Adding Mobility to a Fire Products Collector

A Major Qualifying Project Report submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science
By:

__________________________
Andre da Vitoria

__________________________
Drew Martin

__________________________
Yong Bin Ji

__________________________
Lei Zhang

December 2012

Project Number : NAD TY12

__________________________
Professor Nicholas A. Dembsey, Advisor

__________________________
Melissa Avila, Co-Advisor
Tyco Fire Suppression & Building Products

__________________________
Zachary Magnone, Co-Advisor
Tyco Fire Suppression & Building Products
Table of Contents

1. MQP Organization .................................................................................................................... 7

2. Abstract ..................................................................................................................................... 8

3. Paper: Adding Mobility to a Fire Products Collector ................................................................. 9

Appendix A: Acknowledgements ................................................................................................. A-1

Appendix B: Pre-Qualifying Project (PQP) .................................................................................. B-1

Appendix C: Unexpected Problems ............................................................................................... C-1

Appendix D: Testing Results .......................................................................................................... D-1

Appendix E: Standard operating Procedure .................................................................................. E-1

Appendix F: Testing Room ............................................................................................................. F-1

Appendix G: Finite difference method heat transfer analysis ...................................................... G-1

Appendix H: Finite difference method data tables ....................................................................... H-1

Appendix I: Hood detailed design ................................................................................................. I-1

Appendix J: Duct detailed design ................................................................................................ J-1

Appendix K: Probe Section ............................................................................................................ K-1

Appendix L: Cabinet design ........................................................................................................... L-1

Appendix M: Cooling System ....................................................................................................... M-1

Appendix N: Scientific Presentation Slides .................................................................................. N-1

Appendix O: Non-Technical Presentation ...................................................................................... O-1

Appendix P: Instrumentation Data Sheets .................................................................................... P-1

Appendix Q: Calorimetry Standards ............................................................................................... Q-1

Appendix R: Price List of System Components ........................................................................... R-1

Appendix S: List of Materials Components Considered ............................................................... S-1

Appendix T: Cabinet Instructional Recommendations ................................................................. T-1

Appendix U: Bibliography ............................................................................................................. U-1
List of Figures

Figure 1: Gas Sample Train (ASTM E2067, 2008)..................................................................................................................10
Figure 2: Map of Tyco’s Fire Areas. The locations in red are areas where fire tests are permitted...12
Figure 3: Skeleton of Instrumentation cabinet. The skeleton is made out of extruded aluminum with 6 bolts in each corner to make a string cabinet.........................................................15
Figure 4: Protection times for when the back face of 0.5 inches of Ceramic, Millboard, or Silica insulation will reach 45°C (104°F)..............................................................................................................19
Figure 5: Energy into the cabinet with insulation 0.5in thick with a heat flux of 5 kWm2. ............20
Figure 6: Hood and Exhaust system (ASTM, 2008). ..............................................................................................................B-5
Figure 7: Sketch design of the hood and duct system. ....................................................................................................B-5
Figure 8: Test Setup (plan view). The Fire is represented by the red triangle. The black lines surrounding the fire are the vertical foam plates. The blue circles represent the water mist sprinklers and the rectangular box represents the cabinet which depending on the test would be as close as 10 feet or as far away as 20 feet. The large black lines represent the walls of a residential enclosure........................................................................................................................................D-2
Figure 9: Thermocouple Placement (elevation view). This side view of the cabinet shows its relative position to the fire (the red triangle). There are 4 thermocouples ; TC1 is on the front of the cabinet in the center of the cabinet, TC2 is inside the cabinet attached to the roof, to measure the effects of the fire plume hitting the ceiling and descending downwards, TC3 is inside the cabinet in the exact middle hanging in air, TC4 is a distance away from the cabinet measuring the ambient air in the room. The heat flux gauge was placed on top of the cabinet..................................................................................................................D-3
Figure 10: Temperature differential. The temperature differential records a difference of about 12 seconds at the maximum peak. This is consistent with data in Figure 11 for the range of temperatures being recorded. The negative data at the end is a result of the thermocouple on the front interacting with more water. ..........................................................................................................................D-4
Figure 11: Temperatures from thermocouples on cabinet (see Figure 9). TC2 reaches the highest value, which is the thermocouple located on the cabinet roof. The difference between the highest thermocouple is about 10⁰F. ........................................................................................................................................D-5
Figure 12: Incident heat flux on cabinet. The incident heat flux has a peak of about 2.5kW/m². The data suggests that the heat flux for this fire has a relatively small output because the sprinklers are designed to cool the fire rapidly blocking any heat.................................................................................................................D-6
Figure 13: Thermocouple Locations on Cabinet.............................................................................................................D-10
Figure 14: Fuel Package for UL 1626 test fire. Consists of a wood crib with a heptane pan underneath..........................................................F-2
Figure 15: Cabinet Location in Test Area. The cabinet moves between.................................................................F-2
Figure 16: Steel sheet set up in test area .........................................................................................................................F-3
Figure 17: Thermocouple attached to steel sheet with aluminum tape .................................................................F-3
Figure 18: Thermocouple in ambient air......................................................................................................................F-3
Figure 19: Back of steel sheet, with thermocouple attached to the back and in ambient air ...............F-4
Figure 20: Side view of Steel Sheet.................................................................F-4
Figure 21: Portable Data Acquisition system............................................................................................................F-5
Figure 22: Thermocouple locations for cabinet testing. The triangle signifies the relative fire location.

Figure 23: Side view of cabinet with door off.

Figure 24: Side view of cabinet with full view of inside the cabinet.

Figure 25: Front view of cabinet.

Figure 26: Front view of cabinet suspended inside the cabinet.

Figure 27: Weight of Insulation per thickness. The red squares represent the densest insulation, the millboard insulation; the blue diamonds represent the ceramic insulation. The green triangles represent the silica insulation.

Figure 28: Protection time for when the back face of 0.5 inches of Ceramic, Millboard, or Silica Insulation will reach 45°C. 1.5 inches is the thickest insulation studied and the insulation protects the inside of the cabinet for up to 5 kW/m². When the cabinet is experiencing 10 kW/m² the ceramic insulation (red) while the millboard insulation gets to 45°C after 26.4 minutes and the silica (green) reaches 45°C after 4.5 minutes.

Figure 29: Protection time for when the back face of 0.25 inches of Ceramic, Millboard, or Silica Insulation will reach 45°C (104°F). The insulation universally protects the cabinet when the heat flux is 1 kW/m². When the heat flux is 5 kW/m² ceramic insulation protects the cabinet until the end condition, but millboard protects the cabinet for 4.4 minutes and the silica protects the cabinet for 0.73 minutes. When the cabinet experiences 10 kW/m² the ceramic insulation (red) decreases to 2.94 minutes, while the millboard insulation gets to 45°C after 2.62 minutes and the silica (green) reaches 45°C after 0.44 minutes. When a fire of 20 kW/m² is present the protection times continue to decrease, ceramic protecting the cabinet for 1.9 minutes, millboard for 1.9 and silica for 0.31 minutes.

Figure 30: Protection time for when the back face of 0.25 inches of Ceramic, Millboard, or Silica Insulation will reach 45°C (104°F). The insulation universally protects the cabinet when the heat flux is 1 kW/m². When the heat flux is 5 kW/m² ceramic insulation protects the cabinet for 2.62 minutes, while millboard protects the cabinet for 6.1 minutes and the silica protects the cabinet for 0.38 minutes. When the cabinet experiences 10 kW/m² the ceramic insulation (red) decreases to 0.66 minutes, while the millboard insulation gets to 45°C after 0.23 minutes and the silica (green) reaches 45°C after 0.12 minutes. When a fire of 20 kW/m² is present the protection times continue to decrease, the ceramic insulation is protecting the cabinet for 0.46 minutes, millboard for 0.2 minutes and silica for 0.1 minutes.

Figure 31: Temperature Profile.

Figure 32: The price of the insulation. The pricing of the insulation follows the analysis results, with ceramic being the most protective material analyzed. Millboard and Silica being subsequent insulations in both quality of protection and price.
Figure 40: Insulation Protection with heat flux equal to 20 kw/m²

Figure 41: Cost of the insulation per thickness:

Figure 42: Rack system to support hood over a fire source. The hood is orange and the duct is green.

