrete scientific principals.

Predicted Fire Environments

Fire intensity depends exclusively upon the fire scenario that is being recreated in the test chamber. A fire size needs to be selected that challenges the protection provided by the garment while remaining within the appropriate design range of fires. The major difficulty with fire intensity comes from attempting to recreate the design fires.

Convective and Radiative Heat Transfer

The exact modes of heat transfer to a test specimen are extremely difficult to both predict and control.[30] Furthermore, determining these values for design fires can also be difficult. The only way to be certain that the fire is being recreated to a high level of accuracy is to run full-scale tests identical to the design fire utilizing the same compartment configuration and fuel source. Although exact reproductions of the fire scenario will not be made, the environment created in the test chamber will be a close approximation providing a reasonable comparison between test chamber results and real fire performance.

Engine Compartment Fires

Two types of fires are common in the engine room, pool fires and jet or spray fires. Flammable liquids are likely to be the fuel source for nearly all machinery space fires. Engine room fires are the most common due to the large quantities of flammable liquids, the likelihood of leaks resulting from equipment failure, and the number of ignition sources.

Supply Area Fires

These areas include mess halls, lounges, storage areas and galleys. These areas are the second most likely to be involved in a fire. Cellulosic materials including tables and chairs, wall coverings, and stored goods typically fuel fires in these compartments. Ignition sources are usually traced to faulty wiring or carelessly discarded smoking materials

Berthing Area Fires

Fires in berthing areas typically involve cellulosic materials, especially mattresses. Ignition sources are carelessly discarded smoking materials and in many cases as the result of arson. Studies have shown that a small amount of alcohol can easily ignite a mattress. Fires in these compartments typically behave in a manner similar to other furniture fires.

Deck Storage Area Fires

Fuel sources on the deck are typically fresh paint, cleaning agents, or aviation fuels. Ignition sources include faulty electrical equipment and sparks resulting from repair activities, particularly welding. Although this is the least likely area for a fire to occur, the potential for a very large fire is great due to the large volumes of fuel carried by aircraft. Fires on the deck are usually similar to pool fires.

Specific Fire Scenarios

Three specific fire scenarios were selected for quantitative analysis; spray fires, pool fires and bunk fires.

Hydraulic Oil Spray Fire

An attempt can be made to use the existing research on spray fires and apply it to the Navy application to predict a range of spray fire scenarios suitable for clothing performance testing. However, the wide range of pipe sizes and pressures typical of Navy ships have not been investigated. Spray fire heat release rates are highly dependent upon droplet size, which can not be analytically determined. The pipe diameter and the pipe pressure can be used to crudely define the heat release rate of a spray fire. Bernoulli's equation was used to calculate the fluid exit velocity from which a fluid mass flow rate can be determined. Pipe sizes from 1 to 10 cm and pressures from 101 kPa to 13600 kPa were investigated. These result in a range of heat release rates from a low of 50 kW to a high of 100 MW for the largest pipe diameter at the highest pressure.

The heat flux to a planar target parallel to the fire at varying distances was determined for a spray fire resulting from a 5 cm discharge diameter at a pressure of 7000 kPa. Average heat fluxes over the whole of the target ranged from a maximum of 100 kW/m2 at a distance of 0.5 meters from the fire to a minimum of 4 kW/m2 at a distance of 6 meters from the fire.

The same fire was modeled using CFAST, a zone fire model to represent the compartmentalized case. The fire was specified as a constant heat release rate. Spray fires with a heat release rate of 1000, 5000 and 10,000 kW were modeled. Target heat fluxes ranged from a low of 4 kW/m^2 for the 1000 kW fire at a distance of 4.24 m from the flame to a high of 31 kW/m^2 for the 10,000 kW fire at a distance of 1.41 m from the flame.

3.4.2 Pool Fires

Pool fires are divided into two major classifications, confined and unconfined. Confined pool fires are pool fires that can not spread in an unobstructed manner. Confined pool fires would result from oil and other flammable liquid spills in small machinery spaces. Although it is possible for the confined fire case, the unconfined fire is the more conservative approach and the most likely scenario. Five fuels were investigated for their behavior in pool fire situations; Fuel Oil #6, Gasoline, Kerosene, JP-4, and Hydraulic Oil. Pool diameters from 0.25 m to 10 meters were investigated. It was determined that the most critical parameter for determining the heat release rate is the pool diameter. The hydrocarbon fuels presented here had very similar heat release rates for a given pool size. Heat release rates ranged from 20-25 kW for 0.25 m diameter pools to 100 MW for 10 m diameter pools.

The heat flux to a plane perpendicular to the pool and facing the floor was calculated for a variety of distances. The pool used in these calculations was a 5 m diameter JP-4 pool fire. The average target heat flux 5.5 m from the center of the fire was 50 kW/m^2. The average target heat flux 15 m from the pool was 2 kW/m^2. Pool fires were also modeled for the compartmentalized case. Heat fluxes for a 2.5 m diameter JP-4 pool fire where between 26-30 kW/m^2 throughout the compartment.

Bunk Fires

Bunk fire heat release rates were taken from studies conducted by the Navy [29]. Bunk fires were only investigated in the compartmentalized case. Peak heat release rates of 6 MW for 4 burning bunks and 7.5 MW for 10 burning bunks were calculated. Peak target heat fluxes ranged from 10 kW/m2 to 17 kW/m^2 for the 4 bunk case and 21 kW/m^2 to 28 kW/m2 for the 10 bunk case.

Heat Flux Measurements

One difficulty in recreating fire environments is measuring the heat fluxes that are being produced by the test equipment. Improperly placed or poorly installed heat flux gauges can easily result in errors in excess of 50% of the measured value [30]. If temperature readings from the test chamber are used to control the furnace, small measurement errors can greatly influence the test specimen due to the T^4 relationship between temperature and radiation. These factors will need to be considered when designing the test equipment to reproduce the fire scenarios presented.

Future Work

One important compartment configuration that could not be investigated due to the lack of experimental data is compartments with only a horizontal vent on the ceiling. This is a venting situation very typical of ship compartments but not likely for land structures, and thus has not been studied. No predictions of the fire environment resulting from this venting configuration can be made until this research has been conducted.

Another limitation is the lack of reliable flame temperature data. The radiant flux calculations are based on accurate flame temperature values, but very little data is available for flame temperatures of diffusion flames for the fuels investigated. Furthermore, the flame temperatures that are available are not consistent.

The accuracy of the results collected from any future test protocol will depend on three major factors; accurately identifying real fire scenarios, accurately reproducing these fire environments, and accurately representing the behavior of a real human with the mannequin. The work done here begins the process of identifying fire scenarios, but does not attempt to narrow the possible choices to be used for fabric evaluation. Selecting appropriate design fires can only be accomplished when the purpose of the clothing being tested is known.

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Nomenclature

A_{exit}	area (m^2)
c	specific heat (J/kg C)
$(cp)_b$	volumetric heat capacity of the blood (J/m^3 K)
D	Diameter (m)
ΔE	activation energy for skin (J/mole)
E	flame emissive power (kW/m^2)
g	acceleration due to gravity (9.81 m/sec^2)
G	blood perfusion rate (m^3/sec/m^3 of tissue volume)
H_f	flame height (m)
ΔH_c	heat of combustion (kJ/kg)
k	thermal conductivity (W/mK)
k’	effective absorption coefficient
k_{emis}	effective emission/absorption coefficient (m^{-1})
L_f	flame length (m)
L_{beam}	mean equivalent beam length of the flame (m)
m	mass flow rate (kg/sec)
m’’	mass burning rate per unit surface area (g/m^2-sec)
m''_{∞}	asymptotic mass burning rate for large pool fires (g/m2-sec)
P	frequency factor, (sec^{-1})
p	pressure (Pa)
ρ	density (kg/m^3)
Q	heat release rate (kW)
q	heat flux per unit surface area (W/m^2)
R	universal gas constant (8.315 J/kmol K)
t	elapsed time (seconds)
T	Temperature (K)
T_b	blood perfusion temperature (K)
V	fluid velocity (m/sec)
V_s	Volumetric spill rate (m^3/sec)
x_{ch}	chemical combustion efficiency
y	liquid pool fire regression rate (m/s)
Φ	flame-element shape factor correction
τ	atmospheric transmissivity (taken as 1)
Ω	quantitative measure of burn damage at the basal layer in the dermis
Φ	flame-element shape factor correction

Subscripts

amb	ambient
b	Blood
beam	equivalent beam length
ch	chemical
exit	nozzle exit
emis	emission/absorption coefficient
f	flame
inlet	nozzle inlet
line	flammable liquid pipe line
max	maximum
rad	radiation
skin	skin
tc	thermocouple
tcinitial	thermocouple initial

1.0 Statement of Work

The ultimate goal of this project is to develop a test methodology that will determine the level of protection against heat and flames offered by Navy issue clothing. This test is to cover both protective gear and uniforms whose primary purpose is not to provide protection. The development of a comprehensive test protocol that will allow the comparison of the fire performance of equipment during typical navy fire scenarios will ultimately improve the safety provided by navy issue uniforms.

The purpose of this report is twofold. The first is to evaluate current test methodologies used to determine the protection provided by articles of clothing, including daily wear uniforms and garments designed specifically for protection from heat and flames. The following test methodologies are examined to determine their advantages and limitations, as well as their applicability to the requirements of the U.S. Navy.

- **ASTM F 1358-95** Standard Test Method for Effects of Flame Impingement on Materials Used in Protective Clothing Not Designated Primarily for Flame Resistance [1]
- **FTMS 5903.1** Standard Test Method for Flame Resistance of Cloth; Vertical [14]
- **Thermal Protective Performance (TPP) Test** [6,7]
- **Instrumented Manikin Test** [4,5,10]

Additionally, the feasibility of introducing a fully instrumented robotic mannequin test is discussed.
The strength and weaknesses of each of these methods were examined as well as the ability to correlate the results from each test to fabric behavior in actual fire environments. A critical appraisal of these methods is required to justify the development of an improved test for the U.S. Navy.

The second part of this report presents fires typical of Navy vessels and the environments generated by these fires. Using the results of this study, a range of appropriate fire conditions can be selected. These fires may then be reproduced in a future test apparatus. This goal is accomplished by reducing the complexity of naval vessels to a smaller number of compartments representative of the variety of compartment configurations possible. Once the contents of characteristic compartments as well as unenclosed spaces are known, it becomes possible to predict the types of fires that would be expected in these compartments as well as the pyrolysis rates of the fuels. The pyrolysis rates can then be used with a variety of modeling tools including zone type models to predict the fire environments created.

To determine the effect of different variables on the fire scenarios, a parametric study of many of the critical model input variables was conducted. The purpose of this study was to develop an understanding of the effects of critical parameters on the development and severity of the fire environment. The results of this investigation can then be used to predict a wide range of fire scenarios that could be incorporated into any future test platform.

2.0 Examination of Existing Test Methods

One of the challenges of this project is determining the level of protection that can be provided by Navy uniforms when exposed to typical shipboard fire scenarios. The fire environments encountered on a military vessel are unique compared to fires that normally occur on land and an improved test methodology that addresses the peculiarities of these fires needs to be developed. An examination of the existing test methods will demonstrate the advantages and limitations of current test procedures and provide the basis for the development of a test more appropriate to Navy applications.

Two aspects concerning the fire performance of selected fabrics must be considered.[7] The first is the flammability of the fabric. How susceptible is the material to combustion, smoldering or melting when exposed to an ignition source. All materials will burn given a high enough heat flux, thus some reasonable resistance to combustion needs to be selected based on the fire environment that the wearer of the garment might encounter.[1] Also, the method used to test the flammability of a fabric can greatly influence the performance of that fabric in a given test. An examination of existing tests will determine if a single test, or a combination of several will give results that can be used to determine the suitability of a particular fabric for use in Navy uniforms.

The second aspect of the fabric that needs to be examined is the transmission of energy through the material.[2,6] Fire conditions could potentially subject the wearer to convective, radiative and possibly conductive heat sources. A test of the materials ability to insulate the wearer from these sources is imperative to determining the performance of the fabric. Again, the test needs to take into account the peculiarities of the Navy's specific applications.

Many additional variables need to be considered when testing fabrics. Dirt and moisture in the fabric can greatly alter the performance of the material. The fit of the garment as well as trim and metal fasteners can also have an effect on thermal penetration resistance. While test methods can not completely replace experience gained by observing real world performance they are the only feasible method for generating a meaningful data set for selecting the fabric that will provide the greatest level of thermal protection.

2.1 Factors Affecting Burn Injuries

In the process of developing test methodologies for determining the level of safety provided by any protective fabric an investigation of the key factors leading to burn injuries must be conducted. These factors can be broken down into two major categories, factors related to the protective fabric and factors unrelated to the protective fabric.

2.1.1 Factors Unrelated to Protective Fabric

Two major elements unrelated to the protective fabric warrant consideration when determining the likelihood of burn injuries. The first is the type and intensity of heat flux exposure and the second is the duration of exposure.[4,8] The intensity of exposure is extremely crucial and often extremely difficult to define when a wide range of fire scenarios exist. Intensity levels can vary from a level where no protection is required to a level where no clothing exists that would provide an adequate level of protection.

Another factor that must be investigated and is related directly to the level of intensity is the type of heat transfer involved. Different protective properties are needed to protect against a heat flux that is predominately radiative as opposed to a heat flux that is predominantly convective. Conductive heat transfer, while often not encountered for the clothing whose primary purpose is not protection from burn injuries, requires different fabric properties than the other modes of heat transfer.[4,8]

2.1.2 Factors Related to Protective Fabric

The properties of the fabric used to assemble the garment are crucial to the performance of the apparel. These properties can be broken down into three major categories; barrier properties, insulating properties, and chemical/physical properties.[4]

The barrier properties of the material apply only to heat transfer through conduction, and thus are probably not important for the applications being investigated. The insulating properties determine the rate of heat transfer through the material. As the outer surface of a material is heated, a temperature gradient exists from the outer surface to the inner surface of the fabric. This gradient can be affected by air trapped in insulation in the garment or air trapped between the garment and the wearer.[27] The insulating properties of the garment can be greatly influenced by the construction and fit of the garment and changes in the fit due to shrinkage resulting from heat exposure. These parameters are important when the material is exposed to a convective heat source, or the surface of the fabric is heated by radiation. The greater the fabric's ability to resist the heat transfer through to the wearers' skin, the greater the level of burn protection provided. Furthermore, substantially different properties are required to protect against convective versus radiative heat sources. The factor of greatest importance when protecting against convective sources is the insulating ability of the fabric. The factor of greatest importance when protecting against radiative sources is the thermal absorbtivity of the outer layer of the fabric.

The chemical and physical properties of the fabric determine the effects of heat and radiation on the properties of the material.[27] These properties may increase or decrease the heat exposure of the wearer. For example, a product that pyrolyses when exposed to heat may increase the heat transfer to the skin of the wearer. This would result in a burn injury that would not have been present if the fabric did not behave in this manner.

2.2 Current Test Methods

Currently four tests are used to determine the performance of clothing not designed primarily for thermal protection and flame resistance. Three of the methods are bench top tests, testing the performance of the fabric only. The fourth method is a full-scale test of the finished garment. Each of these methods will be described briefly and then the strengths and weaknesses of each test examined.

2.2.1 Test ASTM F 1358 95

The Standard Test Method for Effects of Flame Impingement on Materials Used in Protective Clothing Not Designated Primarily for Flame Resistance (ASTM F 1358-95)[1] examines the ease of ignition and burning behavior of materials not designed primarily for flame resistance. This method utilizes a test cabinet containing a small pilot flame, a Bunsen burner burning methane at a specified pressure of 17.2 ± 1.7 kPa (2.494 ± 0.247 psi), a specimen holder and appropriate measurement instruments. The pilot flame is adjusted to a height of approximately 3 mm (0.1179 in). The Bunsen burner flame source is adjusted to a height of 38 mm (1.49 in) with no premixing of the fuel and air. A sample of cloth is folded over a 6 mm (0.236 in) diameter metal rod and clamped in the specimen holder. Once the sample has been fastened the rod is removed, leaving a "loop" of fabric at the bottom of the test specimen. The pilot flame and Bunsen burner are calibrated prior to placement of the specimen in the test cabinet.

Before the test all fabric samples are conditioned by being placed in an atmosphere of 45% to 70% humidity and a temperature of 20 to 25 °C (68 to 77 °F) for a minimum of 24 hours prior to testing. The folded edge of the specimen is exposed to the Bunsen burner flame for 3 ± 0.1 seconds, at the end of which the gas source is closed. The specimen is observed to determine if ignition has occurred. If sustained ignition is not evident after the three second test, the flame is reapplied for an additional 12 ± 0.1 seconds. When ignition is observed, after either the 3 second or 12 second test interval, the time interval required for fabric combustion to self extinguish is measured, as well as the time of any additional afterglow. The apparent cause of extinguishment is also noted. The specimen is removed from the test cabinet and the burn distance measured to the nearest 1 mm. The test is repeated until a total of 10 specimens have been tested.[1]

The major advantage with this test is it's low cost and ease of reproduction. The equipment necessary to perform this evaluation should be available at any flammability testing facility. Because of the small scale of the test and minimal per-sample test costs, many samples may be tested to eliminate any statistically irregular behavior. The procedure allows fabrics to be ranked by their performance in this particular test. Comparisons between, and ranking of a wide range of fabrics would not be difficult.[1]

The major disadvantage with this test is that the results are not useful in determining fabric performance when exposed to real fire scenarios. The results of this method can not be extrapolated to predict the behavior of a full garment in an actual fire. Therefore, any rankings of protective fabrics generated from the test can not be used to rank the level of protection offered by garments constructed from these fabrics. The rigorously defined configuration of the fabric specimen does not include configurations that would likely be used in a garment such as seams or single layers of fabric. The test can be used as part of a methodology used to determine the level of protection provided by a garment. However, it does not result in any information that would be useful in predicting the performance of a particular garment.

2.2.2 Standard Test Method for Flame Resistance of Cloth; Vertical (FTMS 5903.1)

This test method [14] is similar to the test discussed in section 2.1 of this report. The same test cabinet, and flame source/fuel delivery system is used. The major difference is the configuration of the test specimen and the examination of the specimen after the test. In this test method, a single layer of fabric 70 mm x 305 mm (0.472 x 11.99 in) is placed in the specimen holder and subjected to the flame of the Bunsen burner for 12 ± 0.1 seconds. The after flame and after glow times are measured. The char length is measured by making a small tear in the fabric at the highest point of charring and then suspending weights from the fabric until the fabric rips and fails completely. The distance from the bottom of the test specimen to the tear as measured along the edge of the specimen is the char length. While this process is somewhat complex, it is necessary to eliminate the guesswork associated with determining the edges of the fabric in areas that have been damaged by the test.[14]

Advantages of this test method are its low cost and repeatability. Fabrics may be ranked according to their performance in this test which, in combination with other tests, will help determine which fabrics have the best fire resistant properties. Because the conditions of the test are easily reproducible, and the test is not expensive or complicated to conduct, a large number of samples may be tested to eliminate any statistical irregularities.

The primary disadvantage of the test is that the results are not meaningful outside the conditions of the test. No predictions can be made about the level of protection offered by a garment from data collected using this test methodology. A ranking of fabrics tested using this method will not correlate to an equivalent ranking of the protection offered by garments created using these fabrics. While the results of the test can be useful when combined with other test methods, this single test itself is only valid for comparing the performance of other fabrics when subjected to these same test conditions.

2.2.3 Thermal Protective Performance Test [6,7]

The thermal protective performance test rates textile materials for thermal resistance and insulation when exposed to flux levels of 8.4 W/m^2 (2.0 cal/cm^2sec) for a short duration [6]. The Thermal Protective Performance Test used to determine if the layers of material that comprise the protective clothing are adequate to protect the wearer from burn injury. The TPP test is conducted by exposing a material or multiple layers of material to heat from a standard source and measuring the amount of energy passing through the sample. This is then correlated with experimental data developed by Stoll to determine the extent of burn injuries that would result from the exposure. The heat source consists of a flame, which provides the convective portion of the heat, and a quartz heater, which provides the radiative component. An equal 50/50 split between the radiative and convective components of the heat load is maintained.[6] Discussions with the engineers conducting this evaluation at the Navy Fabric Research Center in Natick, Massachusetts indicates that although an equal 50/50 split is specified in the protocol for this procedure, the actual ratio of convective to radiative flux is unknown and can vary widely. This lack of consistency renders any results from this test procedure highly questionable.

The greatest advantage of this particular test is that the rate of heat transfer through the fabric is measured, which can be used to determine the likelihood of burns. Utilizing both a convective and radiative source also allows greater measurement of the overall performance of the fabric. Fabrics tested in this method can be ranked according to the likelihood of a burn injury given the environmental conditions generated during the test. Also, this test gives materials a rating, "The thermal protective performance rating is the exposure energy required to cause the accumulated heat received by the sensor to equal the heat that will cause a second-degree burn in human tissue." [6] One major improvement to this procedure when compared to the previously mentioned protocols is the ability to evaluate multiple layers of fabric. Most protective clothing is not comprised of a single layer of fabric, thus the ability to test all of the layers together represents a significant advancement from procedures which only evaluate single layers of fabric. However, as with the other bench top protocols, the behavior of the garment can not be directly extrapolated from the behavior of the fabric.

The most important disadvantage to this test is the effect of fabric mounting on the results of the test. Typically, an air gap is left between the test specimen and the calorimeter to simulate loose fitting clothing. The deformation of the fabric can alter this air gap considerably resulting in unpredictable results. If the specimen is mounted flat against the calorimeter then the heat transfer to the mass of the calorimeter keeps the specimen cool resulting artificially long times to develop burn injuries.[17] An additional problem with this method is the single level of exposure specified in the protocol. By testing at only one exposure, no information concerning the performance of the fabric at other exposures is generated. Furthermore, the likelihood of the actual exposure used during fabric evaluations matching the criteria defined in the test protocol is very low. Because of this, no extrapolations of the performance of the fabric, and ultimately the garments can be made.

There are other variations of the Thermal Protective Performance test. However, the above procedure is the one used by the Navy in their test program. The similar test, ASTM test method D 4108-87: Test Method for Thermal Protective Performance of Materials for Clothing by Open-Flame method utilizes a simple Bunsen burner for the heat source, eliminating the radiant portion provided by the quartz heater.[2]

2.2.4 Instrumented Manikin Test [4,5,10]

The instrumented manikin procedure is different from the previous process because it does not simply evaluate the material used in the manufacturing of the garment, but tests the complete ensemble of garments on a life size manikin. The development of this protocol began in the 1960's. It continues today at the College of Textiles at North Carolina State University (NCSU). The most common fire environment that the mannequin is subjected to is the test conducted in the NCSU chamber simulating a flash fire exposure. The Navy has experimented with other mannequin test methodologies with some success but difficulties in reproducing results have been encountered.

The NCSU test set up relies on a test chamber containing propane burners, fans to simulate wind conditions, the manikin and necessary instrumentation to record the conditions within the chamber. The test chamber is designed to simulate a flash fire exposure. This scenario is created using eight propane burners calibrated to generate a level of exposure of about 8.4 W/m2 (2 cal/cm^2 sec). The duration of the exposure can be varied with typical times ranging from 2.5 to 10 seconds. The burners are arranged to fully engulf the manikin in highly luminous flames.[5]

The manikin itself contains 122 sockets for heat sensors distributed uniformly over the body. Each of the sensors is connected to a shielded cable which is run outside the test chamber to a data acquisition system which can be used to predict burn injuries.[4] This heat flux is determined from the values from the thermocouples placed flush with the surface of the mannequin. The relationship between the temperature recorded by the thermocouple and the heat flux is presented in the equation

$$T_{tc} - T_{tcinitia} = \frac{2q\sqrt{t}}{\sqrt{\pi k p_{tc} c}} \qquad (1)$$

Where

T_{tc} is the measured temperature of the thermocouple (K)
$T_{tcinitial}$ is the initial temperature of the thermocouple (K)
q is the heat flux (W/m^2)
t is the elapsed time (seconds)
k is the thermal conductivity (W/mK)
ρ_{tc} is the density of the thermocouple (kg/m^3)
c_{tc} is the specific heat of the thermocouple (J/kg C)

By rearranging the equation, the heat flux can be determined from the temperature rise of the thermocouple, the thermal inertia of the thermocouple and the duration of the exposure. It is desired that the thermal inertia of the thermocouple should be similar to the thermal inertia of human skin.

To determine the extent of burn injuries the duration at which the basal layer of the skin has risen above 44 C is determined. Experiments on human and pig skin found that the destruction of this skin layer could adequately be described by the following equation.

$$\frac{d\Omega}{dt} = Pe^{-\frac{\Delta E}{RT_{skin}}} \qquad (2)$$

Where

Ω is a quantitative measure of burn damage at the basal layer in the dermis
P is the frequency factor, (sec^{-1})
ΔE is the activation energy for skin (J/mole)
R is the universal gas constant (8.315 J/kmol K)
T_{skin} is the absolute temperature at the basal layer in the dermis (K)
t is the total time for which the skin temperature is above 44 C (sec)

To determine the temperature of the skin at any depth a heat transfer model of human skin was developed. [10]. The model divides the skin into three tissue layers and accounts for blood flow through arteries and veins. The mathematical model is demonstrated below.

$$cp\frac{\partial T_{skin}}{\partial t} = k\frac{\partial^2 T_{skin}}{\partial x^2} - (cp)_b G(T_{skin} - T_b) \qquad (3)$$

Where

(cp)b is the volumetric heat capacity of the blood (J/m^3 K)
G is the blood perfusion rate (m^3/sec/m^3 of tissue volume)
T_b is the blood perfusion temperature (K)

T_{skin} is the tissue temperature (K)
x is the depth into the skin (m)

During a typical simulation, the temperature measured by each of the thermocouples is used to determine the heat flux to the skin. This value is then used to calculate the temperature of the interior layers of the basal skin layer from which burn injuries can be calculated.

An additional use of the thermal manikin has been developed by the Navy and Air Force for scenarios where a flash fire exposure is not suitable. In this test, the heat exposure is created using a pool fire burning Heptane. The manikin is suspended from a movable assembly and separated from the burning pool fire by fireproof curtains. The assembly is propelled along a track at a calculated velocity that results in the desired exposure time. After the manikin passes through the fire, there is additional set of curtains on the opposite side of the fire to protect against additional exposure. Another variation of the test uses a mannequin suspended from a boom that moves in a large arc using a rotational boom instead of the straight track.[28]

The advantages of both of these tests are that they investigate the behavior of the entire garment in the same fashion that it will be worn. In addition, burn injury to a simulated wearer is predicted providing a quantification of the level of protection offered. The data acquisition system allows the observation of the development of burns as a function of time, which will assist in future garment design by identifying burn prone areas.

There are numerous disadvantages to this system. The first is that only one type of fire scenario is tested for each type of manikin test. The NCSU test simulates only a flash fire of highly luminescent flames while the test conditions used by the Air Force and Navy only simulate a stationary mannequin passing through a pool fire. Additionally, no significant study has been conducted to determine if the placement of the burners have any significant impact upon the results of the test, or even how closely the burner configuration simulates the environment encountered in a flash fire scenario. In addition, the mannequins are static, they do not move like real human beings. As a wearer moves, the fit of the garment against different parts of the body can change which could greatly alter the protection offered by that garment.[16] Additional biological consideration such as sweat can also play important factors and are not considered.

2.2.5 Instrumented Robotic Manikin Test

Researchers at the Pacific Northwest Laboratories have attempted to overcome the shortcomings associated with the traditional thermal manikin by developing a robotic manikin. This manikin can simulate the movement of a wearer as well as simulating several biological processes such as perspiration and respiration.[13] These have been used to determine the effectiveness of protective clothing in the same manner as the traditional manikin but efforts are under way to develop thermophysiological controls. This would be a great leap forward because it would incorporate simulated tissues as opposed to direct interpolation from surface mounted heat sensors. Furthermore, these would allow body core temperature and skin surface temperature simulation. Efforts are currently in place to couple all of the physiological systems in such a way as they realistically simulate human physiological behavior. For example, a high rate of activity would increase the perspiration and respiration rate. Currently this particular mannequin has not been used in fire tests but adapting the mannequin to handle this environment would not be difficult.

The major hurdle facing this apparatus is acceptance in the scientific community. The test data from the mannequin have not been substantiated against additional data, and no accepted usage guidelines for the technology exist. These hurdles could easily be overcome by the endorsement of this technology by a recognized authority.

2.3 Justification for an Improved Navy Test

None of the tests presented here accurately investigates the performance of clothing designed to provide protection against heat and flames. Exposure times, heat fluxes and modes of heat transfer are difficult to predict in a real fire, but all the tests investigate very specific thermal environments. Some variation is allowed in some of the tests, but not enough to rank the protection provided by an article of clothing. In the case of the Navy, there are a large number of likely fire scenarios, each one radically different from the other. None of the test methods currently in use addresses the diversity of potential shipboard fires.

The bench top tests offer little value in testing behavior of a garment and are best suited for selecting an appropriate fabric when designing protective garments. They are also useful as quality control checks when manufacturing protective fabrics. Data collected from these types of tests can not be used to predict the performance of the completed garment in a real fire scenario. Furthermore, just because a fabric performs well in one test does not mean that it will perform well in another test, and it doesn't mean that it will be the best performer for general protection from heat and flame. These tests are useful only when combined with other tests and the results analyzed and compared to the level of protection desired. This data can then be used to select an appropriate fabric but it would still be difficult to predict the performance of the completed garment until full-scale tests were conducted.

The two manikin tests are much better at evaluating performance of a protective garment. However, they are hampered by the inability to test a wide range of fire scenarios. Garment fit is an important factor in burn injuries. Because fit changes as a wearer moves, the robotic manikin is a more accurate test than the simple manikin but has not yet been widely accepted as a valid test.

Perhaps the best test would incorporate the robotic manikin and a test chamber similar to the NCSU chamber that is set up to allow a wide range of fire scenarios, from pool fires to flash fires to simulated structure fires. A test sequence that involves a wide range of fire environments could be developed. If enough fire scenarios were investigated, it could become possible to predict the behavior of the garment under different scenarios by observing trends in protective behavior. This comprehensive testing along with the motion of the mannequin would allow the performance of a garment to be quantified with much more confidence than current test methods.

3.0 Prediction of Fire Environments Typical of U.S. Navy Ships

The complete evaluation of existing test methods and the development of new ones require the characterization of the expected fire exposures. With an infinite number of fire scenarios possible, it is impossible to investigate all of them. Judicious examination of typical ship fires allows careful selection of a smaller number of fire scenarios that cover the spectrum of reasonable survivable fires. In this study, efforts were made to select widely varying fire scenarios to cover all possible types of fires. This should allow qualitative analyses of scenarios not specifically examined but which are analogous to one of the investigated fire scenarios. This report presents possible fire scenarios and then selects the most reasonable and likely scenarios for extensive investigation.

One important factor to consider when developing fire scenarios for full scale testing is the survivability of the scenario assuming the fabric provides adequate levels of protection. For very high heat fluxes or long exposures, burn injuries are not the only factor that could result in death or injury. In many cases, death would not result from burn injuries but from inhalation of hot products of combustion, resulting in carbon monoxide poisoning or irreversible damage to lung tissue. Designing clothing to provide protection from environments so severe that death will result from other causes is neither cost effective or logical. The fire scenarios presented here do not consider these important factors.

3.1 Critical Parameters Required to Determine Clothing Exposure

The investigation of protective clothing is dependent upon three major variables that are characterized by a fire. These three variables directly and indirectly define the exposure to which the test specimen is subjected. These parameters are; Fire Intensity measured as heat release rate, Convective and Radiative heat transfer to the test specimen, and the duration of exposure of the test specimen.

3.1.1 Duration of Exposure

The duration of exposure can be difficult to classify, depending upon the actions of the crewmember wearing the apparel including time of egress and the mental capacity of the individual. Determining the time to failure of a garment given a particular fire scenario can circumvent this problem. The failure criterion depends upon the exact usage of the apparel being tested. A reasonable failure for a daily wear uniform may be 10% of the body burned value selected by the appropriate individuals. Failure for fire fighting gear might be a 75-degree temperature rise on the inside of the fabric. Regardless of the criteria used to define the failure of the garment, the total elapsed time between initial exposure and failure can be used to compare the level of safety provided by each tested garment. With computerized data acquisition systems, comparisons between fabrics can be much more complex involving a much greater number of variables, but often times this analysis is not possible due to monetary constraints. For these conditions, a time to failure can be a reasonable measure to the level of protection offered by a garment. After the garments undergoing evaluation have been exposed to a variety of fire scenarios, the results can be compared. This allows the garment providing the best overall protection to be selected.

3.1.2 Fire Intensity

Fire Intensity depends exclusively upon the fire scenario that is being recreated in the test chamber. The difficulty in selecting this parameter come in determining appropriate design fires based on the fuel load and fuel type in a given compartment. Careful consideration is needed to determine reasonable sizes of a simulated fire based on both the available fuel and ventilation in the compartment, and the level of protection the tested garment is designed to provide. Fires that are much larger than the garment is intended to provide protection from will quickly cause a failure in the garment and little will be learned. On the other had, the design fire needs to be large enough to represent a considerable hazard to the occupants in the compartment to evaluate the protectiveness of the clothing. A fire size needs to be selected that challenges the protection provided by the garment while remaining within the appropriate design range of fires. The major difficulty with fire intensity comes from attempting to recreate the design fires. It has been demonstrated that specific heat fluxes are difficult to reproduce due to variations in furnace refractory materials, placement of furnace measurement devices, and differences between the fuels used in the test chamber and the characteristics of the fuels that would be burned in an actual fire.[30] Actual fires are very susceptible to uncontrollable variables and thus are inappropriate for laboratory experiments. However, artificial fires created with radiant panels and convective heat sources such as laboratory burners often do not provide sufficiently accurate recreations of the actual fires that are being simulated.

3.1.3 Convective and Radiative Heat Transfer

The exact modes of heat transfer to a test specimen are extremely difficult to both predict and control.[30] Furthermore, determining these values for design fires can be difficult as well. Very small changes in the orientation of clothing, the type of fuel burning, the ventilation in the room and many other variables can change these modes of heat transfer very drastically. To circumvent these difficulties relatively simple geometric relationships between the fire and the target are used, and for the more complex compartmented fire scenarios, zone models are used to predict these values. The only way to be certain that the fire is being recreated to a high level of accuracy is to run full-scale tests identical to the design fire utilizing the same compartment configuration and fuel source. Unfortunately, this is an expensive process, which cannot be conducted extensively. An alternative to this process is to use the calculated values and attempt to recreate them as accurately as possible for each test. By accurately reproducing the selected value for every performance evaluation, the reliability of cross test comparisons will be greatly enhanced. Although exact reproductions of the fire scenario will not be made, the environment created in the test chamber will be a close approximation providing a reasonable comparison between test chamber results and real fire performance.

3.2 Possible Shipboard Fire Scenarios

An analysis of shipboard fire scenarios was conducted to determine the types of fires that could be expected. Over a six year period from 1974-1969 major shipboard fires could be categorized into the four following categories listed in order of decreasing fire occurrences; (1) Machinery Spaces, (2) Supply Areas, (3) habitability spaces, and (4) deck storage areas. [20] The types of fires expected are unique for each of these spaces, and in the case of machinery spaces and deck storage the fire environment can be extremely difficult to predict.[20-25]

3.2.1 Machinery Spaces

Machinery Spaces include engine spaces, steering gear spaces, generator spaces, auxiliary machine spaces, repair shops and any other area where machinery is housed. These types of spaces have resulted in the greatest number of fire incidents and fire fatalities due to the abundance of ignition sources in close proximity with flammable liquids. Ignition sources include hot or overheated equipment, faulty wiring, and repair activities such as cutting and welding. Ignitable liquids include engine fuel, lubrication oils and greases, hydraulic fluids, and cleaning solutions. Flammable liquids can accumulate as the result of an engine component failure, poor housekeeping, or accidental spillage.

3.2.2 Supply Areas

Supply areas include the mess hall, laundry room, galley, and other storage areas similar in nature. Typically, these compartments contain predominantly solid fuel sources with limited amounts of flammable liquids in small quantities. With the exclusion of the galley, ignition sources are typically faulty electrical equipment or smoking paraphernalia. Cooking activities typically provide ignition sources in the galley, with grease fires being the most common occurrence in this space. Fuel sources are always present in the form of furniture and clothing, although poor housekeeping can increase the likelihood of a fire.

3.2.3 Habitability Spaces

Berthing areas include both crews' quarters and officer wardrooms. The predominant sources of combustible material in these spaces are mattresses and bedding materials. Additionally there is expected to be clothing and other combustibles contained within metal lockers but these lockers are typically closed and are not expected to contribute significantly to the fuel load. [15] Ignition sources have historically been smoking paraphernalia or arson activities although faulty electrical equipment could be another potential source of ignition. It has been demonstrated that a serious fire could result in these areas even when the fire initiation source is small due to the extreme flammability of mattress materials and abundance of easily ignited materials.

3.2.4 Deck Storage Areas

Deck Storage areas can be extremely difficult to classify due to the dynamic nature of topside activities. Furthermore, the role of the ship plays a large part in determining the combustible materials that will be available on deck. Common source of deck fires have been painting and cleaning activities, when flammable liquids used in these operations are ignited by smoking or faulty electrical equipment. Welding during repairs has also been a source of ignition for these types of fires. Another potential source of fuel is jet propellant spilled during aircraft refueling operations or as the result of an aircraft crash.

3.3 Predicted Fire Environments

3.3.1 Engine Room

Two types of fires are common in the engine room, pool fires and jet or spray fires. Flammable liquids are likely to be the fuel source for nearly all machinery space fires. Engine oil, Diesel oil and hydraulic fluid are the flammable liquids that typically ignite in these areas. The review of several marine accidents indicates that engine lubricating oil or hydraulic fluid leaking under pressure can easily be ignited by the multitude of hot surfaces found in these compartments.[8] In cases where these fluids are under very high pressure a jet fire can be produced. If the pressure is not great enough to cause these combustibles to form a droplet spray or the spray is not ignited, then the fuel can collect on the floor of the compartment resulting in a pool fire or a combination pool/spray fire. Depending on the fuel used for the engines, a leak in the fuel delivery system could also result in a jet or pool fire.

One of the difficulties is determining the appropriate scenarios for the development of these fires. For flaming jet fires, the fuel delivery rate can be determined if the size of the failure through which the fuel is flowing as well as the pressure at which it is being released is specified. For the pool fires an additional variable, the time between the start of the leaking combustible and ignition also needs to be specified. This allows the size of the initial pool of flammable liquids to be determined.

Khan, et al, determined a variety of correlation's in the paper "Characterization of Hydraulic Fluid Spray Combustion" [18] for a number of different types of hydraulic oil and flow rates. An empirical relationship was developed that determines the total heat release rate is proportional to the product of the combustion efficiency, net heat of combustion, and fluid exit velocity.

$$Q_{CH} = 0.11 x_{ch} \Delta H_C V_{exit} \qquad (4)$$

Where

Q_{ch} is the chemical heat release rate (kW)
x_{ch} is the combustion efficiency
ΔH_c is the heat of combustion (kJ/kg)
V_{exit} is the fluid exit velocity (m/sec)

The nozzle used to generate this empirical relationship had an exit diameter of 0.38 mm (0.015 in). This is a very small opening, much smaller than those expected aboard a Navy Vessel. Consequently, this equation is not useful for this application.

Combustion efficiencies were shown dependent upon discharge orifice type and exit velocity. Typical values ranged from a low of 0.2 using a solid cone nozzle, Polyglycol in Water hydraulic oil and an exit velocity of 65 m/s (213 ft/sec), to a high of over 0.95 using a hollow cone nozzle, a variety of different hydraulic oils, and fluid exit velocities between 20 and 70 m/s (65.6 and 229.6 ft/sec). Typical values for the radiant fraction of the total heat release rate vary from a high of 0.40 for phosphate esters to a low of 0.12 for water-in-oil emulsions.

3.3.2 Berthing Areas and Supply Areas

These two areas can be lumped together because of the similarities in fuel types that exist in these spaces. Fires in these types of compartments closely mimic those typically found in land based structure fires. This is a significant advantage because it allows the large body of knowledge that has been developed for these fires to be applied to equivalent shipboard fires. The major differences between the two are the metal bulkheads typically used in ships. The emissivity of the bulkheads is much higher than the emissivity of typical structures and increases the radiative feedback to the pool. The metal bulkheads can also be an advantage as they allow heat to conduct out of the compartment reducing gas temperatures. In this case, concentration will be placed on the berthing areas because of the considerable fuel loads contained in these areas. Fires in supply areas such as the mess hall will be similar in nature but less severe because of these differences in total combustible loads.

Extensive full-scale experiments have been conducted on berthing compartment fires aboard Navy ships [29]. This information can be used to determine the fire scenarios that are reasonable for this compartment. Since the development of these fires are well defined and relatively predictable, it would be desirable for garments to be subjected to the growth of the fire from ignition until a reasonable level of fabric failure. With steady state fires, exposure duration needs to be selected, oftentimes somewhat arbitrarily. By subjecting the clothing to the full growth of the fire, the elapsed time between fuel ignition and unacceptable burn injuries can be measured. This will provide a better understanding of the level of protection offered by a given article of clothing.

Full scale fire tests of ship accommodation quarters utilizing a single three tier bunk indicates that fire sizes of approximately 100 kW (23.9 kgcal/sec) are possible during a five minute period after the onset of self sustained ignition. Depending upon the ventilation condition and contents of the berthing compartment, maximum rates of heat release as high as 1400 kW (334.6 kgcal/sec) and as low as 11 kW (2.63 kgcal/sec) were observed. The radiant fraction of these fires is close to those seen in structure fires, with an emissivity of approximately 0.2 to 0.3

3.3.3 Deck Storage

Deck fires are similar to engine room fires, but can not be treated the same due to differences in fuels and the lack of compartmentation effects. Pool fires, and to a lesser extent, jet fires would be expected on the surface of the deck. It is expected that the majority of fires on the deck would be the result of cleaning and painting of the deck or the refueling of aircraft. Therefore, expected fuels are paint, cleaning fluids, and aviation gas. Pool fires can occur from painting and cleaning activities or the spillage of jet fuel. Jet fires could develop as the result of leaks developing in high-pressure fuel delivery systems for aircraft refueling. The size of a pool fire that results from painting or cleaning can be determined by determining the average amount of paint or cleaning fluid that is still flammable during a painting operation. For a fuel spill or jet fire, the same variables needed for the engine compartment must be specified; i.e. pressure, size of fuel line rupture, and time between the initiation of the leak and ignition.

Full-scale tests of pool fires are readily discovered in the literature and their behavior well documented. Heat release rates are highly dependent upon the fuel type, size of the pool, and the surface on which the pool is burning. Radiant fractions can be as low as 0.1 for small, clean flames to as high as 0.8 for large pool fires with highly luminescent flames. Predictions of an exact fire environment are highly dependent upon accurately specifying the conditions under which the fire occurs. For a fire on the deck, additional atmospheric factors such as wind speed and direction need to be considered when determining exposure conditions. The loss of heat from the burning pool into the metal decking plates will effect the burning rate of the pool, but this effect will be difficult to quantify and is ignored.

3.4 Specific Fire Scenarios

Three specific fire scenarios were selected for quantitative analysis. Spray and Pool fires for a variety of fuels are investigated in both enclosed spaces and out in the open. Bunk fires are investigated in enclosed spaces only.

3.4.1 Hydraulic Oil Spray Fire

Spray fires have not been extensively studied and can be very difficult to predict. The controlling factor in spray fires is often the droplet size, which is highly dependent upon the conditions of the release of the flammable liquid. Khan et al indicates that there are three distinct classes of spray fires; Vapor jet diffusion flames defined by a high proportion of droplets vaporized in a distance very short compared with the overall flame length; droplet spray flame occurring when droplets flight length is longer than the flame length and turbulent diffusion flame characterized by a mixed region of spray combustion with droplets existing along all or almost all of the flame length [18]. The ability to predict the type of flame is beyond the scope of this project as it is not possible without knowing the precise configuration of the discharge orifice and the atomization properties of the fuel. An attempt can be made to use the existing research on spray fires and apply it to the Navy application to predict a range of spray fire scenarios suitable for clothing performance testing. The inability to precisely determine spray fire parameters given a fire scenario does not effect the usefulness of recreating a calculated fire environment if it can be determined that the predicted values are within the range of reasonable values for this fire configuration. From the standpoint of fabric testing the ability to consistently reproduce the calculated environment is of greater importance for making accurate comparisons between different fabrics or clothing configurations.

The most likely spray fire scenario involves the bursting of a high-pressure oil or hydraulic line, with the resulting spray of flammable liquid ignited by adjacent hot surfaces. The total heat release rate will depend upon three major factors, the net heat of combustion of the liquid, the size of the discharge orifice, and the discharge pressure. To simplify the analysis and generate the worst case scenario it was assumed that the failure mode would be the complete severing of a given oil or hydraulic line. The failure mode would be equivalent to a weakness in a line resulting in a bulging and subsequent failure of the line. The burst hose end would have the shape of a slightly diverging nozzle, as the hose would stretch during the failure at the weak point in the line. From this type of failure, a pressurized hose can assume to be terminating at a virtual nozzle.

In this study, the average net heat of combustion for typical hydraulic oils was calculated to be 130 kW/m^3. A range of discharge diameters from 1 to 10 cm (0.39 to 3.9 in) and a range of pressures from 101 kPa (6.9 psi) to 13600 kPa (2000 psi) were investigated. The combustion process was assumed 90% efficient because efficiency is in large part influenced by the configuration of the fluid release point, which is not known, and thus a high number is selected to remain conservative. Khan demonstrated combustion efficiencies of 0.90 for flows above 30 m/sec (98.4 ft/sec), thus assuming a combustion efficiency of 0.9 will yield conservative, yet reasonable results.[18]

To determine the heat release rate from a spray fire the volumetric flow rate must be calculated from the exit velocity of the flammable liquid and the pipe diameter. To determine the exit velocity given the pressure the Bernoulli equation is used for flow through a diverging nozzle, applied at the inlet diameter of the nozzle, considered equal to the hose diameter and the exit diameter of the nozzle, considered to be 115% of the hose diameter (15% increase in diameter at burst point). Figure 3.4.1-1 below demonstrates this configuration.

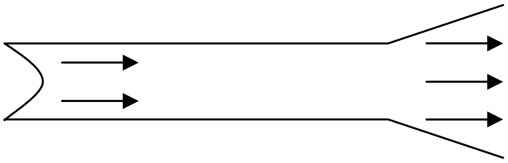


Figure 3.4.1-1: Virtual Nozzle Configuration

The Bernoulli equation applied in this manner can be rearranged to solve for the exit velocity in the following manner.

$$\frac{p_{line}}{\rho} + \frac{V_{inlet}^{2}}{2} + gz_{in} = \frac{p_{amb}}{\rho} + \frac{V_{exit}^{2}}{2} + gz_{out} \qquad (5)$$

$$z_{in} = z_{out} \qquad (6)$$

$$\frac{p_{line}}{\rho} + \frac{V_{inlet}^{2}}{2} = \frac{p_{amb}}{\rho} + \frac{V_{exit}^{2}}{2} \qquad (7)$$

The above applies the Bernoulli equation at the inlet and outlet to the virtual nozzle ignoring any effects resulting in elevation changes. If the continuity equation is then applied, the exit velocity may be solved.

$$\rho V_{inlet} A_{inlet} = \rho V_{exit} A_{exit} \quad (8)$$

$$V_{inlet} = V_{exit} \frac{A_{inlet}}{A_{exit}} \quad (9)$$

$$\frac{p_{line}}{\rho} + \frac{\left(V_{exit} \frac{A_{inlet}}{A_{exit}} \right)^2}{2} = \frac{p_{amb}}{\rho} + \frac{V_{exit}^{\ 2}}{2} \quad (10)$$

$$V_{exit} = \frac{\sqrt{2\left(\frac{p_{amb}}{\rho} - \frac{p_{line}}{\rho} \right)}}{\frac{A_{inlet}}{A_{exit}} - 1} \quad (11)$$

Where

V_{inlet} is the fluid velocity at the inlet to the virtual nozzle (m/sec)
V_{exit} is the fluid velocity at the exit point of the virtual nozzle (m/sec)
p_{line} is the absolute pressure measured in the line (Pa)
p_{amb} is the ambient pressure (Pa)
A_{inlet} is the area of the hose at the inlet to the virtual nozzle (m^2)
A_{exit} is the area of the discharge orifice of the virtual nozzle (m^2)
g is the acceleration due to gravity (9.81 m/sec^2)
ρ is the fluid density (kg/m^3)

Figure 3.4.1-2 plots fluid exit velocity as a function of line pressure. The above equations demonstrate that the absolute pipe diameter does not effect the exit velocity, only the ratio between the inlet and exit diameters. Since a constant 15% diverging nozzle was used, the pressure is the only variable that affects exit velocity.