Figure 43: Top of compartment in building 2A

Figure 44: Flowchart showing the sensor and probe data gathered

Figure 45: Probe section diagram

Figure 46: Laser Smoke Measurement System

Figure 47: Laser from Thorlabs

Figure 48: Type K thermocouple (yellow(+) red(-))

Figure 49: Examples of protected connectors for an attachment of the cone calorimeter

Figure 50: Prototype water cooled plate used in Cone calorimeter

Figure 51: Single stage vapor compression refrigeration (Pepper, 2006)

Figure 52: American Comfort 1000BTU personal Air Conditioner
List of Tables
Table 1: Insulation Materials and Properties .................................................................16
Table 2: Protection times for the minimum amount of insulation......................................17
Table 3: Maximum insulation thickness due to the weight criteria of the cabinet..................17
Table 4: The price of the insulation. The pricing of the insulation follows the analysis results, with ceramic being the most protective material analyzed. Millboard and Silica being subsequent insulations in both quality of protection and price. ..........................................................21
Table 5: Overview of system costs. ..................................................................................22
Table 6: Thickness of insulation from Semi-infinite analysis .............................................G-3
Table 7: Insulation Materials and Properties ..................................................................G-5
Table 8: Maximum Insulation Thickness due to the weight criteria of the cabinet..............G-7
Table 9: Insulation options...............................................................................................G-14
Table 10: Minimum insulation values and .........................................................................G-14
Table 11: Table show thickness of insulation needed using Semi-Infinite Solid analysis ....L-12
Table 12: Insulation Materials and Properties..................................................................L-14
1. MQP Organization

This MQP is a compilation of a paper and various briefings. The paper is a conference style paper focusing on the challenges, reasoning and process of designing the Mobile Fire Products Collector system. The paper will focus on the evaluation of the prototype instrument cabinet, including a capstone design exercise and the thermo-fluid design exercise. The rest of the paper will be appendices covering the various briefings of relevant information not covered in the conference paper.
2. Abstract

Fire products collectors are designed to measure key fire characteristics, such as heat release rate (HRR). HRR is a metric used by fire protection engineers for hazard evaluation of the fire scenario. Typically, a large scale fire products collector is stationary so that it can only be used in one lab space. In a situation where multiple test facilities or multiple fire test setups are used, a mobile version of the typical fire products collector becomes the most cost effective solution. In order to realize the advantages of a mobile system, a unique fire products collector was designed to be optimal for limited space, improved mobility and increased proximity to the fire location. Design criteria included the ability to collect data for fires up to 1MW, use across multiple test facilities and protect all of the parts of the system from the fire test. The design was analyzed using heat transfer, mass transfer and static analysis techniques as well as cost-benefit comparisons to a stationary system.

Tyco’s laboratories provided a typical lab scenario setup for a case study of the application of a mobile fire products collector. For the purpose of the study, the fire products collector system design was subdivided into four primary components used for typical laboratory testing requirements: the hood, the duct, the probes and the instrumentation cabinet. Of the four components, the hood and duct are the least mobile because of their size and weight, therefore multiple hood and duct systems were designed to fit each lab. The sampling portion of the duct and the mobile cabinet with all of the instrumentation are able to be moved and can be shared between the two different test bays in order to reduce the cost significantly.

Protection of the analysis equipment in the mobile cabinet is paramount to the success of the fire products collector. To ensure effective mobility and protection, a prototype instrumentation cabinet was built. Experimental testing indicated that the maximum fire insult on the cabinet at a distance of 10ft (3.05m) from the fire scenario was found to be approximately 95°F (35°C) at an incident heat flux of $2.5 \frac{kw}{m^2}$. To provide a safety factor, optimization analysis was conducted to ensure effective protection from heat fluxes up to $5 \frac{kw}{m^2}$ and to keep the weight below 103kg (225 lbs). Through creating a mobile version of the fire products collector, the cost efficiency of the system was improved by approximately 66%.
3. Paper: Adding Mobility to a Fire Products Collector

Introduction
The fire problem is a complex phenomenon that still needs to be studied. Although understanding of fire has advanced considerably, the science of fire is greatly needed to advance our ability to protect life and property. The goal of the project is the design and development of a mobile fire products collector for use at Tyco Fire Protection Products (TFPP) in their testing facilities in Cranston, RI.

A fire products collector is a system that is used to measure the heat release of the fire. The hood and duct components of the system are used for collecting the smoke and gases from the fire. The size and weight of which makes mobility impractical. The probe section and the instrumentation section contain the components for the collection and analysis of the data. The ability of the probe section and the instrumentation cabinet to transition between multiple facilities creates the highest cost-benefit to a facility with multiple test areas.

The paper at hand will demonstrate a solution that adds mobility to the system. The mobility varies from part to part depending on the capital expense along with the relative size and weight and durability.

Background

Heat Release Rate
The heat release rate is considered by Babrauskas to be the single most important metric to understand the fire development process and in effect describes the size of the fire (Babrauskas & Peacock, 1992). The heat release rate is defined as the enthalpy change per unit time as a result of a fuel being combusted (Cote & National Fire Protection Association, 2003). There are several different methods and scales of finding the heat release rate of materials, however we will be looking at full scale tests. The two major types of full scale tests are open burning heat release rate calorimeters and room fire tests.

Applications
The stochastic nature of fire creates a challenge when studying fire or testing products. The way to correlate results of different fires tests is vitally important to ensure appropriate analysis. One way that fires can be compared is by using oxygen consumption calorimetry to find the heat release rate of the fire.

The time at which sprinklers will activate is contingent upon the temperature at the sprinkler head. The typical way to correlate the strength of a fire to the activation time of the sprinkler is by using the heat release rate. By knowing the heat release rate of tests fires the time at which life and property is protected can be found more precisely.
The heat release and other relevant data gathered during a test can be used to enhance better model validation. Processing power is becoming more inexpensive, thus the cost of one fire test can be utilized through computer simulations to study hundreds of similar fires.

**Calorimetry**

The main concept behind oxygen consumption calorimetry was discovered in 1917 by Thornton (Cote & National Fire Protection Association, 2003). Oxygen has a nearly constant energy release per unit range of mass of 13.1MJ/kg for a large range of hydrocarbons. This measurement yields an error of only ± 5%. The precision of the oxygen consumption method can be increased by measuring other gases produced by a fire; including carbon dioxide, carbon monoxide, and water vapor. These methods also provide additional data used for determining life safety.

**Fire Testing**

Fire product collectors have existed in one form or another since their development was refined in the 1970s and early 1980s by researchers at the National Bureau of Standards, using oxygen consumption calorimetry. (Custer, 2008)

The mobile fire products collector will operate as a medium to large scale calorimeter, being able to analyze fires up to 1MW. The parts of the system that would have to be reconsidered would be the duct, hood, instrument cabinet and probe section. Relevant standards were consulted such as ASTM E2067 (ASTM, 2008) and ASTM E1354 (ASTM, 2011). The standards gave empirical measurements for some details of the system which further constrained and developed the solution.

Oxygen consumption calorimetry requires a specific order of processes to accurately calculate the percent mixture of the gas. Primarily this process is defined after the hood and duct collect the smoke and gases from the fire. Figure 1 shows the process after the gas sample ring collects the gas. The gas analyzer is the most important part of the process; however its operating conditions require the gas to be heavily filtered to remove any particulates, moisture and excessive heat from the system.

![Figure 1: Gas Sample Train (ASTM E2067, 2008).](image-url)
Design Process

Design Specifications
The design is focused on the optimal way to measure the products of test fires and improve the research and development at Tyco’s Cranston Facilities. This is accomplished with the added ability to measure the heat release rate, smoke opacity, and toxic gases from the fire.

The Cranston site has multiple fire areas where testing is conducted. To maximize the cost-effectiveness of the fire products collector the maximum number of test facilities shall have the ability to use it. Thus the design of the system included partial mobility of the system.

As the project progressed, data was collected from a typical fire test run at the Cranston site to understand the environment that the instrument cabinet would need to protect against. The instrumentation in the previously mentioned calorimeter is sensitive to temperature, airborne particles and moisture.

The specifications for the solution were:

- Mobility between different facilities of the Cranston site
- Cannot impede other operations within adjacent areas to its area of operation
- Conform to relevant standards
- Must not require more than two people for relocation (weigh < 225 lbs (102kg))
- Survive in and Collect data from a one Megawatt fire

Fire Testing Areas
Figure 2 displays a layout of the six areas that are capable of conducting fire testing. All of the fire test areas are in either building 2A or building 3. Each building contains vastly different areas for testing with some of the differences being the environmental management system and the fire size allowed in each area.
Figure 2: Map of Tyco’s Fire Areas. The locations in red are areas where fire tests are permitted.

Building 2a
Building 2A houses test area A, which is designed to be formed as a residential compartment. The application of the fire products collector in this space would be to collect smoke from outside the doorway of the compartment. This smoke would be sampled by the mobile fire products collector and then discharged into the local smoke management system. Currently the smoke management system that is in the building is a Hot Dawg, which exchanges 2000 CFM ($56.1 \text{ m}^3/\text{min}$) of smoke polluted air into clean air.

Building 3
Test area C and test area E provided the best spaces available for fire testing, because they would need the least amount of modification, one duct, and provide plenty of space for different configurations for fire testing. Test area C has a movable ceiling and is the largest of the areas considered, which increases the variety of fires that can be conducted. Test area E is the smallest test area available and is used for smaller fires, but the area can also be adjusted to a wide variety of fires. The demo cell areas are used for demonstration purposes only and are not available for fire testing purposes. Both C and E are open fire testing areas.

Fire Products Collector
The fire and smoke collection system can be broken into four sections.

Hood
The hood structure is able to be disassembled for storage when not in use in both buildings. To ensure easy assembly and disassembly extruded aluminum makes up the exoskeleton for the hood, with steel sheets being attached to the exoskeleton. The gaps in the hood are patched with steel or aluminum tape to ensure a smooth surface for the smoke to travel over. There will be two different hoods for Building 2A and Building 3. Each building used different sized hoods to fit the different locations. For more detailed hood design see Appendix I: Hood detailed design.
Duct
Each area will have its own ducting section added as a part of the structure. The ducts are immobile because of the unmanageable length and width, thus ducts would be installed in Building 2A and Building 3. For more detailed duct design see Appendix J: Hood detailed design.

Sensor Duct Section
The probe duct section gathers all of the information from the combustion gases. The probe section is approximately 1.2 m (4 ft) long and houses the pressure transducer, thermocouples, gas sampling port, the helium-neon laser and the blower. To increase cost effectiveness, the probe section is mobile. It is also recommended that the cabinet be moved with the probe section because of its cost. For a more detailed design see Appendix K: Probe Section.

Cabinet Design
The majority of the capital that is invested in the fire products collector is contained in the cabinet, which is why mobility and protection are critical for system operation. Mobility allows the cabinet to have greater exposure to different test facilities. To remain mobile the cabinet was kept under 103 kg (225 lbs). The cabinet is responsible for protecting the components inside from smoke, soot, water and heat, while it is collecting data to analyze the gas. See Appendix L: Cabinet design.

A compartmentalized, sealed case offered the most protection for the instruments, while allowing easy access to the instrumentation within. The cabinet is broken into two internal compartments that are airtight and thermally insulated to segregate the mechanical components from the precision instruments. The most important function of the instrument cabinet is to protect the instrumentation against the fire insults. Further analysis for the heat result is described in full in Appendix L: Cabinet design.

Cabinet Contents
The instrumentation needed inside the cabinet is the gas analyzer and the data acquisition system. These devices operate best at approximately standard ambient temperature and pressure as defined by International Union of Pure and Applied Chemistry (IUPAC) as 298.15K (25°C, 77°F). The precision of the oxygen measurement from the gas analyzer is the most because it has the largest effect on the error in the calculation of the heat release rate (Cote & National Fire Protection Association, 2003). The instrumentation needs to be isolated from the outside environment. The cooling system needs the air from outside the cabinet and can be exposed to the outside environment through filters.

Protection
Protection from Smoke Toxicity
Extensive consideration to the possibility the cabinet being fully or partially engulfed in smoke was given. The cabinet is made out of an 18 gauge galvanized steel shell, is sealed with replaceable aluminum adhesive tape. Galvanized steel is chemically unreactive and will not be affected by the fire. Additionally all other components will be steel to reduce the effects of corrosion.
Protection from Soot
To protect the cabinet from soot the cabinet functions as a sealed box. The two compartments are both insulated and air tight. A positive pressure system for the instrumentation section of the cabinet keeps all the soot out. The cooling system pushes air into the instrumentation cabinet section, creating the positive pressure system while also cooling the air surrounding the instrumentation. The air is then released through a one way louvered and insulated valve. The cabinet needs to be sealed so that air and smoke cannot get in using calking or aluminum tape.

Protection from Water
The cabinet is sealed to protect against water from the sprinklers and up to 150mm (6 in) of water on the floor. The cabinet is protected from the water insult from sprinklers above, by a drip edge on the top plate of the cabinet. The drip edge covers the top of the box and ensures any dripping will land on the floor not on the cabinet.

Humidity is monitored remotely during a test with a wireless weather station (Amazon, 2012). The cooling system may create a cool environment where water can condense. To reduce the risk of water entering the cabinet through vents, these entrances will be protected by louvers and carbon filters (McMaster (1667T38), 2012). The cooling unit installed is capable of removing 0.5 liters of water vapor per hour (American Comfort, 2012). See Appendix L: Cabinet design for more details on the protection of the cabinet.

Detailed Analysis

Structural Analysis
In the evaluation of the structural integrity of the cabinet’s skeleton (see Figure 3) some assumptions were made to simulate a plausible worst case scenario. The first assumption is that the cabinet does not deform. The second assumption is that the bolts fail in shear. A shear failure is more likely than tension or compression as materials, such as steel, tend to fail about twice as quickly in shear (Norton, 2011). Tension failures will also be considered unlikely as the cabinet is not being subjected to any pulling force. Lastly a repeated loading study is also unnecessary as the cabinet will not have any large spinning or oscillating components exerting a load on its members. When calculated the safety factor is 38.
Figure 3: Skeleton of Instrumentation cabinet. The skeleton is made out of extruded aluminum with 6 bolts in each corner to make a string cabinet.

Thermal Analysis
The thermal insult on the cabinet, requires that a full thermal analysis to be completed to ensure the protection of the instrumentation. First the approximate thermal characteristics of the cabinet are calculated by using the semi-infinite analysis to determine penetration depth. A more detailed analysis was completed using the finite difference method of the insulation considered for the protection of the cabinet. For more information see Appendix G: Finite difference method heat transfer analysis.

Finite Difference Method
The finite difference method is derived from the one dimensional transient conductive heat transfer equation:

\[ \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \]

where \( \alpha \) is the thermal diffusivity, \( \frac{k}{\rho c} \). The environment that the cabinet is exposed in will most likely have a direct heat flux from the fire at the front face of the cabinet with a convective cooling factor accounting for the temperature of the air around the cabinet. The internal layer of the insulation had no heat generation. The back face of the insulation is open to the air inside of the cabinet which is a known surface convection.

\[ q''_f + h(T_{\infty} - T_{p1}) = k \frac{T_2 - T_1}{\Delta x} \] (Specified heat flux boundary condition)

\[ \bar{h}(T_{\infty} - T_1) + \dot{q}_{c,1} \frac{\Delta x}{2} = -k \frac{T_2 - T_1}{\Delta x} \] (Known surface convection boundary condition)

**The nodal and boundary equations:**
The front boundary condition equation is as follows (Kreith, Manglik, & Bohn, 2011):
\[ T_{p+1}^{1} = T_{p}^{1} (1 - 2Fo) + 2FoT_{m}^{1} + Fo \left[ \frac{\Delta x}{k} \epsilon q''_{rad} + Bi(T_{\infty} - T_{p}^{1}) \right] \]

where the \( T_{i}^{x} \) variable represents the temperature at time \( t = \{1, \ldots, i, \ldots, i + 1\} \) and thickness \( x = \{1, \ldots, x + 1, \ldots, n\} \). The front boundary is affected by the heat flux from the fire plus a convective cooling factor from the ambient air. To determine the Equation for the internal nodes:

\[ T_{p+1}^{n} = Fo(T_{p+1}^{n} + T_{p}^{n-1}) + (1 - 2Fo)T_{m}^{i} \]

The internal nodes are calculated from an average of the surrounding nodes, because there is no heat generation in the insulation. For the back boundary condition:

\[ T_{p+1}^{n} = 2Fo(T_{m+1}^{i} + BiT_{\infty}) + (1 - 2Fo - 2BiFo)T_{m}^{i} \]

The back boundary uses the equation for convection to simulate the heat transfer from the insulation to the air inside the cabinet.