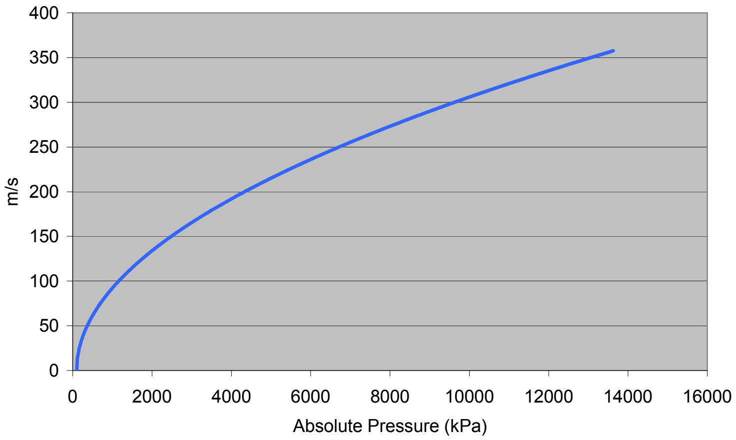


Figure 3.4.1-2: Hydraulic Oil Theoretical Discharge Velocity

The heat release rate was calculated by determining the volumetric flow rate from the discharge area and then applying the net heat of combustion and the combustion efficiency. As the exact nature of the hydraulic oils used aboard navy ships were not available for use in the project, a “standard” fluid whose properties were determined by averaging a variety of available hydraulic oils. The properties of this "typical" hydraulic oil are available are shown in Table 3.4.1-1.

Standard Hydraulic Oil	
Heat of Combustion (kJ/kg)	46.4
Chemical Combustion Efficiency	0.84
Convective Fraction	0.56
Radiative Fraction	0.28
Density (kg/m3)	760

Table 3.4.1-1: Properties of Hydraulic Oil Used in Calculations

Mass flow rates can be computed from the exit velocity and area of the nozzle.

$$\dot{m} = V_{exit} A_{exit} \rho \qquad (12)$$

Where

m is the mass flow rate (kg/sec)
V_{exit} is the exit velocity of the flammable liquid (m/sec)
A_{exit} is the discharge area (m^2)
ρ is the fluid density (kg/m^3)

The heat release rate can then be computed [31]

$$Q = \dot{m} \Delta H_c x \qquad (13)$$

Where

Q is the heat release rate (kW)
ΔHc is the net heat of combustion (kJ/kg)
x is the combustion efficiency

Figure 3.4.1-3 shows heat release rate as a function of pressure for a variety of pipe diameters.

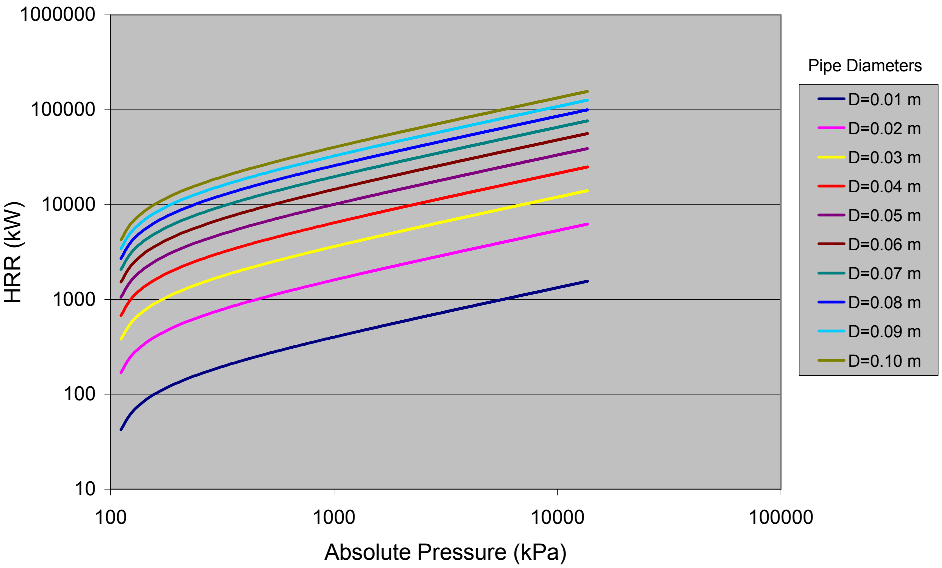


Figure 3.4.1-3: Spray Fire Heat Release Rate

The pipe diameter and the pipe pressure can crudely define the heat release rate of a spray fire. To determine a more accurate value the exact geometry of the rupture would need to be specified and then extensive computational fluid dynamic field type models would need to be employed to ascertain droplet size, spray patterns and combustion efficiencies. For the purpose of the Navy, the first order approach applied here should provide a reasonable number that can be easily reproduced for product testing and evaluation.

Of particular importance for spray fires is the radiant fraction of the total heat release rate. Typical radiant fractions for spray fires are on the order of 40% of the total energy output. In order to calculate the radiant flux to a target the flame emissive power can be calculated utilizing the radiant fraction of the total heat release rate of the fire and the total area of the flame. The flame length can be calculated using the correlation developed by Holmstedt and Peterson for solid nozzles.[3] It should be noted that flame lengths are highly dependent upon droplet sizes and thus the calculated flame lengths may not translate to the behavior of a real fire. This is particularly true for the very low and very high pressures where either very large or very small drops would be expected. Flame lengths were calculated using the following equation.[31]

$$L_f = 0.578Q^{0.824} + 0.42 \qquad (14)$$

Where

L_f is the flame length (m)
Q is the heat release rate (kW)

Figure 3.4.1-4 below shows flame lengths as a function of absolute pressure for a variety of discharge diameters.

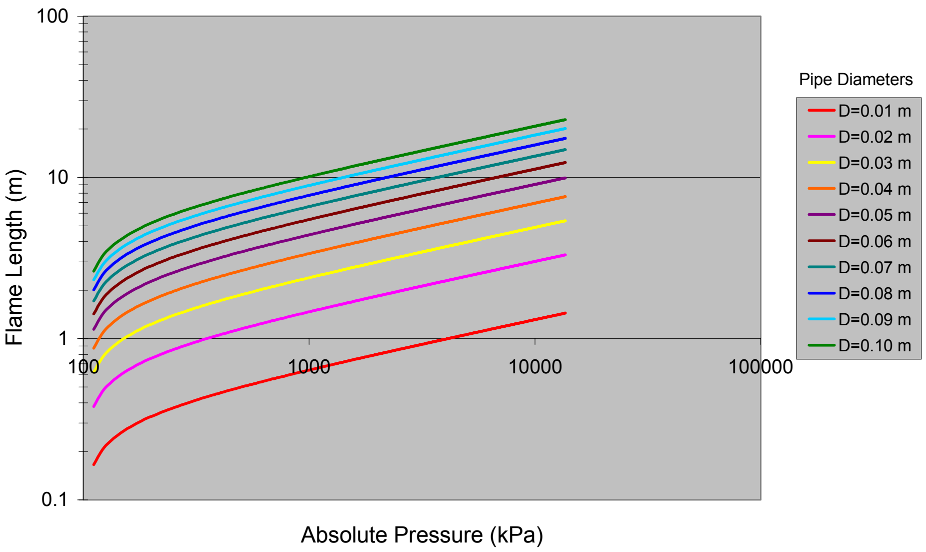


Figure 3.4.1-4: Spray Fire Flame Lengths

The radiant portion of energy transferred from the jet flame to other objects in the compartment is dependent upon the geometry of the object. A shape factor for radiant transfer from a cylinder to a differential element was used to calculate the radiation field to a plane at a specified distance from the fire, which is modeled as a cylinder. This configuration will result in the maximum radiant exposure to the individual. The convective heat transfer to the individual is significantly more difficult to predict as this depends upon the configuration of both the compartment and the target subject. Computing this value directly is very difficult requiring computation fluid dynamics. Simpler field models are available that approach the problem empirically and give reasonable results. For situations where the compartmentation effects are not present, the convective portion of the total heat flux to a target will be minimal. This is only true when the subject is far enough away from the fire so that the exposure to the fire plume will be minimal.

The radiant heat flux to a target can be calculated by relating the flame emissive power to the radiant energy impinging on a differential target area through a shape factor correction. [31]

$$q'' = E\Phi\tau \qquad (15)$$

Where

q'' is the radiant heat flux to the target element (kW/m^2)
E is the flame emissive power (kW/m^2)
Φ is the flame-element shape factor correction
τ is the atmospheric transmissivity (taken as 1)

The flame emissive power was computed using the formula [31]

$$E = \frac{Q_{rad}}{A_f} \qquad (16)$$

Where

E is the flame emissive power (kW/m^2)
Q_{rad} is the radiant heat release rate (kW)
A_r is the flame surface area (m^2)

The figure below shows the flame emissive power calculated for the pipe diameters and pressures investigated.

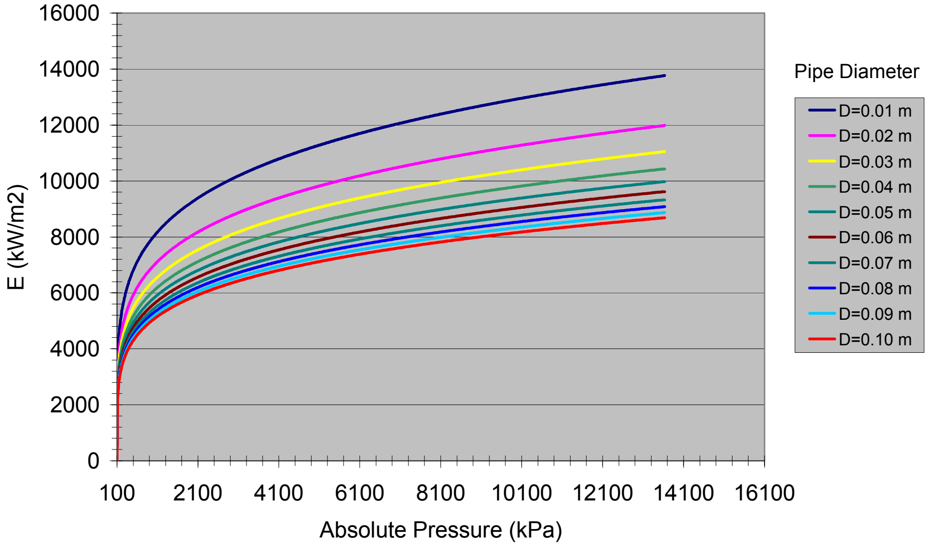


Figure 3.4.1-5: Spray Fire Flame Emissive Power

The strongest dependence of flame emissive power is on release pressure, which the release diameter a much smaller factor. The flame emissive power itself is not particularly useful when determining the radiant fluxes to a target, in this case an article of clothing. To determine the radiant flux at the target, a shape factor correction must be used. For the jet flame case, the shape factor for the transfer from a cylinder to a differential element was applied to a plane place parallel to the jet at different distances from the centerline of the jet flame. The geometric relation between the radiant source and target is seen in Figure 3.4.1-6. The shape factor utilized for the calculations are also shown along with the appropriate equations.[11]

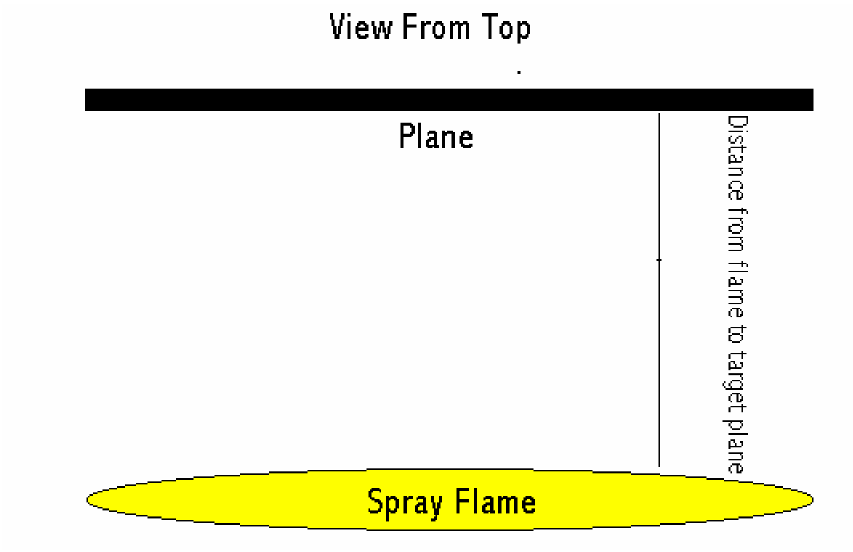
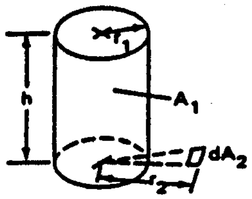


Figure 3.4.1: Relationship between Flame and Target Plane



$$R = \frac{r_1}{r_2} \qquad L = \frac{h}{r_2} \qquad X = \sqrt{\left(1 + L^2 + R^2\right)^2 - 4R^2}$$

$$\Phi_{d1-d2} = \frac{1}{2\pi}\cos^{-1} R + \frac{1}{\pi}\left\{\tan^{-1}\left[\frac{R}{\sqrt{1-R^2}}\right] - \frac{1+L^2-R^2}{X}\tan^{-1}\left[\frac{X\tan\left(0.5\cos^{-1}R\right)}{1+L^2+R^2-2R}\right]\right\} \tag{17}$$

A variety of configurations was investigated with the result available in Appendix A. The results demonstrated here are for a pipe diameter of 5 cm (1.95 in) and a release pressure of 7000 kPa (1015 psi), which is equivalent to a flame emissive power of 8540 kW/m^2 (2041 kgcal/m^{2}sec). Plots are shown for separation distances of 0.5 m, 0.75 m, 1 m, 2 m, 4 m, 6m, and 10 m (1.64,2.46,3.28,6.56,13.12,19.68,32.8 ft).

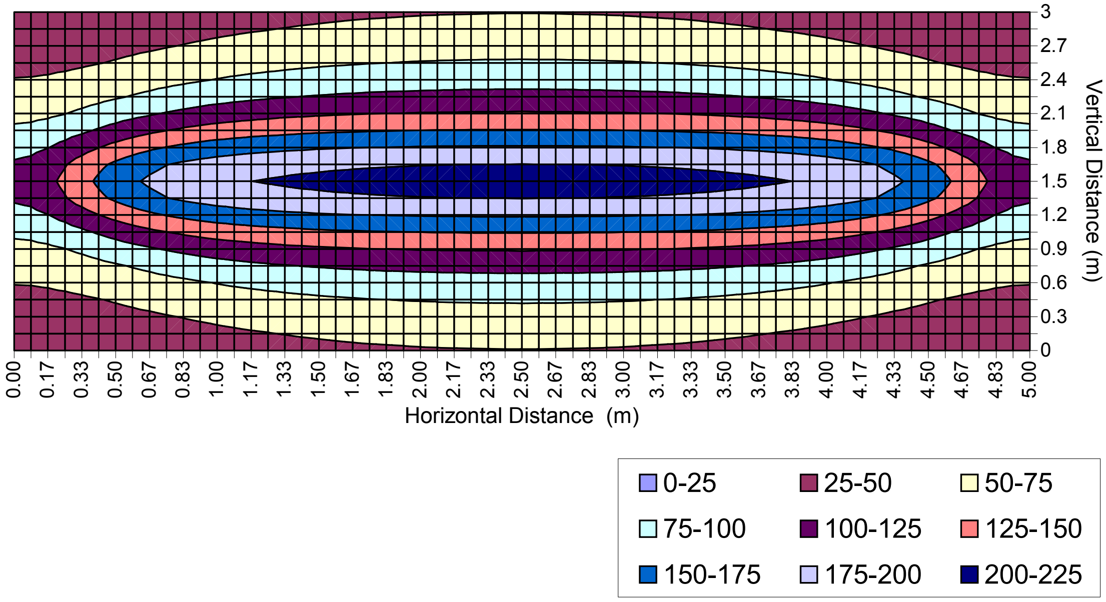


Figure 3.4.1-6: Radiative Heat Flux to Vertical Plane 0.50 m from Jet Flame (kW/m2)

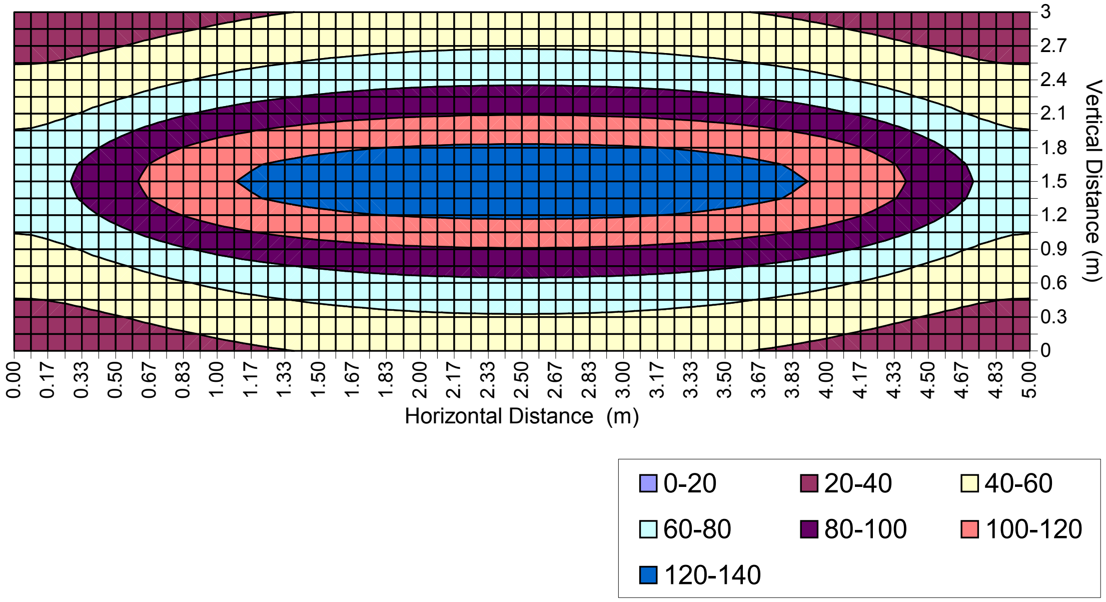


Figure 3.4.1-7: Radiative Heat Flux to Vertical Plane 0.75 m from Jet Flame (kW/m2)

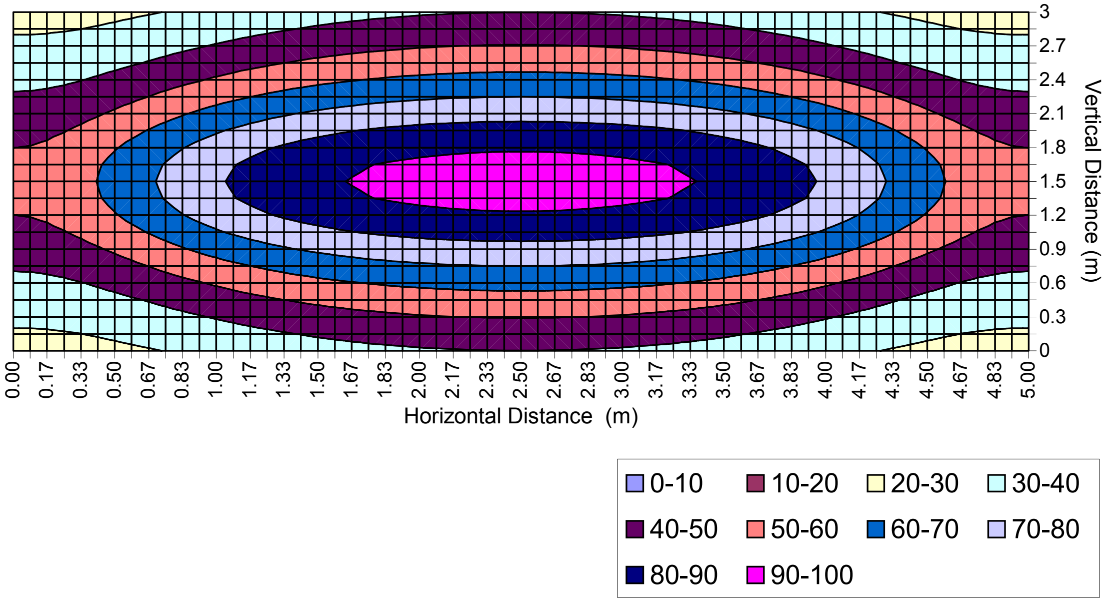


Figure 3.4.1-8: Radiative Heat Flux to Vertical Plane 1.00 m from Jet Flame (kW/m2)

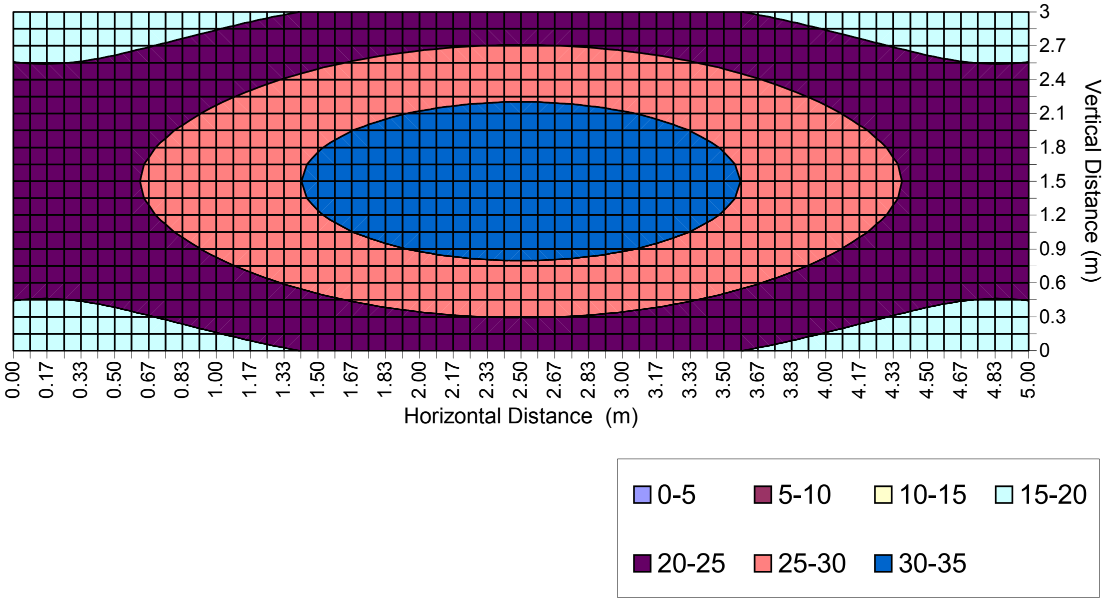


Figure 3.4.1-9: Radiative Heat Flux to Vertical Plane 2.00 m from Jet Flame (kW/m2)