**Initial Conditions**

The initial conditions for the cabinet were set as at time, \( t=0 \); temperature, \( T = T_{\infty} = 298K \). The time step used in the calculation represents the length of time it takes for the heat to transfer through the thickness, \( dx \), limited by the insulations properties. To find the time step the Fourier number is set equal to 0.45, to obey \( (1 - 2Fo) \geq 0 \). The Fourier number \( Fo = \frac{a\Delta t}{\Delta x^2} \) where \( x \) is the thickness divided by the number of nodes, \( a \) is the thermal property of the material and \( t \) is the time. To find the time step: \( dt = \frac{(dx)^2}{a} \cdot \left( \frac{45}{100} \right) \). The chosen heat fluxes are chosen to display more data at smaller heat fluxes, 1 \( \frac{kw}{m^2} \) and 5 \( \frac{kw}{m^2} \), and the extremes 10 \( \frac{kw}{m^2} \) and 20 \( \frac{kw}{m^2} \). An emissivity of 0.3 is chosen to account for the steel cabinet casing. The heat transfer coefficients are 30 \( \frac{kw}{m^2} \) for the convective cooling at the front of the cabinet and 25 \( \frac{kw}{m^2} \) for the inside of the cabinet. See the appendix section titled Initial Conditions for additional details.

**End Conditions for Insulation effectiveness:**

The end conditions, used to define the effectiveness of the insulations, are concerned with the temperature after 30 minutes, weight and cost of the insulations chosen. The insulations that were analyzed are: extra high temperature rigid ceramic insulation; high temperature millboard insulation; and harsh-environment silica insulation all of which are rated for use over 1000°F (538°C) (see Table 1).

**Table 1: Insulation Materials and Properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Max Temp (K)</th>
<th>K (W/m*K)</th>
<th>Density (kg/m^3)</th>
<th>Specific Heat (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>1324.816667</td>
<td>0.0493109</td>
<td>304.38</td>
<td>920</td>
</tr>
<tr>
<td>Millboard</td>
<td>1022.038889</td>
<td>0.1426492</td>
<td>945.18</td>
<td>840</td>
</tr>
<tr>
<td>Silica</td>
<td>1366.483333</td>
<td>0.1373659</td>
<td>160.2</td>
<td>800</td>
</tr>
</tbody>
</table>
**Insulation**

**Temperature Requirements**

The end condition for the temperature was determined by finding the temperature at which the back face of the insulation would reach a temperature that would harm the operators. The calculation assumes that the fire emits a constant heat flux. Once the heat energy is conducted through the insulation the temperature of the back face is found. The time at which the back face of the insulation reaches 45°C (113°F), the temperature at which human skin feels pain (SFPE, 2002), is defined as the protection time (see Table 2). Keeping the back face of the insulation less than 45°C (113°F) will ensure that no harm will affect the operators of the cabinet after a test, and will keep the instruments at an operational level. The end time for the tests is 30 minutes so the maximum protection time is 30 minutes. For full tables of the protection times found see Appendix H: Finite difference method data tables.

**Table 2: Protection times for the minimum amount of insulation.**

<table>
<thead>
<tr>
<th>Heatflux ($\frac{W}{m^2}$)</th>
<th>Insulation Material</th>
<th>Thickness (in.)</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Millboard</td>
<td>0.125</td>
<td>30.00</td>
</tr>
<tr>
<td>5</td>
<td>Millboard</td>
<td>0.125</td>
<td>0.38</td>
</tr>
<tr>
<td>10</td>
<td>Millboard</td>
<td>0.125</td>
<td>0.23</td>
</tr>
<tr>
<td>20</td>
<td>Millboard</td>
<td>0.125</td>
<td>0.16</td>
</tr>
<tr>
<td>1</td>
<td>Ceramic</td>
<td>0.25</td>
<td>30.00</td>
</tr>
<tr>
<td>5</td>
<td>Ceramic</td>
<td>0.25</td>
<td>1.18</td>
</tr>
<tr>
<td>10</td>
<td>Ceramic</td>
<td>0.25</td>
<td>0.66</td>
</tr>
<tr>
<td>20</td>
<td>Ceramic</td>
<td>0.25</td>
<td>0.46</td>
</tr>
<tr>
<td>1</td>
<td>Silica</td>
<td>0.25</td>
<td>30.00</td>
</tr>
<tr>
<td>5</td>
<td>Silica</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>10</td>
<td>Silica</td>
<td>0.25</td>
<td>0.12</td>
</tr>
<tr>
<td>20</td>
<td>Silica</td>
<td>0.25</td>
<td>0.09</td>
</tr>
</tbody>
</table>

**Weight requirement:**

The weight of the cabinet with all instrumentation and insulation is set to remain under 102kg (225lbs) to remain maneuverable by one person and lift-able by two people. The cabinet alone weighs 61kg (134lbs), the instrumentation is 22kg (48lbs) and the cooling unit is 12kg (26.5lbs). This requirement allows approximately 7.48kg (16.5lbs) of insulation to be installed.

**Table 3: Maximum insulation thickness due to the weight criteria of the cabinet.**

<table>
<thead>
<tr>
<th>Ceramic</th>
<th>Millboard</th>
<th>Silica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>Weight</td>
<td>Thickness</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1875</td>
<td>10.71533</td>
<td>0.0625</td>
</tr>
<tr>
<td>0.25</td>
<td>14.28711</td>
<td>0.125</td>
</tr>
</tbody>
</table>
\[ Weight = (Surface\ Area) \times (thickness) \times (density) \]

The weight criterion states the maximum allowable insulation thickness for the easy mobility of the cabinet, as defined by Tyco. The maximum thickness is 0.25 inches for the ceramic insulation, 0.125 inches for the millboard insulation and 0.50 inches for the silica insulation (see Table 3). The calculation performed for the millboard insulation only considered a minimum of 0.125 inch insulation. This is due to the impracticality of calculating something thinner as the number or elements rises as the thickness of the sample declines. For the method and relevant equations used see Appendix G:

When considering the weight requirement, the protection time for the insulations is very small and would not allow protection for the duration of a test. Especially critical is the protection time at the heat flux value of \(5\frac{KW}{m^2}\) because a value of \(2.5\frac{KW}{m^2}\) was measured for approximately one minute during the conducted tests (see Appendix D: Testing Results). In the event of a more powerful test fire the cabinet needs would need to be protected. To ensure protection of the instruments thicker insulations with higher weights must be considered. By adding 14lbs of ceramic insulation, the cabinet would be protected against a heat flux of \(5\frac{KW}{m^2}\) for the full duration of the tests (see Figure 4). The ceramic insulation has a far larger capacity to insulate then the millboard or silica insulation.
Figure 4: Protection times for when the back face of 0.5 inches of Ceramic, Millboard, or Silica insulation will reach 45°C (104°F).

Insulation is an inexpensive way to protect the cabinet from the heat insult. The insulation chosen from the analysis is 0.5 inch (12.7mm) thick ceramic board insulation. The ceramic insulation has a low K-Factor, which equates to the most efficient weight to thickness ratio of the considered insulations. The insulation protects the cabinet for up to 30 minutes from a fire insult of 5 \( \text{kW/m}^2 \) and 3 min from a direct heat flux of 20 \( \text{kW/m}^2 \).

**Cooling Unit**

The gas analyzer and the air conditioner have operational limits at approximately 100°F (40°C). The design focused on insulation 0.5 inches thick with a heat flux of 5 \( \text{kW/m}^2 \) as the ideal solution. Figure 5 shows that using insulation alone will allow between 600-1400 watts into the cabinet, causing an unacceptable rise in temperature over the 30 minute test. A cooling system is justified to keep the instruments at an optimal operational temperature. See Appendix G: Finite difference method heat transfer analysis for detailed calculation of the energy into the cabinet.
The size limitation of the cooling unit greatly reduces the cooling capability of a unit. Because of this the cooling system recommended is the American Comfort ACW100. The cooling unit is not used to protect the cabinet, but keep the instruments comfortable. There is no cooling unit found that can both protect the cabinet from the full insult of a heat flux above $1 \frac{\text{kw}}{\text{m}^2}$, and have a small enough footprint that it will fit in the cabinet. Thus cooling system will only be effective for lower heat fluxes and smaller test times. This cooling system is a size capable of fitting into the cabinet. The weight of the device is 26.5lbs (12kg) with the dimensions being 14in (355mm)x23 in (585mm)x 9 in (230m), and a cooling capability of 240 watts (American Comfort, 2012). This system can increase the protection time of the cabinet to 2min at a heat flux of $5 \frac{\text{kw}}{\text{m}^2}$ to 30min with $1 \frac{\text{kw}}{\text{m}^2}$ hitting the cabinet. As a result of the very low protection times at heat fluxes greater then 1, it is recommended to protect the cabinet at a distance greater than 7.62m (20 ft).
Cost

Ceramic is priced higher than the other insulations, but it performs the best as was shown. Table 4 shows the price per thickness for the insulation analyzed. Despite the high cost of the ceramic insulation it is the best insulator for its weight and is the recommended insulation to be used.

Table 4: The price of the insulation. The pricing of the insulation follows the analysis results, with ceramic being the most protective material analyzed. Millboard and Silica being subsequent insulations in both quality of protection and price.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Insulation</th>
<th>Weight</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.250</td>
<td>Ceramic</td>
<td>14.29</td>
<td>$339.13</td>
</tr>
<tr>
<td>0.500</td>
<td>Ceramic</td>
<td>28.57</td>
<td>$678.26</td>
</tr>
<tr>
<td>1.500</td>
<td>Ceramic</td>
<td>85.72</td>
<td>$1,748.10</td>
</tr>
<tr>
<td>0.125</td>
<td>Millboard</td>
<td>22.18</td>
<td>$118.06</td>
</tr>
<tr>
<td>0.500</td>
<td>Millboard</td>
<td>88.73</td>
<td>$345.82</td>
</tr>
<tr>
<td>1.500</td>
<td>Millboard</td>
<td>266.19</td>
<td>$1,037.45</td>
</tr>
<tr>
<td>0.250</td>
<td>Silica</td>
<td>7.52</td>
<td>$45.20</td>
</tr>
<tr>
<td>0.500</td>
<td>Silica</td>
<td>15.04</td>
<td>$82.14</td>
</tr>
<tr>
<td>1.500</td>
<td>Silica</td>
<td>45.12</td>
<td>$246.43</td>
</tr>
</tbody>
</table>

The thermal analysis demonstrates that the most effective insulation would be 0.5 inches of ceramic insulation. Two impediments to this finding is the weight, which is too heavy for the current cabinet and its weight restriction and the price which is marginally higher than the other insulations. The most convincing reason to install the ceramic insulation is displayed in Figure 4 where it is the only insulation, which protects the cabinet up to a heat flux of \( \frac{kW}{m^2} \) with a thickness of 0.5

Cost Benefit Analysis

The cost of the designed mobile system ranges between ~$43,000 to ~$50,000 dollars, depending on the specifications of the final chosen components, compared to the ~$140,000 it would cost to build 3 separate fire product collectors (see Table 5).

Another detail that must be mentioned is the consistency of a mobile system. If 3 systems were to be implemented that would imply three hoods would be present. This would complicate the operation of some of the other tests being performed within those same bays.

The solution presented will add the capability of measuring fires up to one megawatt. The site will be able to move its fire products collector in and out of bays and in storage adding versatility to the test areas (see Appendix R: Price List of System Components for additional breakdown of costs).
Table 5: Overview of system costs.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Cost Low</th>
<th>Cost High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabinet</td>
<td>$907</td>
<td>$1,007</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>$29,025</td>
<td>$33,689</td>
</tr>
<tr>
<td>Ducting</td>
<td>$4,080</td>
<td>$4,080</td>
</tr>
<tr>
<td>Hoods</td>
<td>$8,238</td>
<td>$8,238</td>
</tr>
<tr>
<td>Insulation</td>
<td>$680</td>
<td>$1,750</td>
</tr>
<tr>
<td>Total System Cost</td>
<td>$42,930</td>
<td>$48,563</td>
</tr>
</tbody>
</table>

**Conclusion**

A fire products collector is a useful tool to gain understanding of fire. Adding mobility to a fire products collector allows the device to be used in multiple locations that may expand the variety of fires to be studied and, eventually, understood.

A fire products collector consists of a hood, duct, probe section and instrumentation cabinet. The hood and the duct are too heavy and obtuse for easy mobility and must be disassembled or installed in the test area. Adding mobility to a fire products collector is adding mobility to the probes and the instrumentation cabinet. In addition the increased hazards of mobility require protection for smoke, airborne particulates (soot), water and heat.

As the instrument cabinet is the most expensive part of the system, measures must be taken to protect all of the delicate devices to ensure proper operation. To protect against thermal insults, two protective systems acting in unison will work best, the insulation protects the whole cabinet, while the air conditioner cools the instruments to an acceptable temperature. However, these systems need to be designed with the notion that personnel will be using them, and must have some degree of consideration towards safety.

Adding mobility to a fire products collector is very cost effective when there are multiple test areas that could potentially be used for fire testing. The expansion of a mobile fire products collector, allows for the collection of the heat release rate, which is the single most important indicator of fire hazard and represents a significant step forward for the capabilities of Tyco’s test areas.

**Future work**

Considerations were made to accommodate the weight and volume of a Hydrocarbon analyzer. The device would require a more in-depth study of the cabinet’s protective system and possibly additional considerations for sampling lines and power lines. A hydrocarbon analyzer would give more insight into burning characteristics of the fire as it would allow the user to evaluate the energy contained in the uncombusted fuel.
The market for fire testing tools tends to lean toward making custom products. One company fire testing technology has a large foothold in the market, with products that could be advanced. For companies that want ease of use, a custom system takes time and expertise to create, and the current market option has limited operator customizability. Focusing mainly on the cabinet, it is scalable to any size testing facility, from a cone calorimeter to full scale testing. The proposed cabinet could replace the current market option increasing the customizability and robustness of the calorimetry performed, by allowing the user easier access to a custom interface and great options in the data and operations supported.

Implementation of the system would the ultimate goal of this project. The project focused specifically on designing the system and the instrumentation cabinet, but the construction, testing and use of the system would be the next logical step of the project.
Works Cited


Appendix A: Acknowledgements
For the duration of the project our team received help from numerous supportive people and entities. First we would like to thank our advisor Professor Nicholas Dembsey for his endless expertise and guidance. We would like to thank our onsite mentors Melissa Avila and Zach Magnone for their patience and site specific expertise that was invaluable to our project. Thanks to Chad Goyette for his endless practical advice and hands on technical guidance that shaped our project from the pen and paper to reality. Thanks, also, to everyone else in the Cranston site’s staff for answering our questions and providing valuable insight in the time of need.

Especially thanks to Tyco Fire Protection Products for their sponsorship of our project, their investment and commitment into future engineers conducting real world projects is commendable. Most central to this effort is George Oliver, the soon to be CEO of Tyco Fire Protection Products, and Paul Piccolomini, VP of product management and mergers & acquisitions. Their efforts to increase multicultural engineering projects help to drive global corporate cooperation.
Appendix B: Pre-Qualifying Project (PQP)
Memorandum

To:    Melissa Avila;
       Professor Nicholas A. Dembsey

CC:    Zachary Magnone

From:    Drew Martin, WPI
       Andre D'Avila DaVitoria, WPI
       Yong-Bin Ji, SJTU
       Lei Zhang, SJTU

Date: April 25, 2012

Subject: Research proposal for the Design of a Mobile Fire Products Collector

Background

There are many different apparatuses available to measure crucial characteristics of fires. These devices range from a cone calorimeter, which burns a 100mm x 100mm specimen, to a furniture calorimeter to a large room calorimeter, such as FM Global's 24 meter x 24 meter large burn lab. Although a significant amount of data has been collected and analyzed from these devices, there is not yet an alternative for a mobile device that can be used in multiple laboratories. The assumed cost associated with a mobile fire products collector would also be significantly less than a large fire products collector as used at FM Global or Underwriters Laboratory.