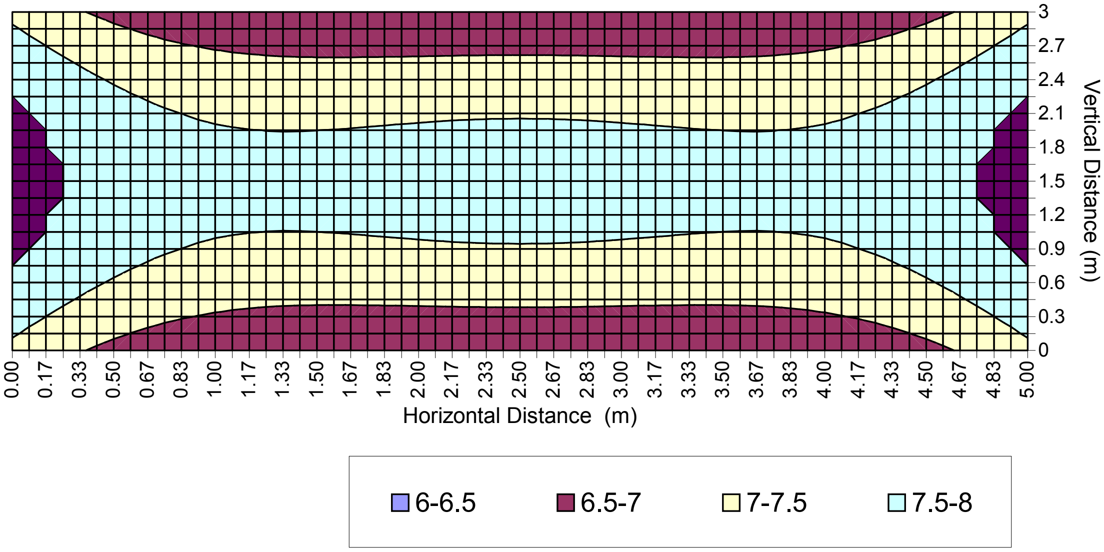


Figure 3.4.1-10: Radiative Heat Flux to Vertical Plane 4.00 m from Jet Flame (kW/m2)

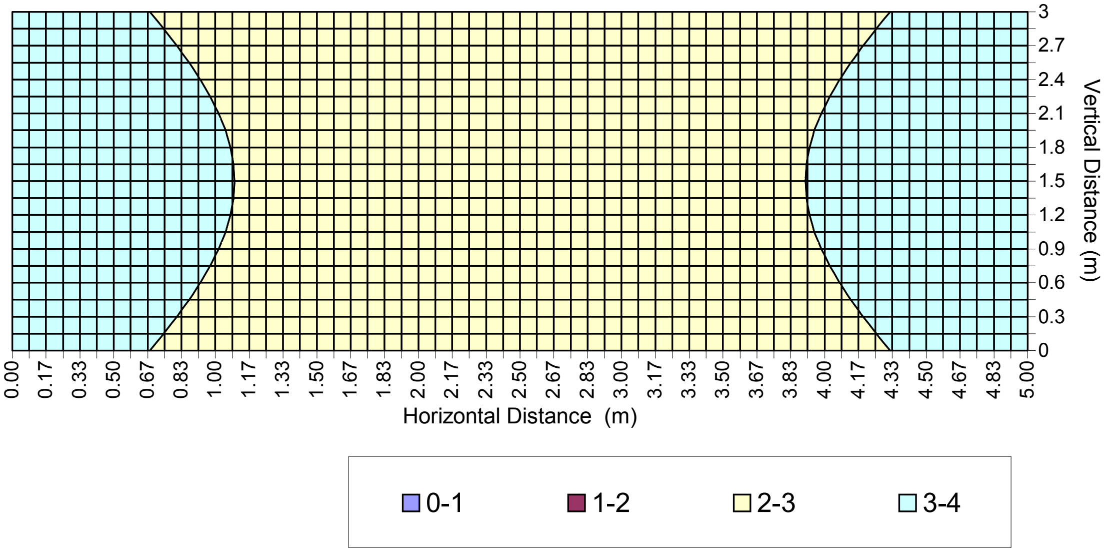


Figure 3.4.1-11: Radiative Heat Flux to Vertical Plane 6.00 m from Jet Flame (kW/m2)

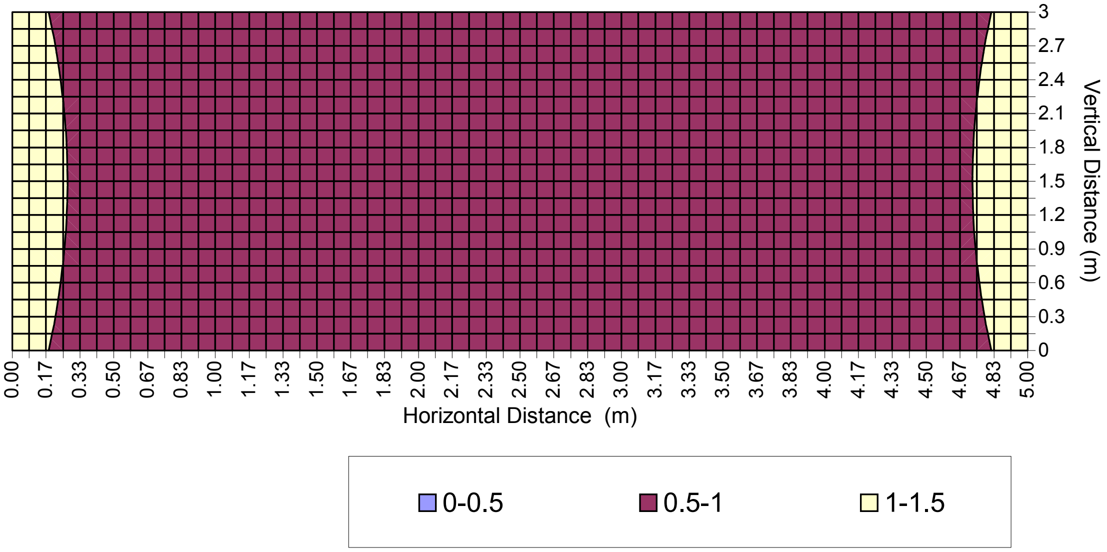


Figure 3.4.1-12: Radiative Heat Flux to Vertical Plane 10.00 m from Jet Flame (kW/m2)

Figure 3.4.1-13 below shows the average and maximum heat flux to the vertical plane as a function of distance from the fire centerline. For distances less than 0.5 meters, direct impingement by the flame and convective heat transfer by the flame becomes an issue, as the plane would be located within the fire.

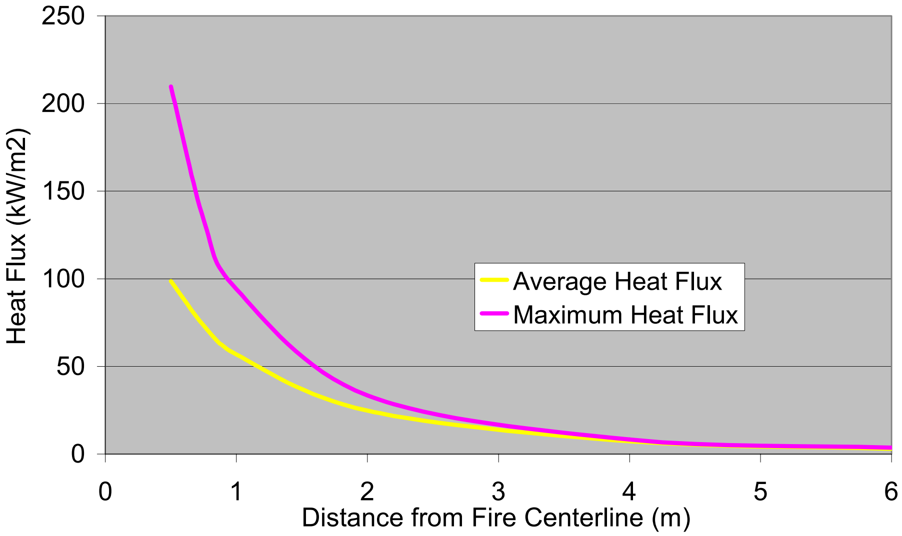


Figure 3.4.1-13: Heat Flux to Target vs Distance

For situations in which there is direct impingement of the jet flame onto the fabric the flame temperature is important to determine. In addition, the convective heat transfer becomes important due to the high exit velocity of the fuel. Flame temperatures are dependent upon the fuel but typically are in the range of 1100-1600 K.[31] Some fuels can have much higher flame temperatures, but those that would be commonly found aboard a navy ship fall within these ranges. The highest flame temperatures would be expected from burning Kerosene or Jet Fuel, with a flame temperature of 1600K. Gasoline and Fuel Oil have flame temperatures of around 1200 K.

3.4.2 Pool Fires

Pool fires are divided into two major classifications, confined and unconfined. Unconfined pool fires exist in areas were the formation of circular pools will not be impeded by barriers such as walls, dykes and drains. Confined pool fires are pool fires that can not spread in an unobstructed manner. Both of these configurations are possible on board U.S. navy ships. Unconfined pool fires are characteristics of those resulting from aircraft refueling accidents or aircraft crash landing damage. Confined pool fires would result from oil and other flammable liquid spills in small machinery spaces. Fuel sources range from very low flash point flammable liquids such as Kerosene and Jet fuels (JP-4 and JP-5) to very high flash point liquids such as lubricating oils. The most likely fire scenario on board a U.S. Naval Vessel is an unconfined pool. Although it is possible for the confined fire case, the unconfined fire is the more conservative approach and the most likely scenario. For pool sizes large enough to completely fill the floor surface area of a compartment, the likelihood of survival would be very small.

Five fuels were investigated for their behavior in pool fire situations. JP-4 and Kerosene are very similar and represent the different types of jet fuel that would be found on board navy ships. Fuel Oil #6 is equivalent to heavier oil hydrocarbons such as diesel fuels used for generators and propulsion engines as well as heavy lubrication oils. Gasoline is a lighter fuel that would be used for hand tools or other portable tools also would be used in some propeller type aircraft. This is the least likely fuel to be involved in a major spill, as it would exist in quantities that would not permit a large-scale spill. The final combustible shares properties that are similar to a variety of hydraulic oils and other light lubricants. Reference [31] lists “transformer oil” but not “hydraulic oil”. However, transformer oil compares very well to a large variety of lighter lubricating and hydraulic oils and thus was selected to represent all of these types of flammable liquids. Properties of these fuels are shown in Table 3.4.1-1.

Table 3.4.1-1: Properties of Fuels used in Pool Fire Calculations

	Fuel Oil #6	Gasoline	JP-4	Kerosene	Hydraulic Oil
Heat of Combustion (kJ/kg)	39.7	43.7	43.5	43.2	46.4
Asymptotic Burning Rate (g/m2-sec)	35	55	51	39	39
Effective Absorption Coefficient (1/m)	1.7	2.1	3.6	0.82	0.7
Chemical Combustion Efficiency	0.9	0.92	0.9	0.9	0.84
Convective Fraction	0.6	0.61	0.6	0.6	0.56
Radiative Fraction	0.3	0.31	0.3	0.3	0.28
Density (kg/m3)	940	740	760	750	760

Heat Release Rates were predicted using the general equation for pool fire heat release rates and the equation relating maximum pool diameter to spill rate. A general equation for pool fire heat release rates is [31]

$$Q = m''\Delta H_c x_{chem} \pi \frac{d^2}{4} \qquad (18)$$

Where

Q is the chemical heat release rate (kW)
m'' is the mass burning rate per unit surface area (g/m^2-sec)
ΔH_c is the net heat of combustion (kJ/g)
x_{chem} is the combustion efficiency
D is the pool fire diameter (m)

The Diameter can be related to the flammable liquid spill rate through the equation

$$D_{\max} = 2\left(\frac{V_s}{\pi\, y}\right)^{\frac{1}{2}} \qquad (19)$$

Where

D_{max} is the maximum pool diameter
V_s is the volumetric spill rate (m^3/sec)
y is the liquid pool fire regression rate (m/s)

Substituting the equation for the maximum pool diameter into the equation for the heat release rate results in the equation for the maximum heat release rate for a give mass spill rate.

$$Q = p_L V_s \Delta H_C x_{chem} \qquad (20)$$

where

p_L is the liquid density (kg/m3)

For the solutions presented here, the pool diameter was selected and the flow rate needed to maintain that pool diameter was then calculated. Figure 3.4.2-1 below shows the maximum heat release rate as a function of pool diameter for the fuels being investigated.

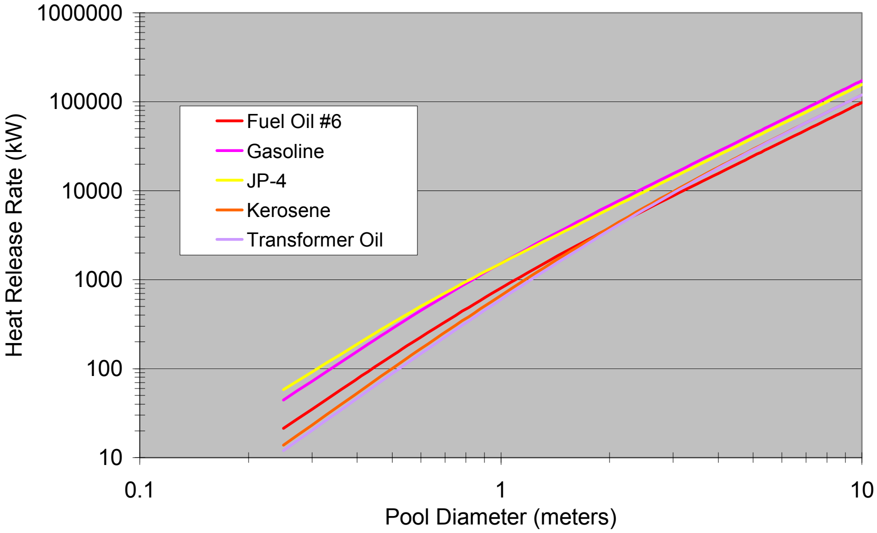


Figure 3.4.2-1: Predicted Heat Release Rate vs Pool Diameter

The flow rates necessary to maintain these pool fire sizes are determined by matching the rate that that the fuel in the pool is burned to the rate of flow into the pool. The mass burning rate of hydrocarbon fuel fires is given by Babrauskas as [31]

$$m'' = m''_{\infty}\left(1 - e^{-k'D}\right) \qquad (21)$$

Where

m’’ is the mass burning rate per unit surface area (g/m^2-sec)
m’’$_{\infty}$ is the asymptotic mass burning rate for large pool fires (g/m2-sec)
k’ is the effective absorption coefficient
D is the pool diameter (m)

Figure 3.4.2-2 shows the mass burning rates for the investigated pool fire configurations.

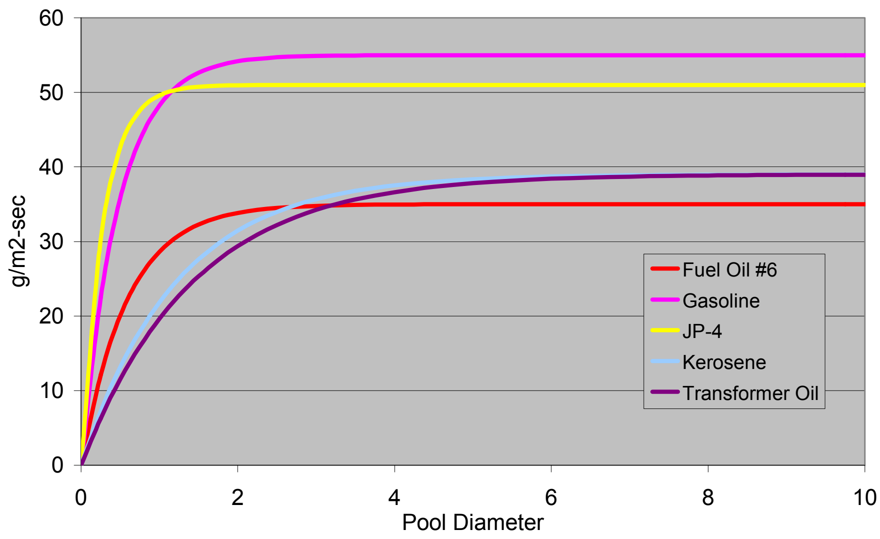


Figure 3.4.2-2: Pool Fire Mass Burning Rate Per Unit Surface Area

Although pool fires grow from ignition to maximum heat release rate very rapid it is not an instantaneous process. The time for the pool fire to grow from ignition to maximum pool size and heat release rate was calculated using the following equation developed by Raj.[31]

$$t_{\max} = \frac{0.564\,D_{\max}}{(gyD_{\max})^{\frac{1}{3}}} \qquad (22)$$

Where

$D_{\max}$ is the maximum pool diameter (m)
g is the gravitational acceleration (9.81 m/sec^2)
y is the pool regression rate (m/s)

Regression rates are dependent upon the fire configuration and thus are difficult to calculate in a general fashion. However, for most hydrocarbon pool fires, regression rates are on the order of 0.1 mm/sec (0.0393in/sec). This value was used for the pool regression rate in all cases. Figure 3.4.2-3 below shows the fire growth time as a function of pool diameter using the above regression rate.

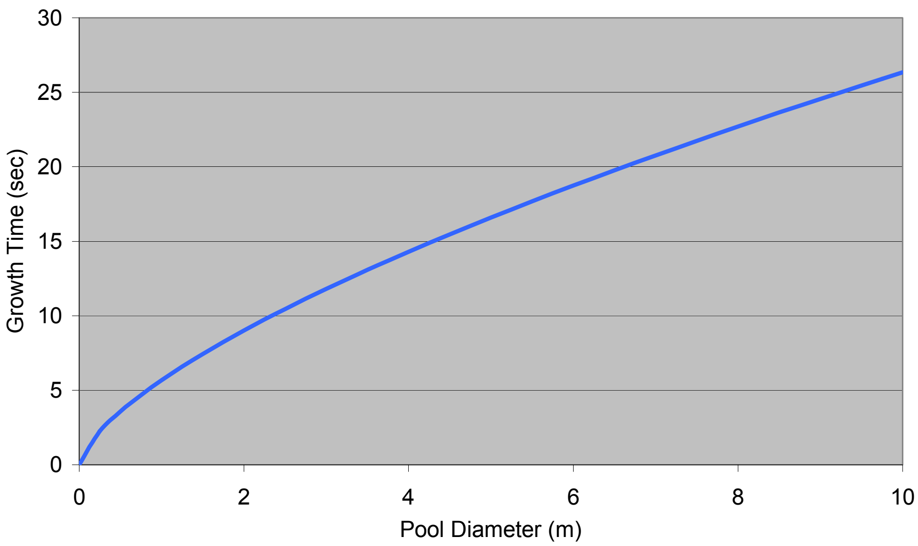


Figure 3.4.2-3: Pool Fire Growth Time to Peak Heat Release Rate

For small pool fires the growth time is not a significant factor, however larger pool fires would not reach maximum heat release rate during the time it would take for evacuation of the fire area. Thus utilizing the maximum heat release rate for these scenarios would be inappropriate and the growth of the fire would need to be modeled.

Another factor that needs to be determined before pool fire radiation can be considered is the flame heights. Flame heights were calculated utilizing the Heskestadt correlation [31].

$$H_f = 0.23Q^{\frac{2}{5}} - 1.02D \qquad (23)$$

Where

H_f is the flame height (m)
Q is the heat release rate (kW)
D is the fire diameter (m)

Figure 3.4.2-4 shows flame heights as a function of fire diameter for the investigated fuels.

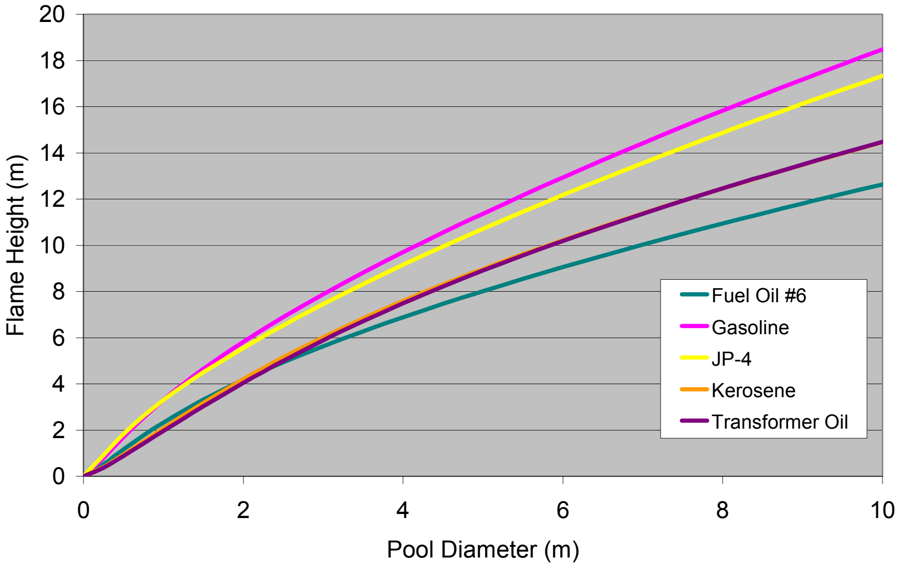


Figure 3.4.2-4: Pool Fire Flame Heights

3.4.2.1 Pool Fire Radiation

Pool fire radiation for unenclosed fires was calculated utilizing the method used for jet fires with appropriate changes to the shape factor calculations made. The same shape factor was utilized but applied in a slightly different manner. Results for a variety of configurations are available in Appendix B. Results are presented here for a 5 meter diameter JP-4 pool at distances of 5.5, 5.75, 6,8,10,15 and 20 meters (18,18.9,19.7,26.2,32.8,49.2,65.6 ft) measured from the centerline of the pool. A flame emissive power of 371 kw/m^2 (88 cal/cm^2) was computed. The resulting radiation field is seen in Figures 3.4.2.1-1 through 3.4.2.1-7 seen below. These figures show the radiant flux to a plane perpendicular to the floor and facing the pool fire. Figure 3.4.2.1 below shows this configuration looking down from above.

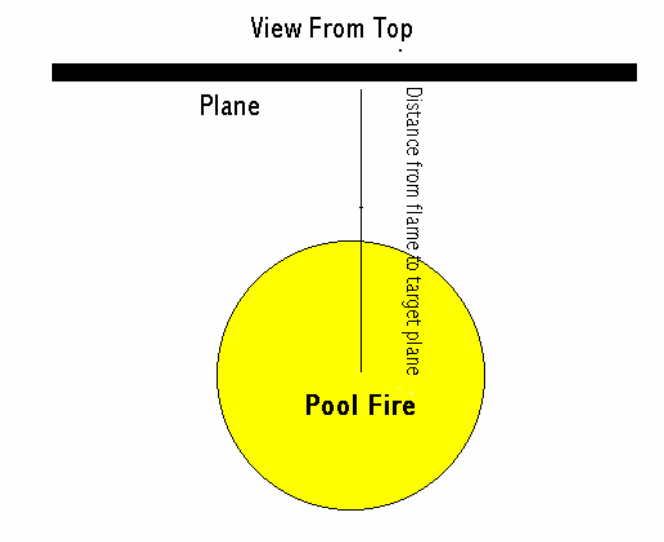


Figure 3.4.2.1 Relationship between fire and target plane

Emissive power for pool fires were computed from the actual flame temperatures using the equation for radiant gray bodies.[11]

$$E = \varepsilon\sigma T_f^{\,4} \qquad (24)$$

$$\varepsilon = 1 - e^{-kL} \qquad (25)$$

Where

E is the flame emissive power (kW/m^2)
T_f is the flame temperature (K)
k is the effective emission/absorption coefficient (m^{-1})
L is the mean equivalent beam length of the flame (m)

Mean equivalent beam lengths have been demonstrated to be approximately equal to the flame radius [12] and thus this value is used. Published values for flame temperatures and emission/absorption coefficients exist, but vary widely.

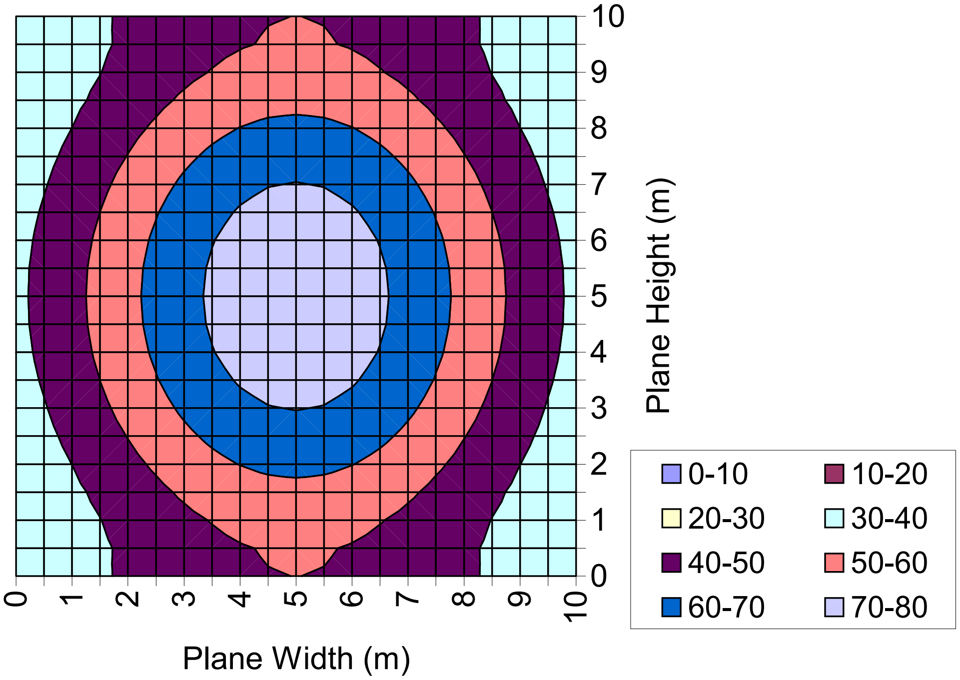


Figure 3.4.2.1-1: Radiative Heat Flux to Vertical Plane 5.5 m From JP-4 Pool Fire (kW/m2)

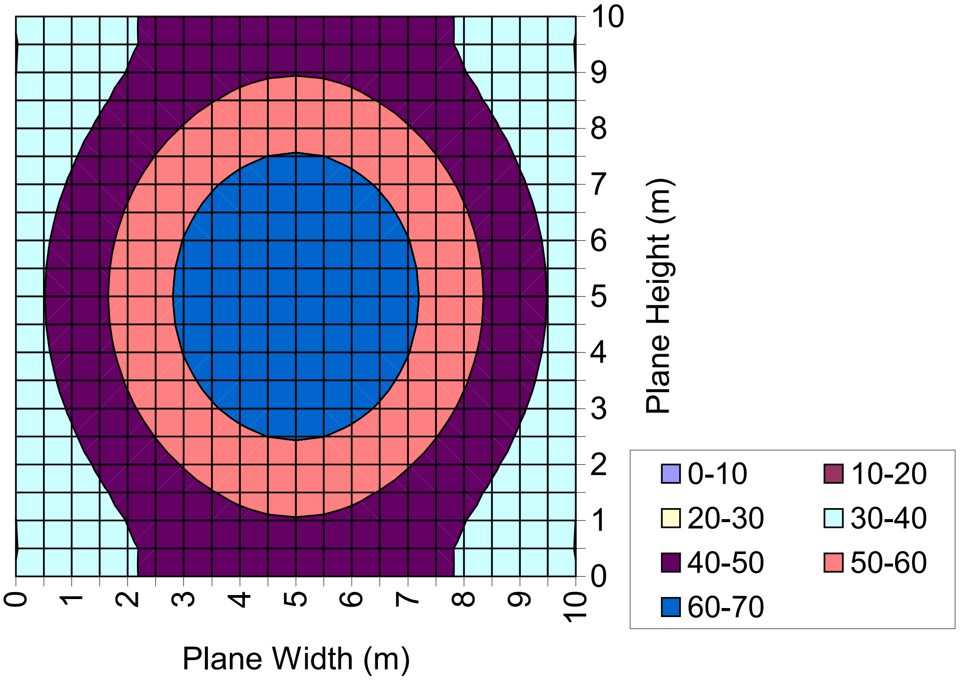


Figure 3.4.2.1-2: Radiative Heat Flux to Vertical Plane 5.75 m From JP-4 Pool Fire (kW/m2)

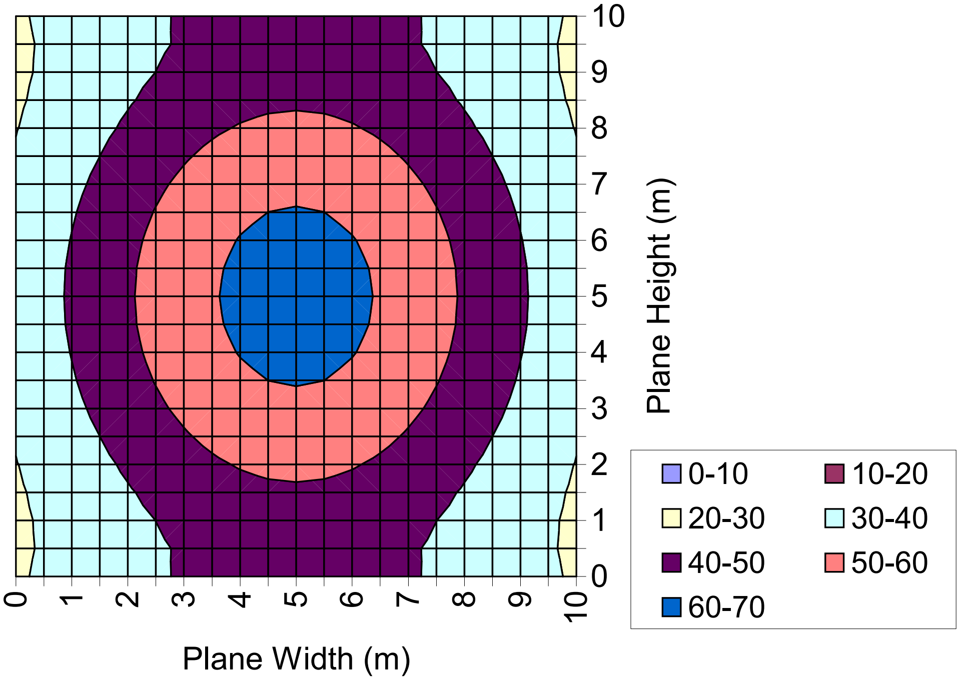


Figure 3.4.2.1-3: Radiative Heat Flux to Vertical Plane 6.0 m From JP-4 Pool Fire (kW/m2)

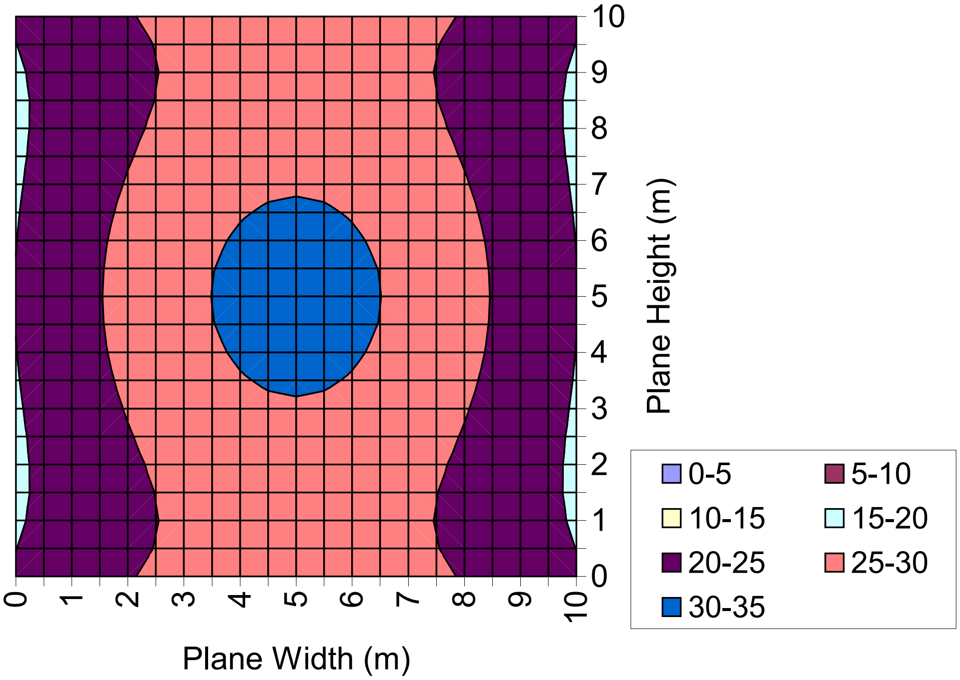


Figure 3.4.2.1-4: Radiative Heat Flux to Vertical Plane 8.0 m From JP-4 Pool Fire (kW/m2)

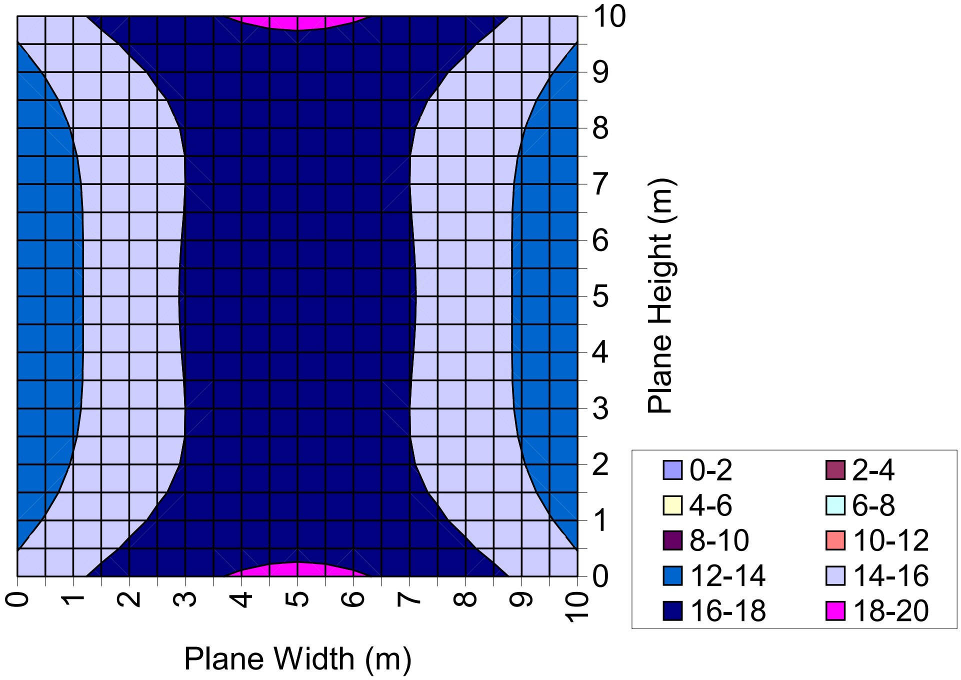


Figure 3.4.2.1-5: Radiative Heat Flux to Vertical Plane 10.0 m From JP-4 Pool Fire (kW/m2)

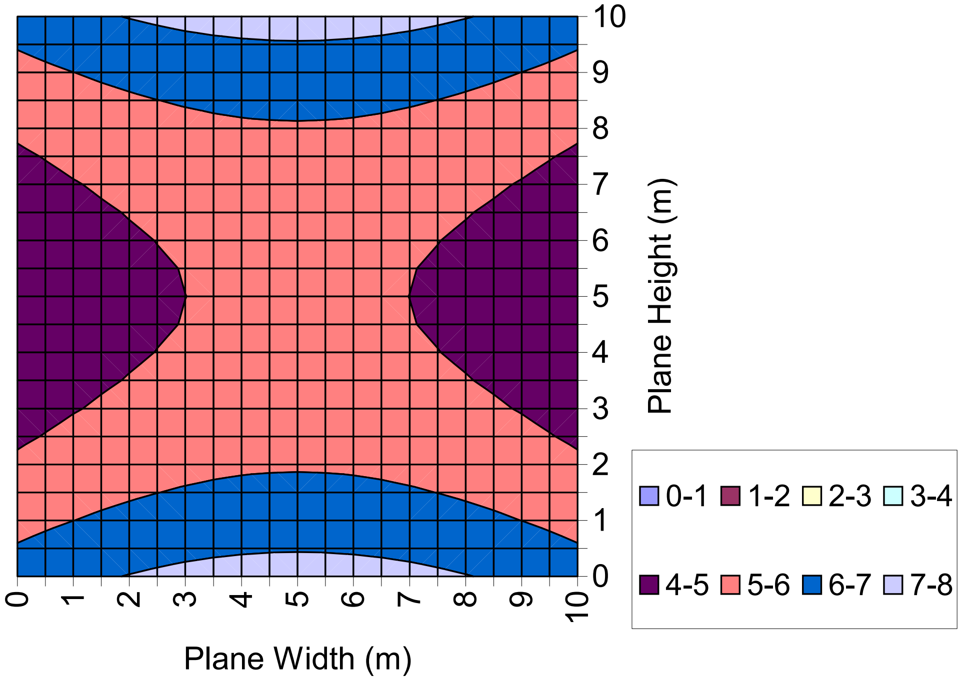


Figure 3.4.2.1-6: Radiative Heat Flux to Vertical Plane 15.0 m From JP-4 Pool Fire (kW/m2)

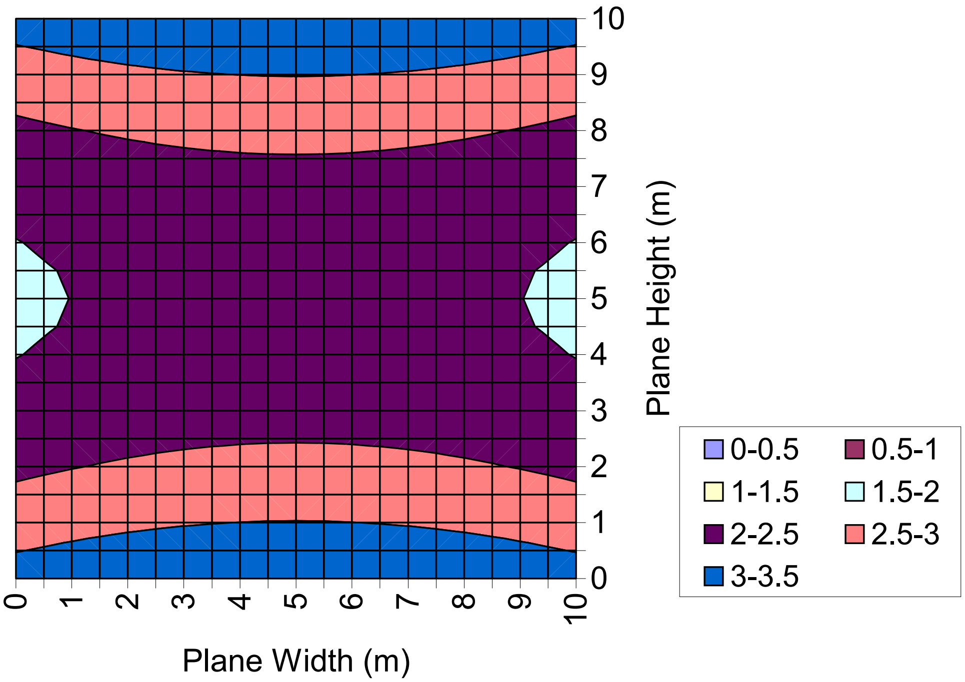


Figure 3.4.2.1-7: Radiative Heat Flux to Vertical Plane 20.0 m From JP-4 Pool Fire (kW/m2)

These figures are useful in a variety of ways. Most importantly, they demonstrate the effects of distance not only on the magnitude of the radiative flux to a target, but also on the distribution of the flux along the plane. If an object is very close to a fire the radiative flux to that object can be very high in some locations and much lower in others. As the target is moved away from the fire, the flux decreases but also the gradient of fluxes throughout the plane becomes much smaller. If the goal is to accurately reproduce the fire conditions within the test chamber, then decisions need to be made regarding the distance at which the fabric is to be tested and then every effort made to reproduce the radiant field presented here for that distance. Simply providing a radiant panel that creates a constant radiant flux will not accurately recreate the actual fire scenario.

4.0 Compartment Modeling

The hazards created by unconstrained fires are limited largely to the radiant flux from the flames as hot products of combustion are quickly dispersed. In constrained fires, such as those within a compartment on board a ship the hazards of the fire are much greater due to the collection of products of combustion and the increased heat flux back to the fuels. Predicting the behavior of fires in enclosures is typically more difficult because of the increase in complexity due to compartmentation effects on both the heat release rate of the fire, and the environment generated by the fire. To accommodate these complexities, computer fire modeling was used to predict the development of the fire environment within compartments on a ship.

The behavior of the fuel and the corresponding heat release rates are altered by two major parameters, radiative feedback to the fuel and available oxygen. In unenclosed fires, the supply of oxygen is virtually unlimited and the only source of radiative feedback to the fuel is the burning flame. In enclosure fires, the ventilation in the compartment and accumulation of products of combustion can significantly reduce the availability of oxygen within the compartment.[12] Radiative feedback to the fuel is also more complex in the enclosed fire scenario. In addition to the radiation from flame itself, radiative feedback from the accumulated product of combustion gasses as well as hot enclosure surfaces contributes to the heat flux to the fuel surface, resulting in a corresponding increase in fuel pyrolysis. These two factors frequently counteract each other, as limited ventilation will reduce the amount of oxygen available for combustion but increased radiant flux to the fuel will increase the available fuel in the compartment.

Additional concerns are the temperature of the gas layers formed in the compartment, the convective heat flux to objects in the compartment, and the radiative heat flux to objects in the compartment. Multitudes of compartment fire models are available to predict these factors. One of the limitations of these models is that the fire must be specified and thus the effects of the compartmentation on the fire heat release rate are not easily calculated. One exception to this is oxygen limited burning. Many of the available codes will reduce the burning rate within the compartment as oxygen concentrations fall below levels that will sustain combustion. The affect of the radiation on the fire growth and heat release rate is not accounted for.

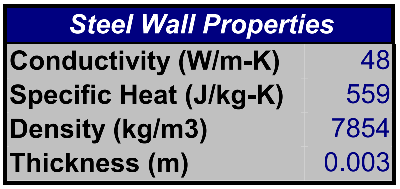
A multitude of compartment fire environment modeling codes is available from a variety of sources. Some of the major codes include CFAST, WPI Fire Code, BRANZFire, and FIRST. These codes come from a variety of sources and each one has its own advantages and disadvantages. CFAST was selected as the most appropriate code for this study as it is developed by NIST, has been reasonably validated, has been in development for many years, has been widely used, and is reasonably robust. Over 50 CFAST models were constructed and run as part of this study. The most significant results are available in the body of the report with additional results available in Appendix C.

4.1 Reference Model

Varieties of model parameters were varied to determine their effect on the environment within the compartment. Fuel types and fire sizes were varied for several cases. The base case model was a compartment

10 meters by 10 meters (32.8 x 32.8 ft) in plan with a ceiling height of 3 meters (9.84 ft). All walls of the compartment were composed of 1/8-inch thick plain carbon steel. The properties of this material may be seen in Table 4.1-1.

Table 4.1-1: Steel Wall Material Properties



Steel Wall Properties	
Conductivity (W/m-K)	48
Specific Heat (J/kg-K)	559
Density (kg/m3)	7854
Thickness (m)	0.003

One door opening 0.91 meters (2.98 ft) wide by 2 meters (6.56 ft) high and one square roof vent of dimension 0.5 m by 0.5 m (1.64 x 1.64 ft) were specified. The fire consisted of a 2 meter (6.56 ft) diameter pool fire of Kerosene specified as a pyrolysis rate of 0.051 kg/sec (0.112 lbm/sec) and located at floor level in the geometric center of the room. The heat of combustion of the kerosene was taken as 1.228×10^8 J/kg, The initial fuel temperature was ambient and the gaseous ignition temperature was specified as 493 K, which is consistent with moderately low flashpoint hydrocarbons. The radiative fraction was specified as 30% of the total heat release rate.

The objectives of this project require that the heat flux to objects located throughout the compartment be known. Four targets composed of the same materials as the compartment walls were set up at varying distances from the fire. These targets were needed to represent virtual people in the modeled environment. The heat flux to these steel targets is used to calculate the exposure heat flux to people wearing protective clothing. Each target was facing the fire and located at a height of 1 meter. This is illustrated in Figure 4.1-1 below. The targets were located at distances of 1.41, 2.82, 3.65, and 4.24 meters (4.62,9.25,11.97,13.9 ft) from the fire centerline.

Ambient conditions were specified as 20 degrees C and a relative humidity of 50%. Each simulation was run for a total of 2009 seconds, although for nearly all cases a steady state scenario was observed within the first 1000 seconds of the simulation. The base case results are exhibited in the following figures.

Figure 4.1-1 shows the convective and radiative heat release rate of the pool fire within the compartment. Note that the peak heat release rate is not equivalent to the steady state heat release rate. The peak heat release rate occurs before all of the initially available oxygen in the compartment has been utilized. After all of the initial oxygen has been consumed, the only source of additional oxygen is from the vent inflow. This becomes the limiting factor in the determination of the sustained heat release rate. Notice that the radiative portion of the heat release rate is 33% larger than the convective component. This particular percentage will be largely dependent upon the fuel being burned. Heavy hydrocarbons that produce sooty flames will have a much greater radiative portion than alcohol type fuels that have very small radiative components.

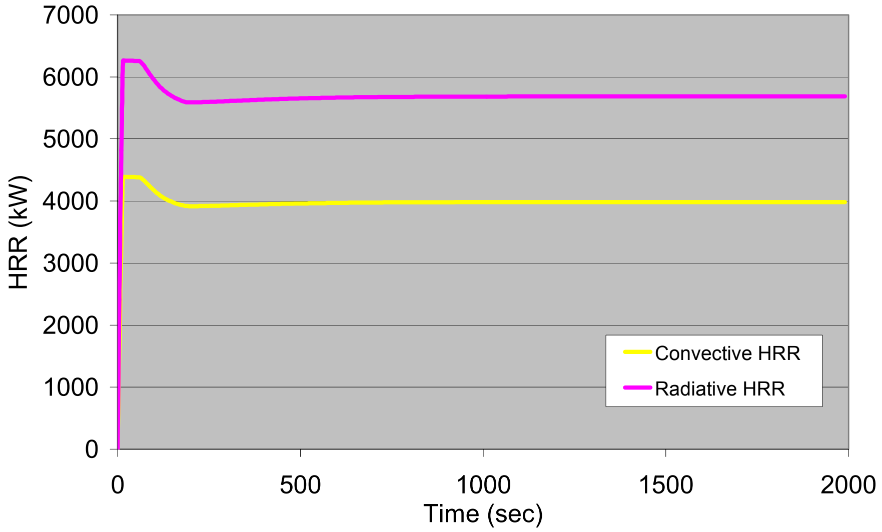


Figure 4.1-1: Fire Heat Release Rate

The second major source of energy within the room is the collected products of combustion. Typical compartment fires demonstrate an effect known as stratification or layering. Stratification occurs due to the temperature difference between the relatively cooler air that either has flowed into the compartment through a vent or has not been directly exposed to the hot products of combustion. This results in two separate distinct layers in the compartment. One composed of relatively cool clean air flowing along the floor and a second layer composed of soot, carbon dioxide, water vapor and other products of combustion in the upper portion of the room. The Figure 4.1-2 below shows the temperatures of these two layers in the base case scenario.

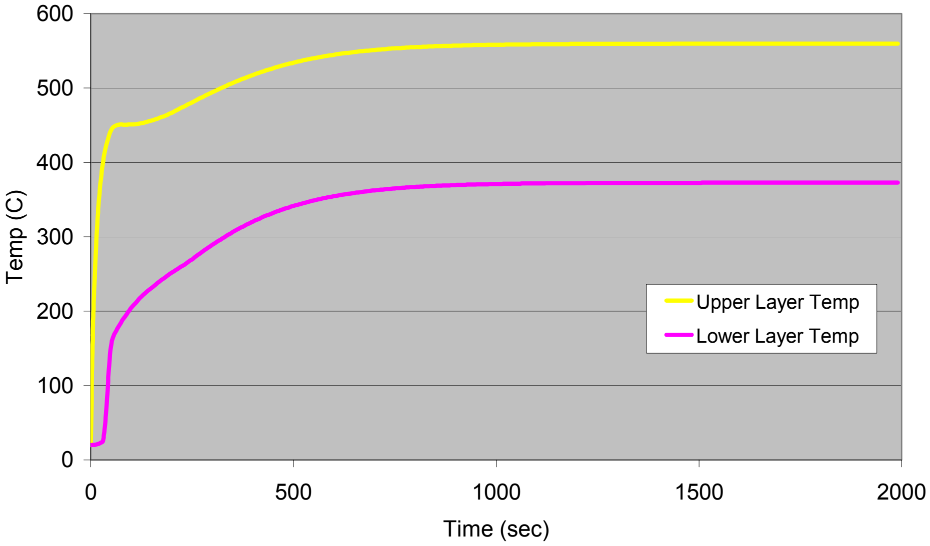


Figure 4.1-2: Compartment Gas Layer Temperatures

The height of the interface between the two layers depends upon the heat release rate of the fire in relation to the amount of ventilation in the compartment. Compartments with large fire source and very small ventilation openings will have interface heights very close to the floor. 4.1-3 below shows the interface height for the base case compartment.