Tyco Fire and Security is a division of Tyco International that focuses on designing products for fire suppression, life safety and security. To achieve this goal Tyco performs numerous tests at their Cranston, RI site to optimize their products to improve safety and security for businesses and residential customers. To improve Tyco's testing capabilities further a mobile fire products collector would significantly increase their flexibility in performing tests.

The design of the cabinet for a mobile fire products collector takes into account the many challenges that a fire brings. A fire is an extremely difficult environment to operate in and there are few materials that offer full protection against a powerful fire. In addition the instruments used to measure the temperature and products of combustion may be damaged by a fire if they are not properly protected and maintained.
Fire Testing Technology has engineered a number of products used for fire testing that offer solutions to various standards groups tests. In addition they offer solutions for the instruments that are necessary for fire tests. Their designs also offer insights as to what the industry requires and the design of existing test beds.

**Problem Statement**

Current market offerings of medium to large scale fire product collection apparatus are not mobile. The introduction of a mobile fire products collector can introduce a new test bed that can be moved from one lab space to another, while remaining fully operational for tests.

**Objective**

The objective is to design a mobile fire products collector including instrumentation and hood to operate a medium-large scale calorimeter instrument cabinet for an apparatus that can withstand the extreme environment of a fire. An analysis of the cost to manufacture the device, including all instruments, will be conducted and a prototype instrument cabinet will be built.

**Results, Deliverables and Benefit**

The result of this project will be a full functional cabinet for a medium to large scale calorimeter. Through this project Tyco will expand it capabilities from small scale calorimetry to a calorimeter that can measure a room burn. The cost analysis that will be required will give Tyco insight into the expenses associated with a calorimeter of this size and help justify the expense of one of these larger devices. A complete conference paper, with supporting appendices will be delivered upon completion of the design. The paper will potentially be published in a conference paper after the completion of the design. The deliverable will include a summary of the process used to complete the design, a design of the calorimeter system, the cost of the device, the prototype instrument cabinet and the results of all tests done and the prototype instrument cabinet.

**Technical Approach**

A mobile enclosure will be built that can be combined with a hood and duct system that will sit above a burn test. This enclosure must be water resistant and heat resistant to repel the heat of the fire and water from sprinklers.

The tests will consist of parking the enclosure next to a fire for a period of ~20 minutes and measuring the ambient heat inside the device as to understand the buildup of heat inside the enclosure. To ensure protection of the instruments the instrument cabinet must be tested to ensure there is no excessive heat transfer from the fire to the cabinet. The fire will be extinguished exposing the enclosure to some water to simulate a sprinkler test hitting enclosure. To ensure the soundness of the design various data points inside and outside the cabinet will be measured
including: Inside temperature, outside temperature, moisture content inside the device, and pressure inside and outside the device.

Executive Summary
There is a gap in the variety of fire testing apparatus that a mobile fire products collector, with the capability of measuring large scale sprinkled fires, will occupy. There are many products available that are sufficient at collecting fire products; however they have the problem of being designed for a specific fire size. Also they are usually contained in a burn room and require a sizable increase in infrastructure, especially if sprinkled and non-sprinkled tests are required. The solution is the development of a mobile fire products collector, which will be a standalone unit that can be moved between labs. The team will design the cabinet for the products collector, so that the collector is able to withstand the heat of the fire as well as remain sufficiently mobile. An analysis of the cost of the device will be completed to justify the completion of the design. The design of the cabinet will be proven with a number of fire and sprinkler test. The majority of the work will be performed by students from Worcester Polytechnic Institute and Shanghai Jiao Tong University, which greatly reduces the cost of the project.

Hood and Exhaust Collections Systems

Hood Design
Several factors must be taken into account for the design of the hood. One factor is the size of the opening of the hood, so that the hood will be suitable for most fire tests performed at Tyco. The hood will be a 3m x 3m (9.84ft x 9.84ft) hood to be capable of testing up to a 5MW fire.

There are two types of tests that are going to utilize this device; a compartment fire and a furniture fire. These two different types of fires require slightly different setups.

The hood will be constructed using the guidelines suggested in ASTM 2067. The hood will be constructed out of stainless steel. The slope of the hood is limited to a 40° slope between the hood and the walls (see Figure 6). The hood is required to be insulated so that the conductive heat loss is no greater than the walls. The steel will be coated with a fibrous cement mix to provide thermal insulation of the steel structure. The insulation will provide a protection for the steel during a long burning fire; however if burning persists the hood could be a source of reflected radiation back to the burning object (NIST, 2004).

It is imperative that all of the gasses leaving the burning specimen are collected. In order to do so a blower is added to the system to ensure that the flow becomes fully developed and the gases are sufficiently mixed.
The purpose of the cables is so that the device can be easily and inexpensively be hung from above and positioned as necessary. This is directly opposed to using a levered system from the ground or a movable car, which would weigh much more and also be much more costly to construct.
The flow in the ducts is where all of the data is measured; therefore the specifications of the duct are explicitly outlined as well as the instrumentation required for testing. The diameter of the ducts heavily contributes to the location of the fully developed flow as well as the volume of gasses in the duct. ASTM 2067 recommends that to measure all the combustion products the probes should be located a distance of 8 to 30 duct diameters to where the gas products are uniformly mixed and the velocity is nearly uniform.

The design has a duct with an estimated length of 15m (49.2ft) assisted with a fan to ensure that the velocity profile reaches a fully-developed profile with some tolerance for end effects. The duct used is made of 14 gauge stainless steel, with an inner diameter of 1m (3.28ft). The inside of the duct will then be coated with concrete as mentioned in (NIST, 2004) to limit energy dissipation from the gases directly contacting the steel of the duct. A 15 meter long duct, including the fan, will weigh about 1100kg (2400lbs). The weight may vary depending on the thickness of the inside coating applied.

<table>
<thead>
<tr>
<th>Component</th>
<th>Fan</th>
<th>Duct</th>
<th>Hood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>180lbs</td>
<td>1800lbs</td>
<td>400lbs</td>
</tr>
</tbody>
</table>

**Mobility**

To improve mobility the size and weight of the device will be minimized. The length of the duct will be reduced as much as possible to maintain a conducive flow characteristic. This will be achieved by a fully developed gas flow as immediately as possible. This may be achieved through a series of nozzles, a diffuser, flow straightener, or guiding vanes or a combination of these devices.

The materials used in the device will be critical to increase the mobility of the device. The limiting factor is the extreme environment the device will have to endure. Therefore many of the materials will need to be heavy duty steel. To overcome this weight problem the use of a device to lift and move the apparatus will be considered. Alternatively if the device can be disassembled into sizes of manageable weight that would be solution considered as well.

**Potential Modifications and Future Work**

The designed device will lay the groundwork for a fully functional mobile fire collector to be built in the future. Depending on the test bay the length of the duct will need to be determined based on the specific needs of each site.

**Schedule, Resources and Cost Estimate**

The research and building will be conducted over a period of six weeks, commencing on Monday July 2, 2012 and completing Friday August 17, 2012. The team will consist of four engineering
students: 2 from WPI in Worcester, MA, USA and 2 from Shanghai Jiao Tong University in Shanghai, China. Students will be working approximately 40 hours per week.

Schedule
1st-3rd week: The system will be designed using modeling software, which will be helpful for modifications of the design. The optimal size, material, and structure of the system will be evaluated. At the end of the design process, a price estimate will be calculated.
4th week: Prototypes will be designed to test the function of the cabinet, especially the thermal barrier and smoke and water proof. Materials to build a simplified cabinet, which includes all the basic characteristics of the final design, will be decided and acquired.
5th week: In this stage, a small numbers of tests will be devised to see whether the cabinet serves its purpose. The water resistance of the device as well as the temperature inside and outside the device must be tested.
6th to 7th week: Data will be organized, optimizations will be proposed for the cabinet, and a Standard Operating Procedure for use of the mobile fire products collector will be written. The report and conference paper will be finalized, prepared for presentation.
Appendix C: Unexpected Problems
In the search for a cooling unit for the instrument cabinet the design team considered many solutions. As previously mentioned options such as fans within the case, insulation and water cooling were heavily considered. Upon investigation most of these products turned up in some form of a commercialized product that was essentially ready for use. However, upon consideration of a cooling unit of the scale that is needed to cool the cold trap of the samples of gas within the cone calorimeter, no real results turned up.