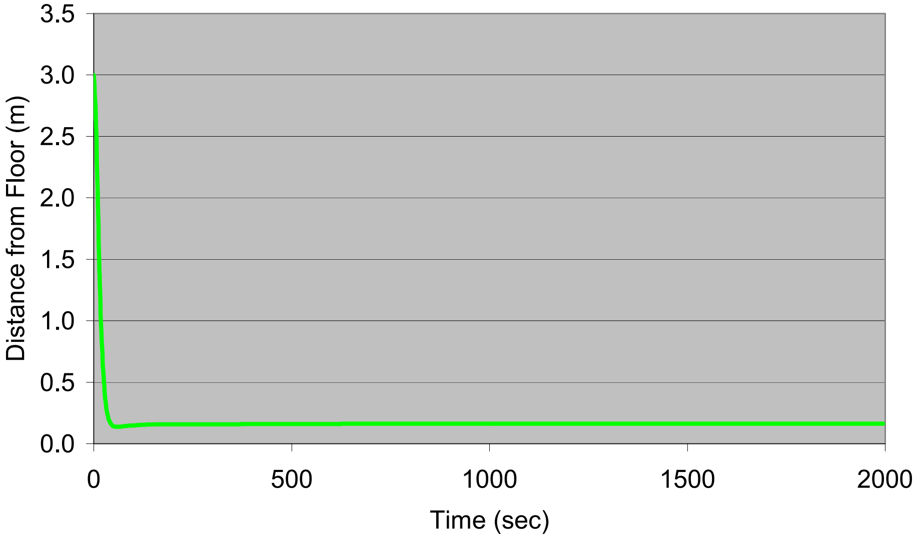


Figure 4.1-3: Layer Interface Height

For the ventilation and fire size in the base case the interface height moves very close to the floor very early in the fire and maintains an equilibrium height of 0.2 meters (7.9 in). This means that the vertical radiation targets, at a height of 1 m are wholly immersed in the upper layer, which is at a temperature of 550 C (1022 F). With radiation having a 4th power relationship with temperature ($\propto T^4$), we would expect the heat fluxes to the targets to be extremely high. Figure 4.1-4 shows the fluxes to the four targets. All targets are placed directly facing the fire, perpendicular to the floor at a height of 1 meter. Each target is placed at different distances from the centerline of the pool fire. Target 1 is at a distance of 1.41 meters, target 2 at 2.82 meters, target 3 at 3.65 meters and target 4 at 3.65 meters.

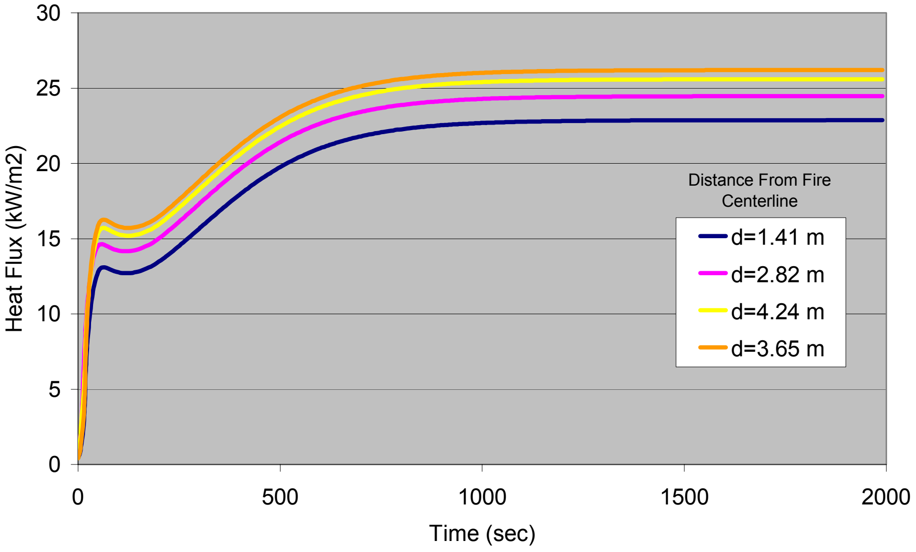


Figure 4.1-4: Radiant Heat Flux to Targets

Figure 4.1-5 shows the equilibrium heat flux as a function of distance from the fire centerline.

Figure 4.1-5: Target Heat Flux vs Distance from Fire

The geometric relationship between the fire, target, compartment surfaces and gas layer makes the heat flux much more complex than the unenclosed space, as can be observed in Figure 4.1-5. With the fire in the center of the compartment, moving away from the fire results in moving closer to hot wall surfaces. In addition, the radiation and convective transfer from the hot gas layer depends upon the exact geometry of the fire, compartment, target configuration. The effects of the location of the targets and fire were extensively examined to determine some basic pattern. Furthermore, targets in the same geometric location but with different orientation can have widely varying heat fluxes.

4.2 Compartment Model Variables

Variables that were specified in the base case model and that have a large impact upon the modeling results were investigated to determine their effects on the model results. This process will allow qualitative comparisons between the modeled results and an actual compartment fire situation, which would most likely not be exactly the same as the base case.

4.2.1 Compartment Dimensions

One of the most basic parameters required by CFAST is the dimension of the compartment. The length and width dimensions were varied from a minimum of 5 meters (16.4 ft) to a maximum of 15 (49.2 ft) meters. The height of the compartment was varied from 2 meters to 4 meters. Using the base case fire but reducing the dimensions of the compartment to 5 meters by 5 meters in plan by 3 meters (16.4 x 16.4 x 9.84 ft) in height greatly increases the intensity of the fire environment within the compartment. The effects on the heat release rate of the fire are small. This is exactly what would be expected as the factor limiting the heat release rate is ventilation. Figure 4.2.1-1 shows the heat release rate curves for the portions that due show variations, which result mainly from the larger initial oxygen supply available in the compartment.

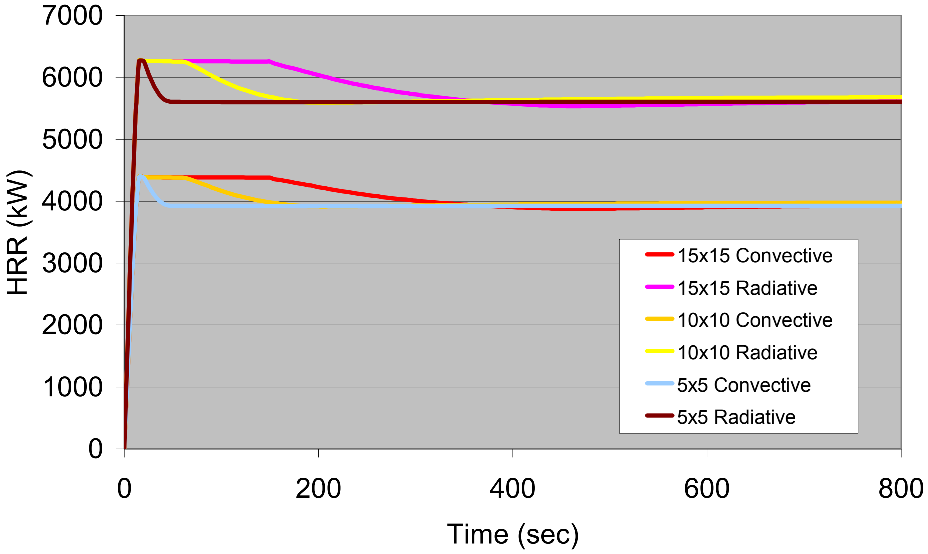


Figure 4.2.1-1: Heat Release Rate Variation with Compartment Dimensions

Figure 4.2.1-1 indicates that similar amounts of energy were released into the compartment regardless of the compartment size. The differences in the heat release rate curves are due to the differences in the initial amount of oxygen available in the compartment. The larger compartment will have a larger volume of air than the base case compartment, which results in peak heat release rates being maintained longer as this oxygen is utilized. Ultimately all fires reach the same heat release rate as they become ventilation limited. The effects of this are very significant differences in layer temperatures and target heat fluxes. Figure 4.2.1-2 below shows the upper and lower layer temperatures for the 5x5, 10x10 and 15x15 meter compartments.

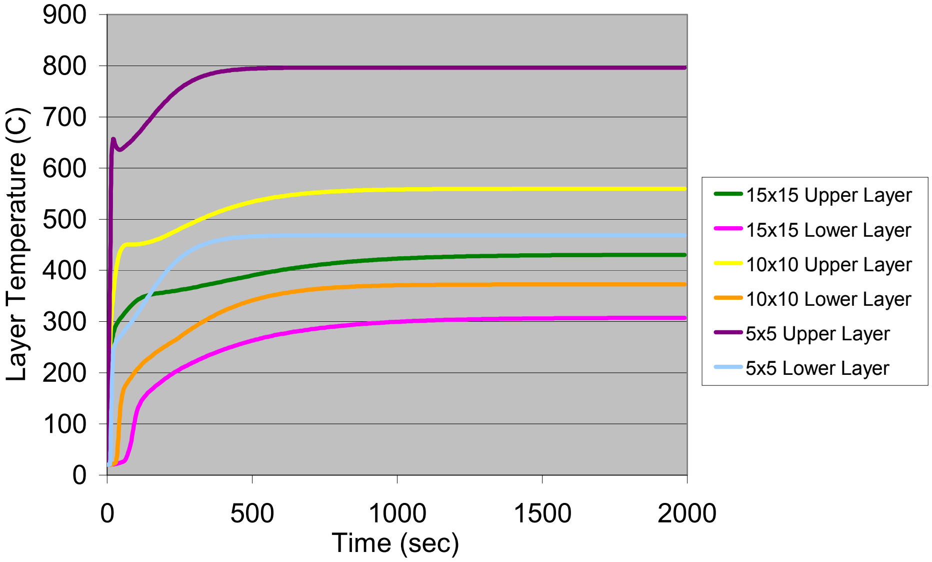


Figure 4.2.1-2: Layer Temperatures for Varying Compartment Sizes

The effect on the heat flux to targets placed in the compartments is more difficult to predict. With the larger compartment, there are greater distances from hot wall surfaces and lower upper layer temperatures. However, the upper layer is much larger which will increase the incident radiation to the target. The reverse is true for the smaller compartment. Figures 4.2.1-3 and 4.2.1-4 show the heat flux to vertical targets at a height of 1 meter measured from the floor of the compartment and facing the fire source for a variety of distances from the fire centerline.

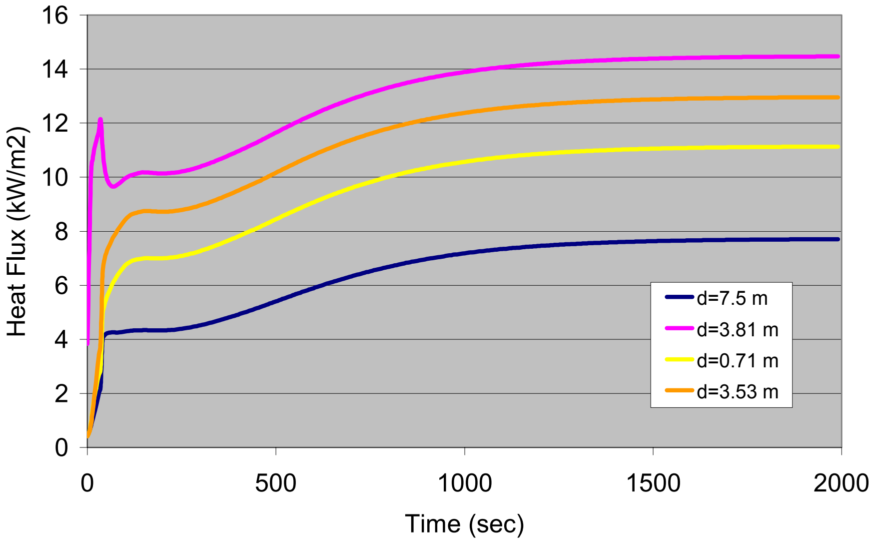


Figure 4.2.1-3: Heat Fluxes to Vertical Target 15x15 Meter Compartment

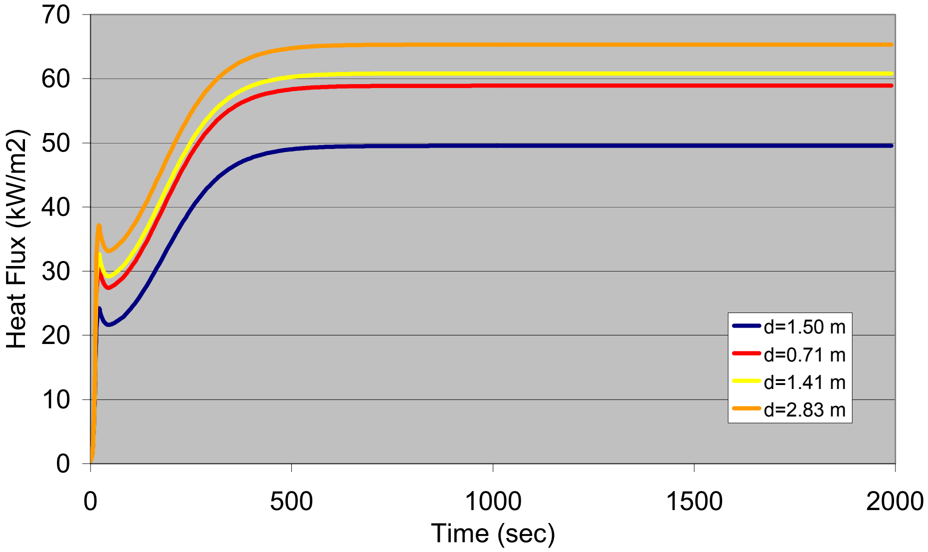


**Figure 4.2.1-4: Heat Flux to Vertical Target
5x5 Meter Compartment**

4.2.2 Effects of Fire Size

Another significant variable is the size of the fire. Reducing the fire size will result in lower heat release rates, lower layer temperatures and smaller incident heat fluxes. The magnitude of these changes was investigated by utilizing the base case scenario with fire diameters of 0.5,1, 1.5,2 and 2.5 meters (1.64,3.28,4.92,6.56,8.2 ft). Figure 4.2.2-1 below shows the convective heat release rate of the fire and Figure 4.2.2-2 shows the radiative heat release rate from the different fire sizes.

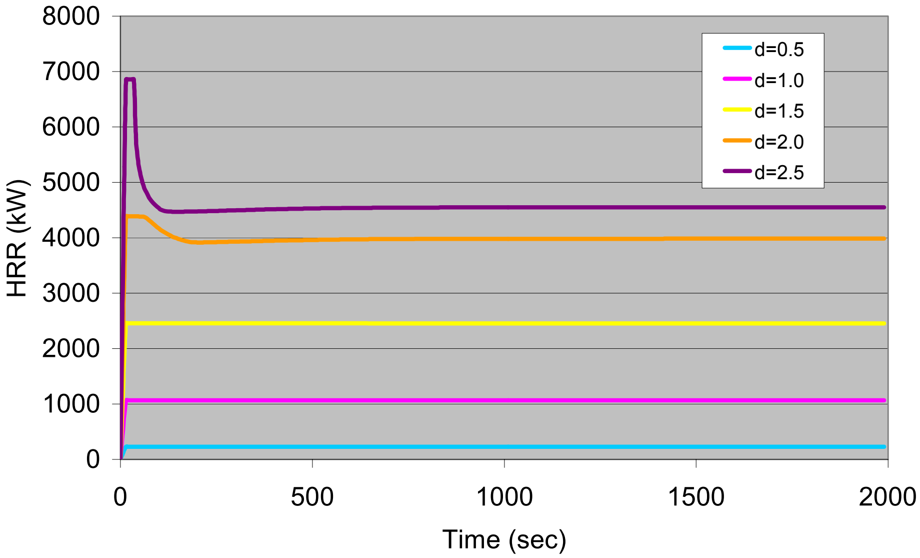


**Figure 4.2.2-1: Convective Heat Release Rate for
Varying Fire Size**

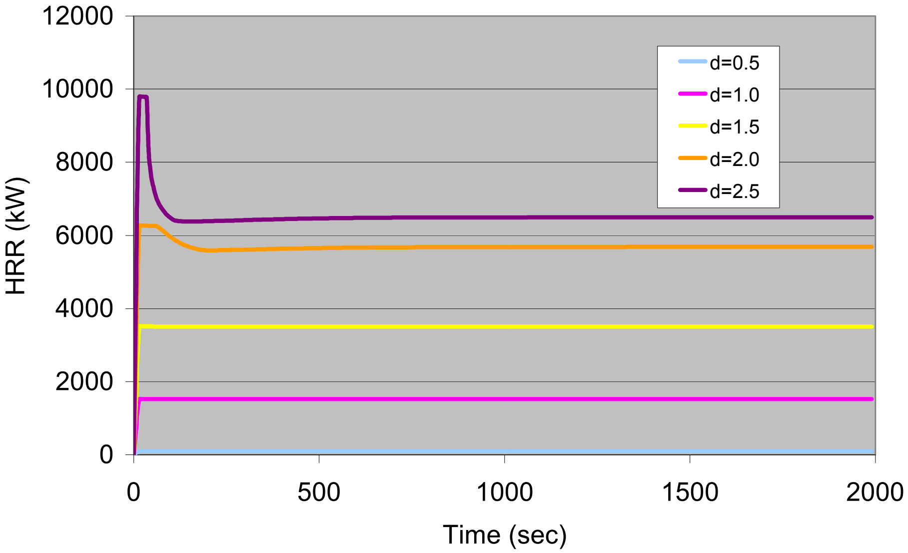


Figure 4.2.2-2: Radiative Heat Release Rate for Varying Fire Size

The above plots also demonstrate the importance of vent configuration on total heat release rate. For the vent sizes used in the base case fire scenario the smaller fire sizes (0.5, 1.0 and 1.5 meters) the availability of fuel is the limiting factor determining the peak heat release rate for the fire. For the larger fire sizes, 2.0 and 2.5 meters the limited vent area and corresponding limit in available oxygen becomes the limiting factor. The peak in heat release rate seen early in the fire exhibits this. The fire grows until all of the initially available oxygen in the compartment is used and then decreases in intensity until a balance between the oxygen entering the room and the oxygen being used in the combustion process is reached. Not all fires have the same peak heat release rate because larger fires will have stronger entertainment into the plume, which, in turn will draw more oxygen in through the vents.

Figure 4.2.2-3 below shows the convective and radiative portions of the steady state heat release rate as a function of fire diameter.

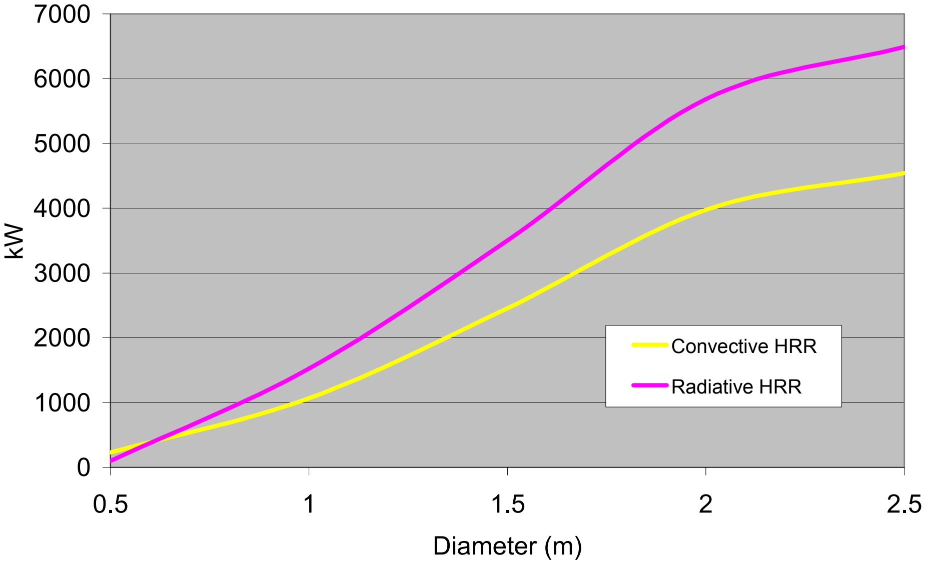


Figure 4.2.2-3: Steady State Heat Release Rate vs Fire Diameter

Figure 4.2.2-3 indicates that the radiative portion of the total fire heat release rate increases as the diameter of the fire increases. Also, additional fuel will not result in an increase in heat release rate due to the limited availability of oxygen.

The effects of fire size on upper and lower layer temperatures are seen in Figures 4.4.2-4 and 4.4.2-5 below.

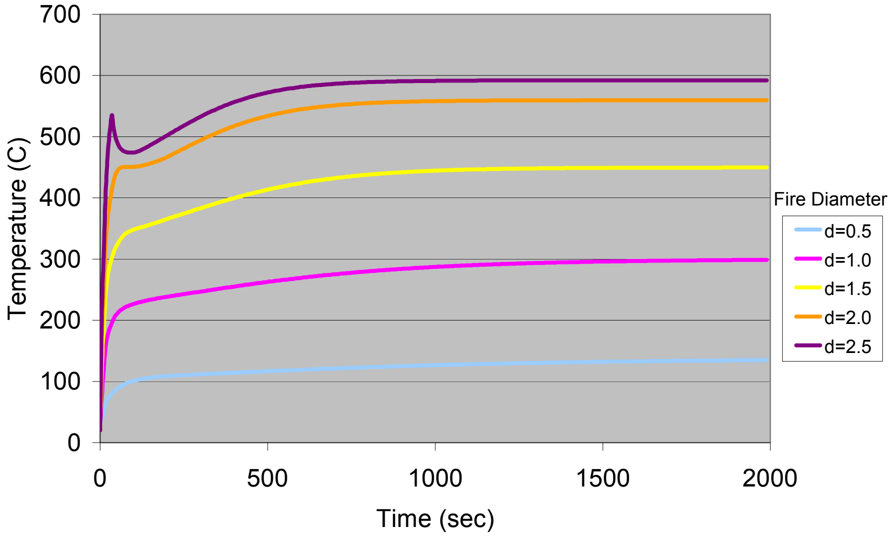


Figure 4.2.2-4: Upper Layer Temperature for Varying Fire Size

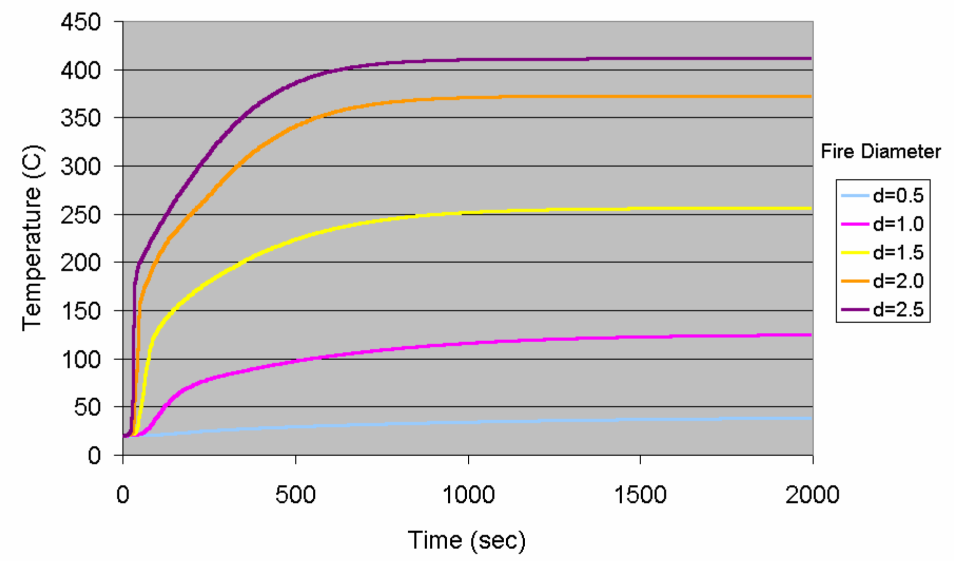


Figure 4.2.2-5: Lower Layer Temperature for Varying Fire Size

Figure 4.2.2-6 below exhibits the relationship between steady state layer temperature as a function of fire diameter.