The scale of the refrigeration system within the cone calorimeter is not so uncommon. The product was labeled as having a capability of ~90 Watts. A small refrigerator, like ones commonly found in dormitories operates on the same magnitude but cools a volume of gas slowly rather than a small sample rapidly. While not monumentally problematic, the machine was made to keep an immobile volume of air cold. This dissimilar operation meant that a refrigeration system from a fridge would have to be modified to fit inside of the instrument cabinet and cool a continuous sample. The issue with the size of the device being the heat exchanger that serves as a condenser.

As a possible solution to this a different kind of heat exchanger was considered. The heat exchanger that was now under consideration is cooled by a liquid instead of by air. After reasoning a liquid cooled exchanger was more space effective the design team began searching for a cooling system with air to liquid heat exchangers. The specific combination mentioned is very common in refrigerators for watercraft. The search was once again on for a product that was readily available. After some searching it was once again found that the combination of scale and application of the necessary device was incredibly uncommon.

After some consultation with representatives from marine refrigeration companies, the possibility of a device intended for medical applications was brought up. Once again the design team searched fruitlessly for the specific device of the scale needed.
Appendix D: Testing Results
Testing
To prove the design of the prototyped cabinet a series of tests were conducted to determine the maximum heat insult that the cabinet would endure during a typical test fire. Fire is a very abusive event and when dealing with extremely expensive and sensitive instruments it is important to ensure that no insult will impact the quality of the instrumentation results or cause the instruments to malfunction. Cabinet testing was performed in test area F in concurrence with sprinkler testing done by the new technology group within Tyco.

Test Fire:
The tests were conducted according to the UL 1626 standardized test fire. The fire is meant to simulate a room corner in a residential occupancy in. The fuel package consists of a wood crib (Figure 2) and simulated furniture positioned in a corner of the room enclosure. The fire is ignited by using hexane ($C_6H_{14}$) as an accelerant. The heptane ignites the crib. The foam is arranged in a fashion that promotes the radiation from the fire to travel up the corner of the room and propagate toward the ceiling, when the water sprinkler will activate and extinguish the fire.

Cabinet Test Setup:
Prior to the completion of the prototype cabinet, a sheet of galvanized steel was used to determine an approximate temperature differential across the material. The carbon steel plate setup is essentially the same as the setup used with the cabinet.

The test setup of the cabinet in relation to the fire was to determine how a typical test fire, like the UL 1626 fire, would affect the cabinet. The cabinet was set up at differing distances of ten to twenty five feet away from the corner where the fire was located (see Figure 8).

![Figure 8: Test Setup (plan view). The Fire is represented by the red triangle. The black lines surrounding the fire are the vertical foam plates. The blue circles represent the sprinklers and the rectangular box represents the cabinet which depending on the test would be as close as 10 feet or as far away as 20 feet. The large black lines represent the walls of a residential enclosure.](image)
Figure 9: Thermocouple Placement (elevation view). This side view of the cabinet shows its relative position to the fire (the red triangle). There are 4 thermocouples; TC1 is on the front of the cabinet in the center of the cabinet, TC2 is inside the cabinet attached to the roof, to measure the effects of the fire plume hitting the ceiling and descending downwards, TC3 is inside the cabinet in the exact middle hanging in air, TC4 is a distance away from the cabinet measuring the ambient air in the room. The heat flux gauge was placed on top of the cabinet.

Sensors:
To measure the heat insult of the fire four thermocouples were used (see Figure 9). For the last two tests a heat flux gauge was added to measure the maximum incident heat flux hitting the cabinet was receiving. To ensure that the water from the sprinklers minimally affected the thermocouples covering were formed to protect the thermocouple bead from water that might result in erroneous data.

An Omega portable data logger was used to record the temperature measurements from the thermocouples. The RDXL4SD portable data logger had the capability for four thermocouples. It had a resolution of 0.1°C with a sampling time of one sample per second (Omega, 2003).

The transducer used to measure the heat flux is a gardon gauge. The sensor is liquid cooled and requires no input voltage to operate. The gardon gauge being used was calibrated within Tyco’s facilities. Because we were looking for a maximum thermal insult official calibration by its manufacturer, Medtherm was considered too time consuming and in-house calibration was sufficient.

Calibration of the gardon gauge was done by utilizing the cone calorimeter and its calibrated heat flux gauge. The gardon gauge (model number: 64-5SB-20) is designed to have a linear voltage to heat flux conversion factor. Using the cone calorimeter it was possible to adjust the heat flux directed as the sensor and record the known heat flux and the voltage from the gauge and match it to a time temperature scale dictated by ASTM E511. This particular gauge was found to have the
conversion factor of $2.29058 \frac{\text{kw}}{\text{mv}}$. This number is used to change the voltage output recorded to a heat flux value.

**Testing Results**

**Steel Sheet (Test 1 and 2):**
The first test, conducted July 29, 2012, used a steel sheet with thermocouples attached to the front and back to find the temperature differential across the steel sheet. Additional thermal couples were placed in ambient air relatively close to the plate and behind the plate (see Figure 10).

![Change in Temperature through steel sheet](image)

Figure 10: Temperature differential. The temperature differential records a difference of about 12 seconds at the maximum peak. This is consistent with data in Figure 11 for the range of temperatures being recorded. The negative data at the end is a result of the thermocouple on the front interacting with more water.

Another data set that pertains to the testing and optimizing the cabinet design is the graph of the differential temperature. There is a relatively small difference between the two sides of the plate, however, as the fire grows to its maximum temperature the difference between the front and back of the plate reaches almost 13.5% (11 °F), see Figure 10 above.

**The Cabinet Prototype Tests**
The test fires, despite having the same fuel package and materials behave differently for each test. The difference in fire from test to test makes perfect repeatability impossible. The main goal of testing is to determine the maximum heat insult from the fire, so that the cabinet can be protected accordingly.

For the final two tests a heat flux gauge was used to measure the incident heat flux or energy transfer to the material surface (Cote & National Fire Protection Association, 2003). The results of the incident heat flux at the cabinet are shown in
Figure 11: Temperatures from thermocouples on cabinet (see Figure 9). TC2 reaches the highest value, which is the thermocouple located on the cabinet roof. The difference between the highest thermocouple is about $10^\circ$F.
Figure 12: Incident heat flux on cabinet. The incident heat flux has a peak of about 2.5kW/m². The data suggests that the heat flux for this fire has a relatively small output because the sprinklers are designed to cool the fire rapidly blocking any heat.

Conclusion
All of the testing done ten tests in total, display the predicted worst case scenario for any test that the calorimeter cabinet would be expected to operate in. The maximum heat flux experienced during the two tests was $2.75 \frac{kW}{m^2}$.

The maximum temperature insult experienced during the two tests was 101.1 °F. This can be compared to the highest temperature experienced inside the cabinet, which is 87 °F. This was the result of a particularly large test experienced on August 7. The average max temperature inside the cabinet is only 84 °F.
Steel Plate Differential test

Test Setup and Plate Location

Temperature Data Plot:

Temperature Data Test 01 (07/27/2012)
Temperature Difference Across Steel Sheet

Temperature Comparison to New Technology Group Data:

Comparison of Collaborative data
Temperature Data Plot:

Temperature Data, Test 02 (07/30/2012)
Figure 13: Thermocouple Locations on Cabinet

Temperature Data Plot:

Temperatures on Cabinet, Test 03 (08/01/2012)
Tempertures on Cabinet, Test 04
(08/02/2012)
Temperature on Cabinet, Test 05
(08/03/2012)
Temperatures on Cabinet, Test 06
(08/06/2012)

Tempertures on Cabinet
Temperatures on Cabinet, Test 07
(08/07/2012)
Temperatures on Cabinet, Test 08
(08/08/2012)
Temperatures on Cabinet, Test 09
(08/13/2012)

Heat Flux Data Plot:

Incident Heat Flux (kW/m²)
Temperatures on Cabinet, Test 10
(08/14/2012)

Heat Flux Data Plot:
Assembly (pre test)

1. Position Ducting and hood in desirable testing area
2. Position Sampling equipment at other end of ducting in desired testing area
3. Assemble Racks
4. Assemble Hood on racks
5. Place Protective barrier around racks
6. Connect hood to stationary duct
   a. Including any extra ducting sections
7. Connect sampling section to opposing end of duct