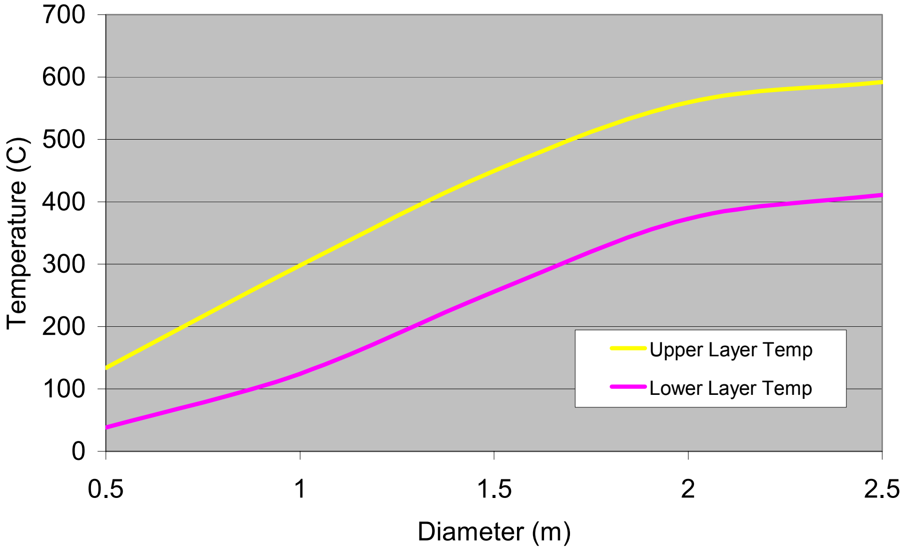


Figure 4.2.2-6: Steady State Layer Temperature vs Fire Diameter

The difference between the two layer temperatures remains nearly constant regardless of the size of the fire. Also, there is a maximum pool size above which the intensity of the fire and the corresponding layer temperatures will not change. The difference in layer temperatures is approximately 200 C regardless of fire size.

Of primary importance to the purpose of this project is the effect of fire size on the heat flux to the targets. A small increase in fire size can have an enormous impact upon the incident heat flux to the targets.

Because the fire is the driving force behind the compartment environment, a change in the fire results in corresponding changes to all of the variables that are driven by the fire. The heat flux to the targets is the sum of many different sources other than the actual fire. A larger fire will indeed increase the portion of the target heat flux resulting directly from the fire, but also will increase the wall temperatures and layer temperatures, which also influence the target heat flux. Figures 4.2.2-7 through 4.2.2-11 demonstrates the target heat flux for the investigated fire sizes.

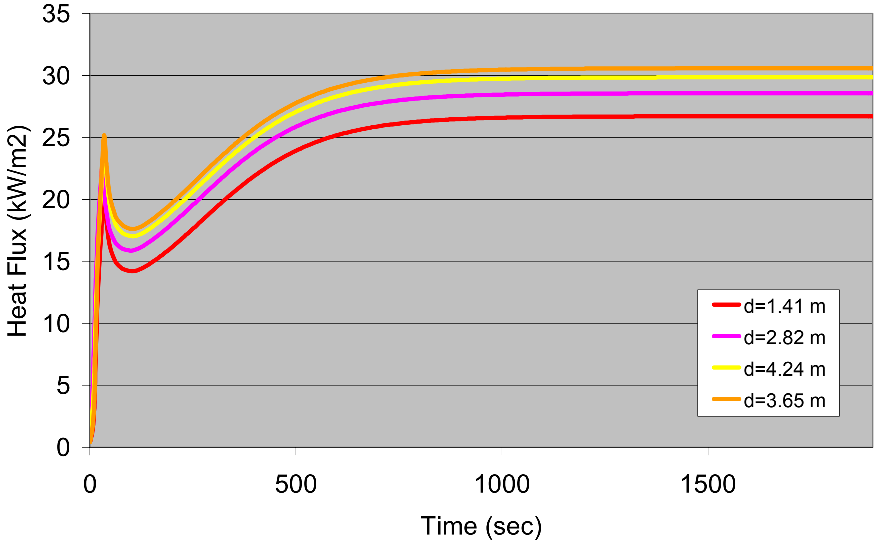


Figure 4.2.2-7: Target Heat Flux for 2.5 Meter Diameter Fire

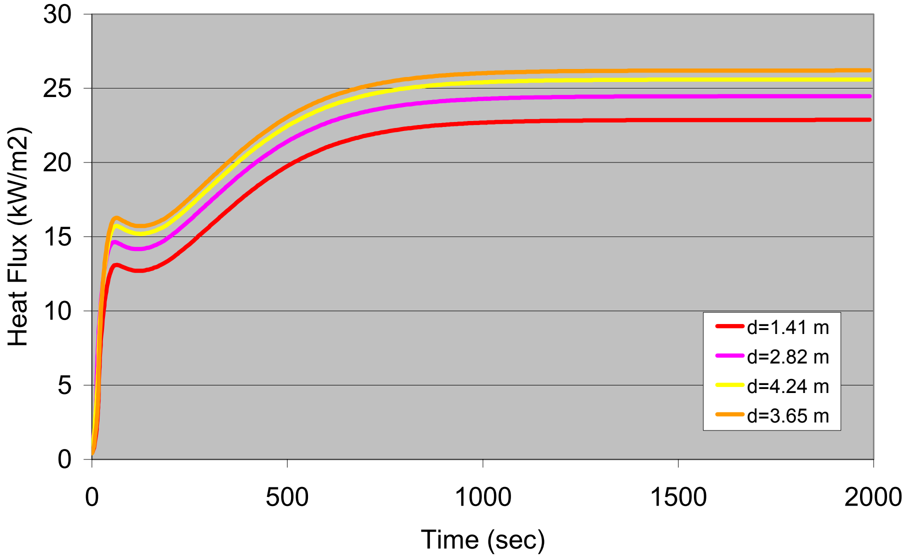


Figure 4.2.2-8: Target Flux for 2.0 Meter Diameter Fire

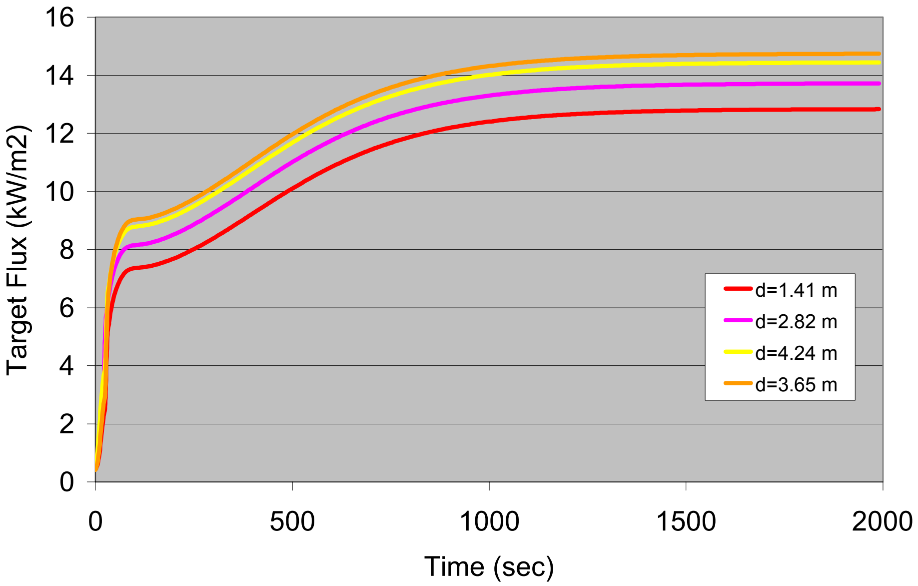


Figure 4.2.2-9: Target Flux for 1.5 Meter Diameter Fire

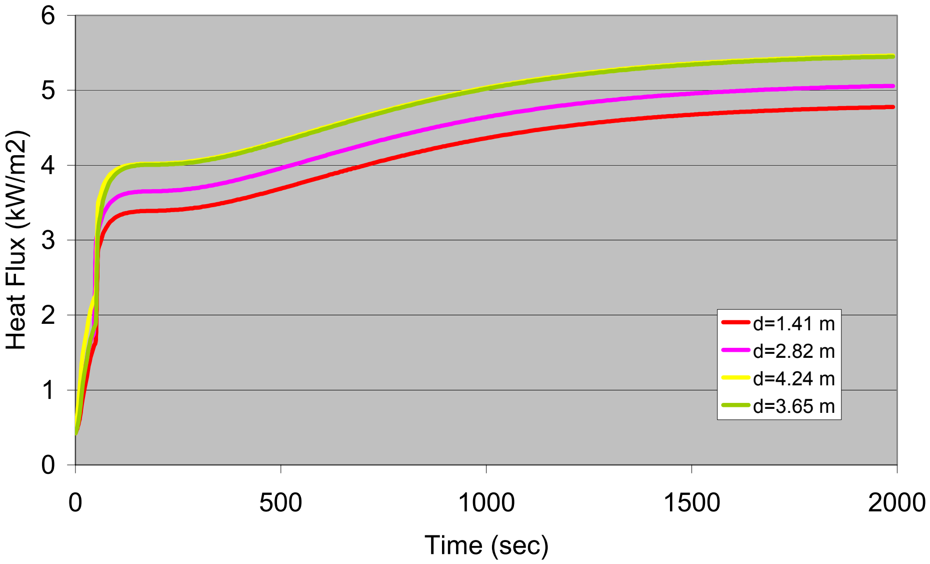


Figure 4.2.2-10: Target Flux For 1.0 Diameter Fire

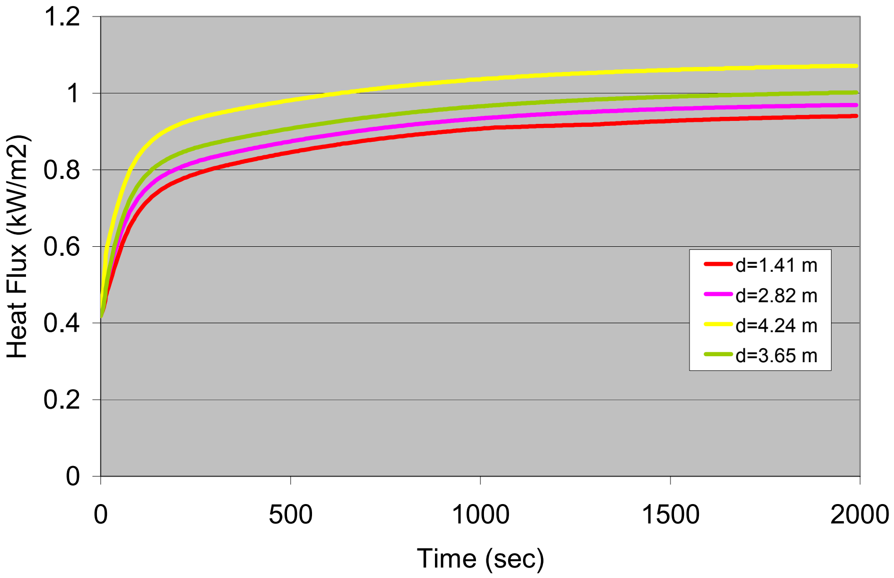


Figure 4.2.2-11: Target Flux for 0.5 Meter Diameter Fire

Figure 4.2.2-12 below shows the steady state heat flux as a function of fire diameter. The figure indicates that distance between the fire and the target has a more significant impact for larger fires than for smaller fires.

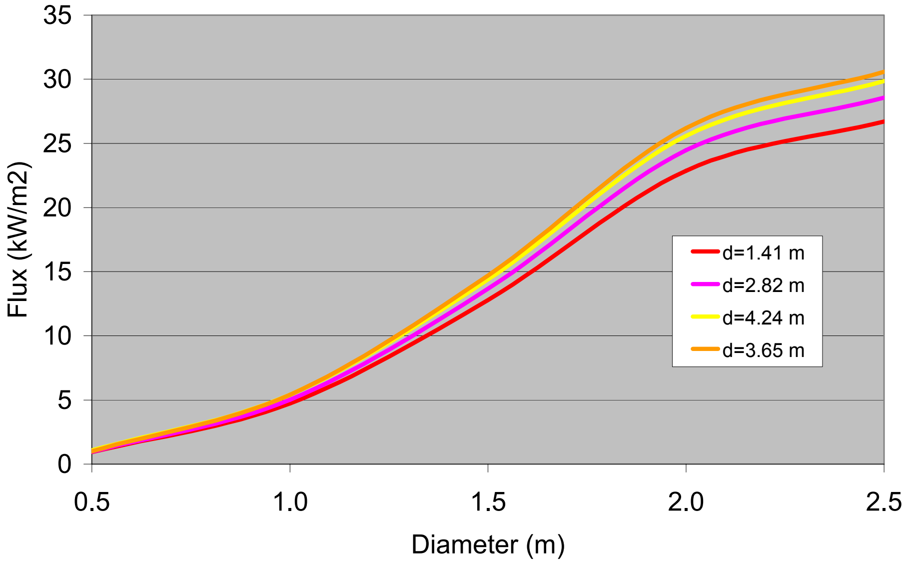


Figure 4.2.2-12: Target Flux vs Fire Diameter

The above figures indicate that the driving force behind the hazardous environment generated by a fire is the fire itself. Determining the correct design fire for any proposed test will, in large part, determine the acceptability of that test standard. Specifying a precise fire size can be difficult, as relatively small changes in spill size can result in huge difference in fire environment severity. The ability to handle the large differences in fire environments is important to consider when designing appropriate test equipment.

Additional variables were investigated and the results are available in Appendix C. All vent sizes were varied and different fuels were utilized. The results of these variations result in no surprises. Increasing the vent size allows sufficient oxygen to enter the compartment to maintain higher heat release rate, increasing the severity of the fire environment. Decreasing the total vent area has the opposite effect. Changing the fuel has very little effect on the total heat release rate as most hydrocarbons require roughly the same amount of oxygen for a specified heat release rate, and all of the larger fires are oxygen limited. Altering the compartment height has the same effect as changing the compartment size.

4.2.3 Vent Areas

Two components are required to have a fire, fuel and oxygen. Often there is significantly more fuel than can be burned given the oxygen supply in a compartment. The rate of oxygen flow into the room is controlled by the configuration of the vent in the compartment, particularly the size of the vents. To determine the effects of the vents on maximum heat release rate the standard compartment was modeled with vent areas of 3.0 m^2, 1.8 m^2, and 1.1 m^2 (32.25,19.35,11.83 ft^2). The effects of vent area on the heat release rate are seen in Figure 4.2.3-1.

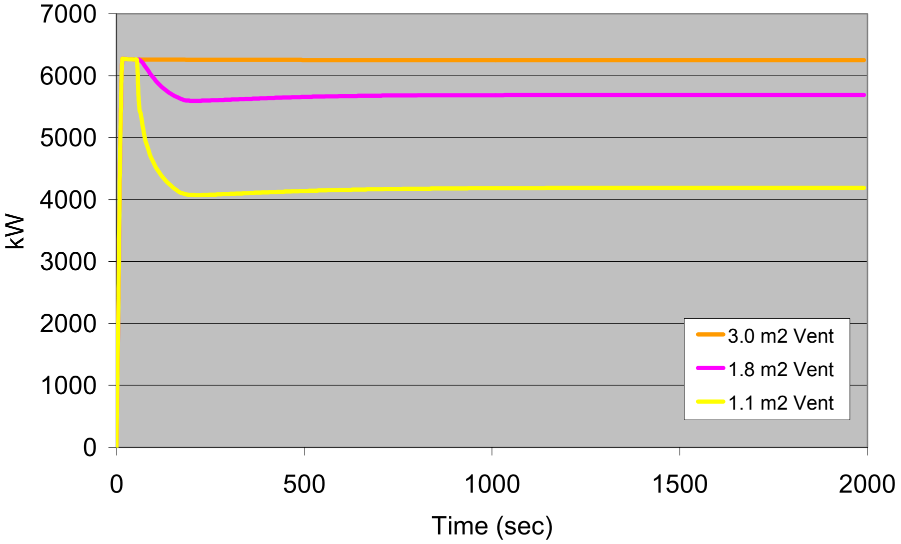


Figure 4.2.3-1: Heat Release Rate for Varying Vent Areas

The effects of vent size on heat release rate can be clearly seen in the above figure. The 3.0 m2 vent area allows sufficient oxygen into the room so that available fuel is the limiting factor for the heat release rate. The 1.8 m2 allows nearly the precise amount of oxygen required for the available fuel supply. This can be determined by noticing the peak at the beginning of the heat release rate curve. At the onset of a fire, there is a predetermined amount of oxygen in the compartment available for consumption. After all of this oxygen is consumed then the only supply is the inflow through compartment vents. Regardless of the vent size the peak heat release rate is the same because this value is limited by available fuel. As the initially available oxygen is consumed and the fire transitions from fuel limited to oxygen limited due to compartment venting, the steady state heat release rate demonstrate the effects of the vent area on the fire size.

The vent size will also have an effect on upper layer temperature. Larger vents will not only increase the fire size, but will also allow more of the hot upper layer to flow out of the room, and allow greater dilution of the products of combustion with atmospheric gasses. The results of vent size on layer temperature can be seen in Figure 4.2.3-2.

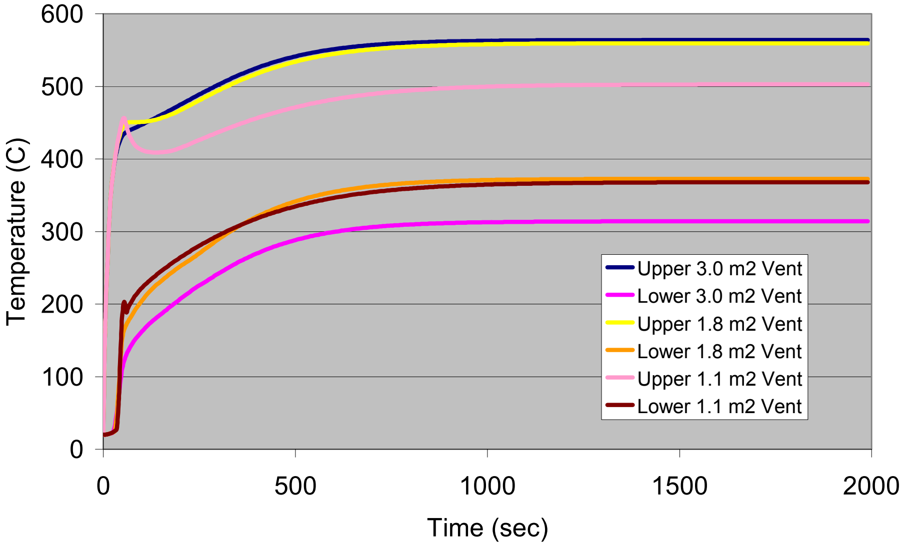


Figure 4.2.3-2: Layer Temperatures for Varying Vent Size

It would also be expected that vent size would also have an effect on heat flux to the standard targets. For a given pyrolysis rate there will be a critical vent size below which the fire will be oxygen limited. This can be easily observed in the Figure 4.2.3-3 plotting heat flux to the targets as a function of vertical vent area.

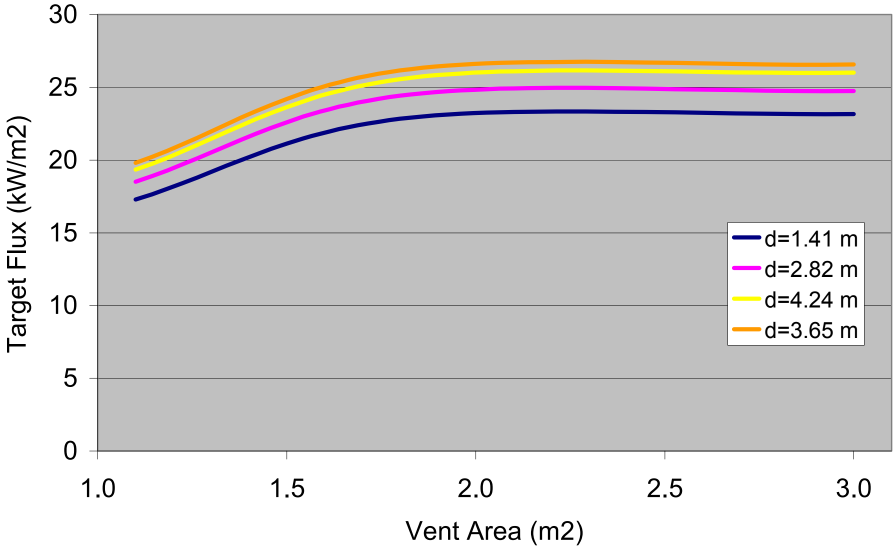


Figure 4.2.3-3: Steady State Target Heat Flux vs Vertical Vent Area

4.2.4 Orientation of Targets

For all of the scenarios presented above, the target surface was oriented vertically and facing the fire. This allows the maximum possible radiant energy from the fire to reach the target. However, it is not clear if this is the extreme scenario. To determine if the heat flux would be more severe if the target orientation was different models with the targets at 45-degree angles from the floor and parallel to the floor were created. Figure 4.2.4-1 shows target heat fluxes for the base case scenario with the face of the targets at a 45-degree angle to the floor. This configuration increases the portion of the heat flux received from the upper layer and the ceiling and decreases the heat flux from the fire and walls. Figure 4.2.4-2 shows targets parallel to the floor and facing the ceiling. This configuration minimizes the portion of the flux from the fire and maximizes the portion of the flux from the upper layer gasses and ceiling.

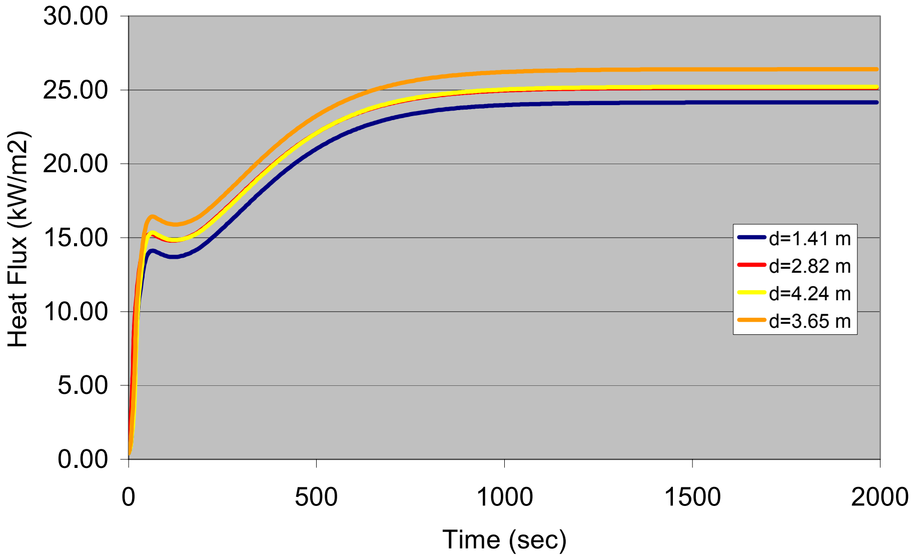


Figure 4.2.4-1: Target Heat Flux with Target Face at 45 Degree Angle With Compartment Floor

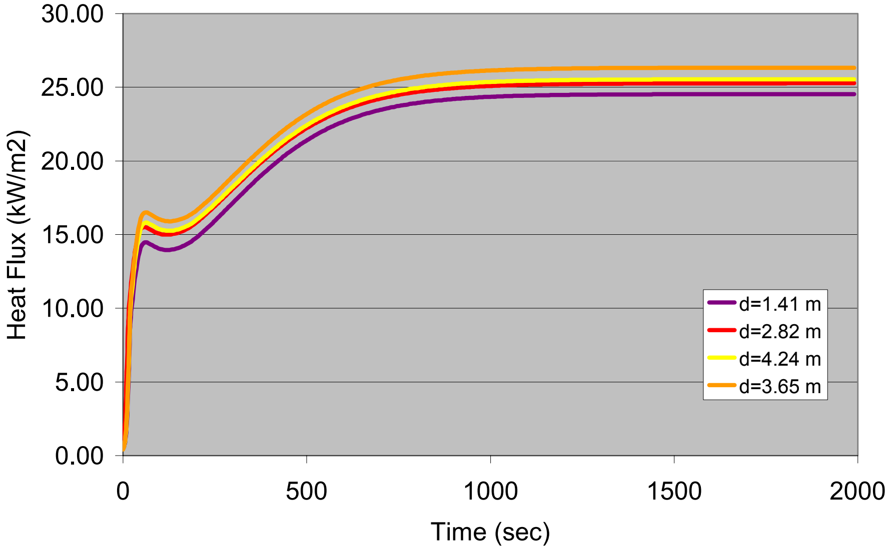


Figure 4.2.4-2: Target Heat Flux with Target Facing Compartment Ceiling.

The above figures indicate that the precise orientation of a planar target does not greatly influence the heat flux to the target. However, this should not be extrapolated to include all shape configurations. The precise shape of an object can greatly influence both the convective and radiative heat transfer to that object.

4.3 Spray Fire Compartment Model

Of particular interest is the modeling of a spray fire confined inside a compartment. This is difficult to accomplish directly as none of the currently available zone models has directly tackled the problem of modeling a spray fire. To overcome this difficulty the heat release rate developed for spray fires in the open air was used to specify the heat release rate for the compartmentalized spray fire. Spray fires with heat release rates of 1000, 5000 and 10000 kW (239,1195,2390 kgcal/sec) were modeled. These could potentially result from a variety of pipe diameter/pressure configurations, which can be seen, in Figure 4.3-1. Spray fires develop very rapidly and thus the growth times are ignored. The fires were modeled at a height of 1meter in the center of the compartment with a constant heat release rate. The upper layer temperature for each of the heat release rates is shown in Figure 4.3-1 below.

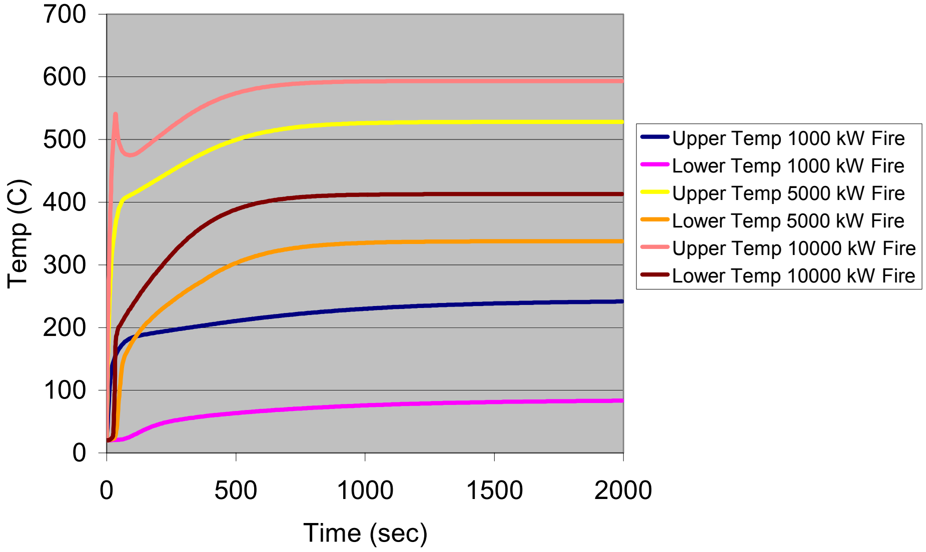


Figure 4.3-1: Spray Fire Layer Temperatures

Figure 4.3-2 below shows the steady state heat flux for the base case fire targets at varying distance from the fire centerline. The data indicates that target flux reaches an asymptotic value for very high heat fluxes.

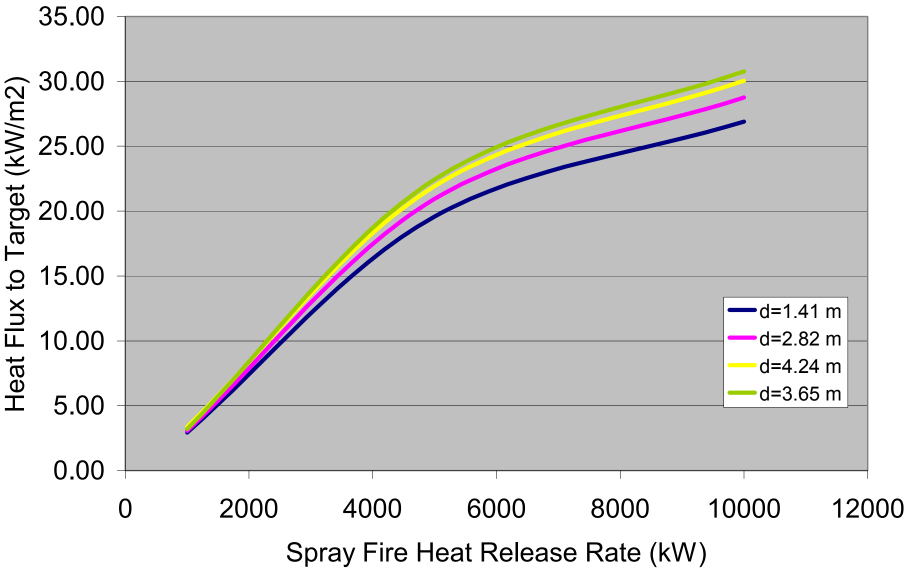


Figure 4.3-2: Spray Fire Steady State Target Heat Flux

4.4 Bunk Fire Compartment Model

The third major type of fire that would be expected on board a Navy ship would be similar to a structure fire. The base case compartment was used with two separate fire scenarios. The first involved a group of four bunks, with the first bunk igniting at t=0 seconds and one an additional bunk igniting every 60 seconds. The second fire scenario involved 10 bunks, with the first bunk being ignited at t=0 and an additional bunk ignited every 50 seconds thereafter. These times were arbitrarily selected, as no data concerning the heat flux required to ignite a navy bunk mattress was available. However testing indicates that bunk fires grow at a moderate pace and igniting the bunks at these times gives heat release rate curves that are reasonable when compared to other models as well as experimental data.[29] The heat release rate curve for both compartments are shown in Figure 4.4-1.

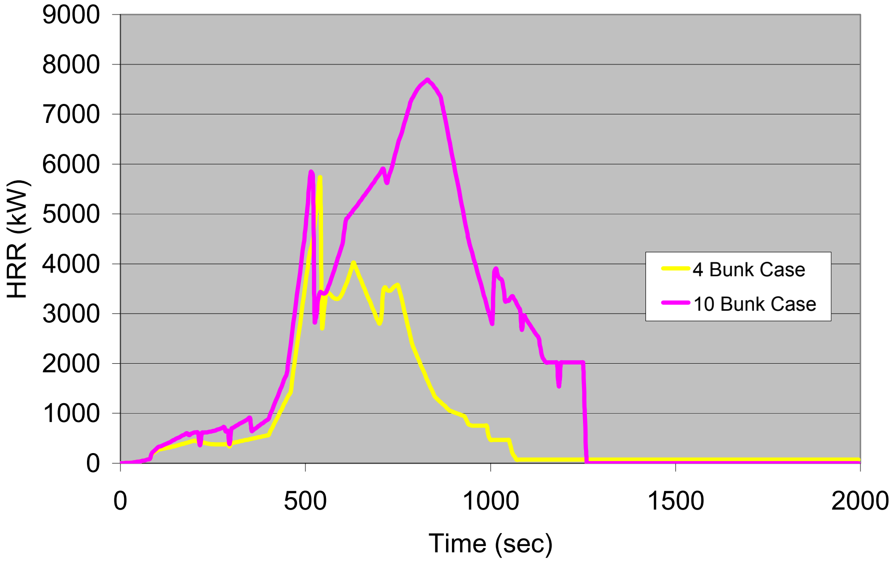


Figure 4.4-1: Bunk Fires Heat Release Rates

Figure 4.4-2 below shows layer temperatures for both fire scenarios. The model demonstrates that the difference between the 4-bunk case and the 10-bunk case are not as large as might be expected. This again demonstrates that the oxygen entering the room becomes the limiting factor for large fire sizes.

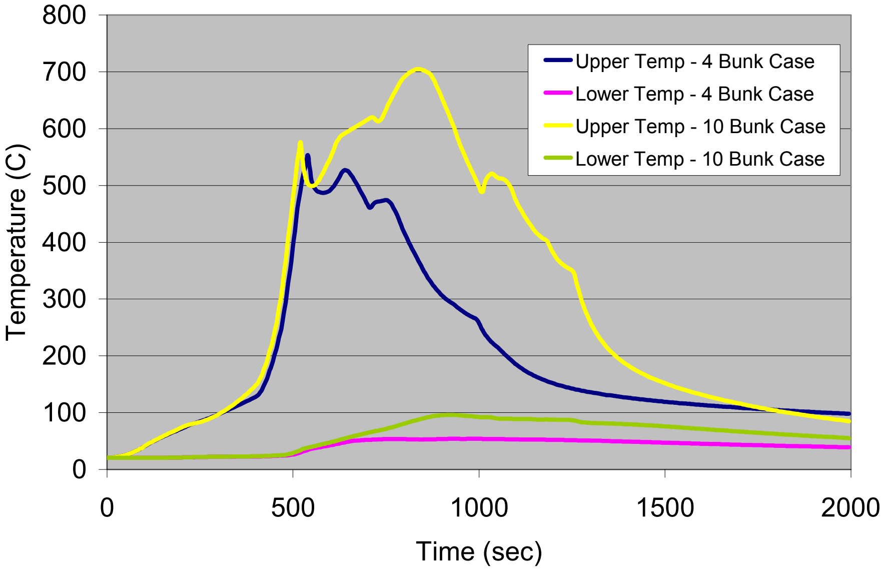


Figure 4.4-2: Layer Temperature - Bunk Fire Scenarios

Heat flux to the targets in the compartment base case configurations can be seen in Figures 4.4-3 and 4.4-4 below.

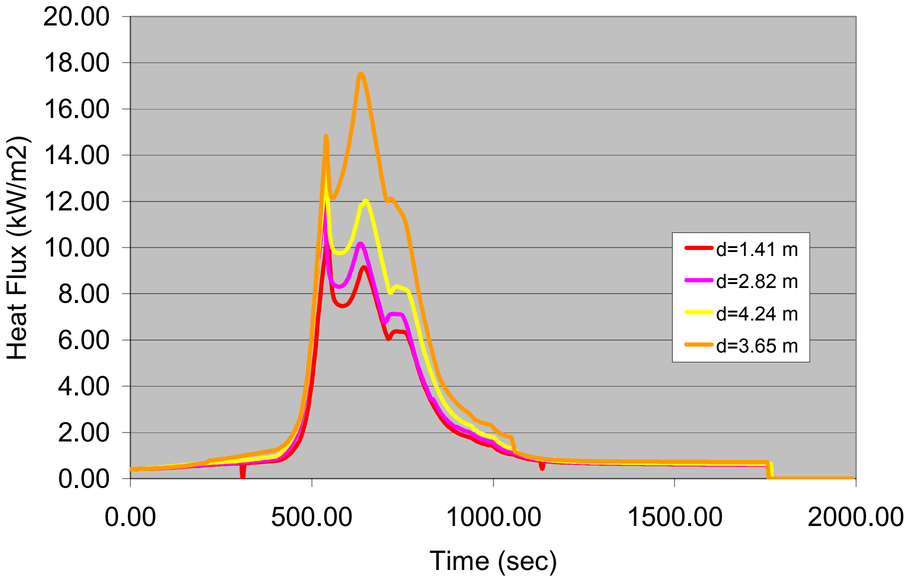


Figure 4.4-3: Target Heat Flux 4 Bunk Fire

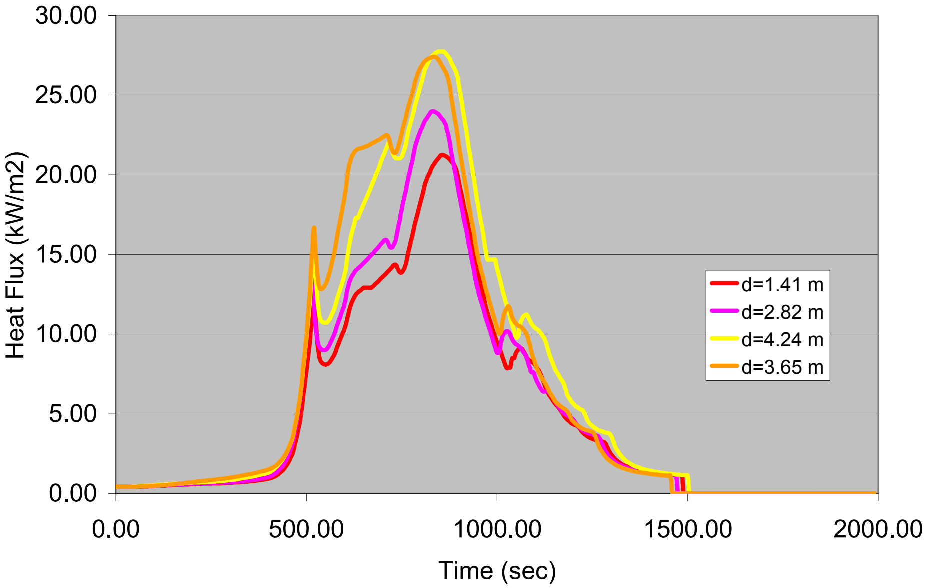


Figure 4.4-4: Target Heat Flux 10 Bunk Fire

The above figures indicate that the heat flux to the target increase as the distance from the fire increases. This is an example of the effects of geometry on heat flux to a target. The heat flux to the vertical target is increased because as the target moves away from the center of the room it can “see” more of the hot upper layer gasses. If the geometry of the compartment or the target were altered then the effects of distance from the fire on the heat flux to the target would change.

5.0 Measurement of Heat Fluxes

Typically, fire tests have been conducted in a furnace type enclosure. Many assumptions were made when determining the comparability between the furnace tests and actual compartment fires. These assumptions may result in discrepancies between an actual fire environment and the fire environment created in the test chamber. The major assumptions differentiating furnace environment comparability to an actual fire environment are presented by Wittasek [30] and include

- All boundary surfaces on the interior of the furnace are diffuse and spectrally gray. The absorptivites are assumed to be equal to the emissivities
- A constant temperature exists over each surface element
- The furnace gas is gray
- The principal mode of heat transfer in the furnace is via radiation

The first three assumptions are required to simplify the mathematical models used to characterize a test furnace. The validity of these assumptions has been extensively studies and it has been concluded that errors introduced by these assumptions are not large enough to greatly effect test results. The simplifications in the mathematics allowed by these assumptions far outweighs the errors that are introduced into the test results.

The effects of the final assumption have been significantly more controversial thus deserves greater attention. Research by Harmathy has indicated that ignoring convective heat transfer is valid as long as the ratio of conductive to convective resistances (the Biot number) is greater than 10.[30]

$$\frac{hl}{k} > 10$$

Traditionally most of the material in test furnaces has been refractory cement, which has a very small k value (1.5 to 2 W/mK) which allows them to easily meet the above criteria. Difficulties arise when the materials used in the furnace are metals such as steel or aluminum. These materials have thermal conuctivitiesas high as 73 W/mK for steel and upwards of 200 W/mK for aluminum. Ignoring the effects of convective heat transfer for these materials introduces significant error into the calculations.

Regardless of the assumptions made when calculating the fire environment contained in a test furnace, measurement of the variables used to control the furnace or determine the conditions within the test chamber are also subject to substantial measurement error. Installation and placement of heat flux gauges greatly influence the accuracy of these devices. Improperly placed or poorly installed heat flux gauges can easily result in error in excess of 50%[30]. If temperature readings from thermocouples are used to control the furnace, even small measurement errors can greatly influence the exposure to the test specimen due to the fourth power relationship between temperature and radiant flux. Examinations of different types of thermocouples have found differences in measured flame temperatures of 550 °C (1022 °F) during the first five minutes of a fire test. Nathan Wittaseck in his Thesis “Analysis and Comparison of Marine Fire Testing Regulations and Procedures” presents a thorough examination of errors present in furnace environment measurements. [30] The comparability between laboratory testing and actual fire conditions will be very dependent upon accurately determining and controlling the environment within the test chamber therefore every effort should be made to reduce any sources of measurement error.

6.0 Conclusion

An examination of the existing test method used to assess the level of protection offered by clothing, whether it be protective or daily wear articles, indicates that current test methods do not correlate behavior in the tests to behavior in actual fire scenarios. Identifying typical fire scenarios and subjecting the completed clothing to the environments generated by these fire scenarios can eliminate these deficiencies. The development of both a test mechanism and a test protocol designed specifically to conduct these kinds of testing will allow comparison between the performance of different clothing and fabrics under real fire conditions which will ultimately enhance sailor safety.

One of the unique problems associated with shipboard fires is the tremendous number of possible fire scenarios that need to be considered. For the purpose of this project, it was demonstrated that the infinite number of possibilities could be reduced to a few representative fires representing engine room fires, storage and berthing area fires, and deck fires. Furthermore, the number of fuels on board a typical naval vessel can be characterized by investigating a much smaller but representative cross section of flammable liquids and solids. While the goal of this project was to determine a reasonable range of fire environments, the most severe environments were not directly dealt with. These scenarios would typically be limited to wartime activities and would be so severe that no amount of protective clothing would provide substantial protection. The analysis presented here is weighted heavily towards controllable fires resulting from accidental fuel spills or ignition, which would be more typical of peacetime type fires. These are the fires that clothing could be expected to protect an individual from substantial harm.

Results are presented for both the compartment fire environments and open fire environments. As is expected, the compartment environments are substantially more severe than open fires despite the peak heat release rate limitations created by the limited venting capacity of internal spaces. It is important to recognize however, that for many of the compartment cases the hazard to the individual quickly switches from the heat of the fire to the toxic products of combustion. While these considerations are important for determining the survivability of a fire environment, they are not important from the standpoint of determining the effectiveness of protective fabrics and thus are not presented during the course of this report.

One of the advantages of identifying a select number of fire scenarios representing a comprehensive cross section of all possible fires is the ability to compare the protection provided by an article of clothing. None of the currently available test protocols will result in a comprehensive performance evaluation for such a wide variety of fire scenarios. The results of this report indicate the wide variations that can be expected aboard a U.S. Navy vessel and it is crucial that any performance evaluation consider this range of exposures. This will alleviate the problems associated with bench top testing where it is impossible to determine the level of performance provided directly from the results of the test. The types of exposures differ depending upon the nature of the fire, the nature of the fuel and the location of the fire (in a compartment or in the open).

One of the difficulties with predicting fires and fire environments is the inherent instability of any fire scenario. Any calculations conducted can only approximate one of the possible fire scenarios, which typically is the most likely fire scenario. Unfortunately, fires are notoriously unpredictable and when viewing any calculations that attempt to predict either a fire or the environment generated by the fire must be viewed with this point in mind. For this particular case, this does not present a major problem, as the intent of the project is to identify likely fire scenarios that can then be reproduced in a test apparatus. As long as the calculated values are reasonable and can be consistently reproduced by the test apparatus then comparisons between fabrics can be made.

As this project progresses, reproducing the calculated environments will become the major hurdle to overcome. Several variables have not been investigated in this project that could directly impact the fire environment within a test chamber. Most notably, heat conduction through the steel walls has been ignored. It has been shown however that fire environments within test furnaces are not greatly influenced by refractory cement lining materials, but can be greatly affected by materials such as steel that have high heats of conduction. These problems will be left to future work as this project continues.

Although this project has only begun, and much work remains to be accomplished before a final test procedure and apparatus are approved, it is not difficult to see the value of such a test procedure. While the direct scope of the project is to improve the safety of the nations sailors, direct applications to all types of clothing designed to protect against heat and flames are easy to visualize. Furthermore, the enhanced understanding generated by studying the behavior of fabrics under lifelike conditions will ultimately lead to advances in the design of these garments, further improving the safety. The ability to easily compare competitors protective clothing offerings will enhance competition within this market and limit unsubstantiated claims by manufacturers. The ultimate goal of all fire protection engineering is to save lives and property, and this project will directly impact the former of those two objectives and should be vigorously pursued.

One isssue that was not examined in this work is the survivability of the fire scenarios presented. While protecting from burn injuries is important, for the more severe cases presented in this study death or serious injury would result from factors not related to the burn injury. These factors include lack of oxygen, carbon monoxide poisoning, lung damage due to hot products of combustion and many others. Testing clothing under fire situations that would not be survivable regardless of the burn injuries is not necessary. When selecting specific fire scenarios to reproduce in a test apparatus the survivability of the environment with respect to the protective equipment being examined needs to be considered.

7.0 Recommendation for Future Work

During the course of the project, several gaps in the available research were discovered to limit the completeness of the analysis. One of the primary weaknesses is the availability of flame temperatures for the particular fuels used aboard naval vessels. The second major limitation was the lack of experimental work concerning compartment vent flows when all vent openings are horizontal.

The lack of reliable flame temperature data inhibits the accuracy of the radiation calculations, as this is a crucial parameter for determining flame emissivity. A large amount of data is available for premixed flames, but the inherent variations in the combustion process when concerned with diffusion flames result in difficulties in generating consistent values. However, these values are easily measured and could be determined through small laboratory experiments for the particular fuels used by the navy. Any increase in the values used for this report will have a significant impact on the values of the calculated radiation due to the power relationship between flame temperature and flame emissivity.

An important variable concerning the protection offered by clothing, whether designed specifically for fire fighting or otherwise, is the duration of exposure to the hazardous environment that the article of clothing will be subjected. To determine this important parameter a risk assessment which might include a statistical study of the behavior of crewmembers under fire conditions needs to be conducted with particular emphasis placed upon the duration of any fire exposure experienced by crewmembers not associated with damage control parties. For clothing whose primary purpose is not protection from heat and flames, the time of exposure will depend upon the time it takes an individual to evacuate the compartment or the time required passing through a flaming region. These values mightbe determined for stereotypical sailors by timed evacuation drills and measurements designed to determine the maximum running speed of a typical sailor. This would allow a thorough determination of the expected time of exposure.

One of the unique aspects of ships when compared with land based structures is the possibility of compartments with no vertical openings but a substantial horizontal opening such as a hatch or scuttle. This particular vent configuration has not been studied and results in fairly complex vent flow with smoke exiting the center of the vent and fresh air entering around the edges of the opening. With venting being one of the primary factors controlling sustainable heat release rates this is a major weakness in the modeling results. No attempt could even be made for this particular vent scheme. An ambitious research program to develop experimentally based algorithms that deal with this particular vent configuration would be a substantial contribution to ship fire modeling.

One of the greatest limitations to the results presented in this report is the lack of generally available information concerning the exact nature of the fuels used aboard U.S. Naval vessels. The range of expected results could be narrowed considerably if the precise properties of these fuels were known. As precise fire scenarios are adopted for use in the proposed test chamber full-scale tests of these fire scenarios should be conducted to determine the accuracy of any models used to predict these results.

These limitations should not inhibit the progress of this project, as reasonable fire environments can be predicted without this additional work. Furthermore, the eventual test device will need to be adjustable to accommodate the range of fires presented in this report. As the understanding of these types of environments increased, the environments created by the apparatus can be fine-tuned to more closely match the expected real life scenario.

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