Calibration (pre test)

1. Turn power on
2. In case the system has a cold trap
   a. Make sure cold trap is empty (in case of using cold trap)
      i. If not, then empty it by opening the drain valve and closing it when the water is drained
      ii. Close cold trap
3. Make sure selector valve is turned to “Calibrate” and not “Sample”
   a. Setting that closes the flow from any sample gases
4. Purge system with nitrogen
   a. Make sure all calibration gas tanks have their valves closed.
   b. Open nitrogen calibration valve
   c. Make sure the Gas analyzer reads 0 Oxygen and 0 Carbon Dioxide
      i. Otherwise zero the values out
5. Calibrate for O2 and CO2 mixture tanks
   a. Make sure calibration gas tanks are all closed
   b. Open CO2 or O2 mixture
   c. Make sure the gas analyzer reads the correct composition (values from tanks)
      i. Otherwise set them to known value of tank mixture
6. Repeat Calibration for other gas
7. Close off Calibration gas valves
8. Check Dessicant and particulate filters
   a. Replace filtering components if necessary

Operation (pre test)

1. Power the fan of the sampling duct system
2 Power the Instrument cabinet
3 Turn on vacuum pump
4 Turn selector valve from calibrate to sample

5 Prepare moisture disposal system
   a In case of cold trap
      i empty cold trap (Step 2a in “Calibration” section)
      ii Turn on and run cold trap until suitable temperature in case of cold trap
   b In case of ice bath
      i Prepare suitable ice bath for gas line
   c In case of only desiccant filter
      i Check filters (Step 8 of “Calibration” section)

Testing (post test)
1 Wait until test has been terminated
   a ensure the room is suitable for human traffic
   b ensure equipment is at suitable temperature
2 Turn off cabinet power
3 Turn off sampling duct
4 Let cabinet cool down
   a if the room temperature is below 105 F and the cabinet is at a higher temperature
      than ambient, open the cabinet and let it sit for 20 minutes

Disassembly
1 Disconnect blower
2 Disconnect sampling duct
3 Disconnect mobile ducting from stationary ducting
4 Disconnect hood
   a Disassemble hood
   b Disassemble racks
5 Move to storage area
Appendix F:  Testing Room
Testing Setup

Figure 14: Fuel Package for UL 1626 test fire. Consists of a wood crib with a heptane pan underneath.

Figure 15: Cabinet Location in Test Area. The cabinet moves between...
Steel Sheet

Figure 16: Steel sheet set up in test area

Figure 17: Thermocouple attached to steel sheet with aluminum tape

Figure 18: Thermocouple in ambient air
Figure 19: Back of steel sheet, with thermocouple attached to the back and in ambient air

Figure 20: Side view of Steel Sheet
Figure 21: Portable Data Acquisition system

Cabinet

Ceiling

Heat Flux Gauge

TC4

TC1

F

TC2

Top

TC3

Figure 22: Thermocouple locations for cabinet testing. The triangle signifies the relative fire location.
Figure 23: Side view of cabinet with door off.

Figure 24: Side view of cabinet with full view of inside the cabinet.

Figure 25: Front view of cabinet.
Figure 26: Thermocouple suspended inside the cabinet
Appendix G: Finite difference method heat transfer analysis
Insulation
To determine the amount of insulation on the box we first need to determine the heat transfer from the fire to the cabinet and how that heat conducts through the box. Initially to determine whether any insulation is needed we can do a semi-infinite calculation to show what of sheet steel would be sufficient to keep the inside of the cabinet below the maximum operable temperature of the gas analyzers.

The Insulations that were analyzed were found on McMaster.com and represent three different types of materials used to make board insulations; Ceramic, Millboard, and Silica.

### Ceramic Insulation
Moisture-resistant sheets are silica ceramic insulation wrapped in polyethylene.

<table>
<thead>
<tr>
<th>Thickness (in.)</th>
<th>Width (in.)</th>
<th>Length (in.)</th>
<th>Max Temp (F)</th>
<th>H (ft^2<em>F</em>h/BTU*in)</th>
<th>Density (lbs/ft^3)</th>
<th>Item #</th>
<th>Weight (lbs)</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1875</td>
<td>19.5</td>
<td>23.5</td>
<td>1925</td>
<td>0.28</td>
<td>19</td>
<td>6841K1</td>
<td>10.715</td>
<td>47.55</td>
</tr>
<tr>
<td>0.25</td>
<td>19.5</td>
<td>23.5</td>
<td>1925</td>
<td>0.28</td>
<td>19</td>
<td>6841K2</td>
<td>14.287</td>
<td>59.8</td>
</tr>
<tr>
<td>0.375</td>
<td>23.5</td>
<td>39</td>
<td>1925</td>
<td>0.28</td>
<td>19</td>
<td>6841K3</td>
<td>21.431</td>
<td>129.43</td>
</tr>
<tr>
<td>0.75</td>
<td>23.5</td>
<td>39</td>
<td>1925</td>
<td>0.28</td>
<td>19</td>
<td>6841K4</td>
<td>42.861</td>
<td>179.46</td>
</tr>
<tr>
<td>1</td>
<td>23.5</td>
<td>39</td>
<td>1925</td>
<td>0.28</td>
<td>19</td>
<td>6841K5</td>
<td>57.148</td>
<td>215</td>
</tr>
<tr>
<td>1.5</td>
<td>23.5</td>
<td>39</td>
<td>1925</td>
<td>0.28</td>
<td>19</td>
<td>6841K6</td>
<td>85.723</td>
<td>308.25</td>
</tr>
</tbody>
</table>

### Millboard Insulation
High temperature and extra high temperature sheets are made of rock wool mineral fibers, clay, and filler.

<table>
<thead>
<tr>
<th>Thickness (in.)</th>
<th>Width (in.)</th>
<th>Length (in.)</th>
<th>Max Temp (F)</th>
<th>H (ft^2<em>F</em>h/BTU*in)</th>
<th>Density (lbs/ft^3)</th>
<th>Item #</th>
<th>Weight (lbs)</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0625</td>
<td>39</td>
<td>39</td>
<td>1380</td>
<td>0.81</td>
<td>59</td>
<td>9362K16</td>
<td>11.091</td>
<td>21.5</td>
</tr>
<tr>
<td>0.125</td>
<td>39</td>
<td>39</td>
<td>1380</td>
<td>0.81</td>
<td>59</td>
<td>9362K11</td>
<td>22.183</td>
<td>34.55</td>
</tr>
<tr>
<td>0.1875</td>
<td>39</td>
<td>39</td>
<td>1380</td>
<td>0.81</td>
<td>59</td>
<td>9362K12</td>
<td>33.274</td>
<td>43.5</td>
</tr>
<tr>
<td>0.25</td>
<td>39</td>
<td>39</td>
<td>1380</td>
<td>0.81</td>
<td>59</td>
<td>9362K13</td>
<td>44.365</td>
<td>63.95</td>
</tr>
<tr>
<td>0.375</td>
<td>39</td>
<td>39</td>
<td>1380</td>
<td>0.81</td>
<td>59</td>
<td>9362K14</td>
<td>66.548</td>
<td>85.37</td>
</tr>
<tr>
<td>0.5</td>
<td>39</td>
<td>39</td>
<td>1380</td>
<td>0.81</td>
<td>59</td>
<td>9362K15</td>
<td>88.73</td>
<td>101.2</td>
</tr>
</tbody>
</table>

### Harsh-Environment Silica Insulation

<table>
<thead>
<tr>
<th>Thickness (in.)</th>
<th>Width (in.)</th>
<th>Length (in.)</th>
<th>Max Temp (F)</th>
<th>H (ft^2<em>F</em>h/BTU*in)</th>
<th>Density (lbs/ft^3)</th>
<th>Item #</th>
<th>Weight (lbs)</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>(in.)</td>
<td>(in.)</td>
<td>(in.)</td>
<td>(F)</td>
<td>(ft^2<em>F</em>h/BTU*in)</td>
<td>(lbs/ft^3)</td>
<td>(lbs)</td>
<td>(lbs)</td>
<td></td>
</tr>
</tbody>
</table>
Semi-Infinite
To determine that the sheet steel was not sufficient to protect the cabinet from the estimated heat flow the next step was to use a semi-infinite solid analysis. Using the semi-infinite analysis the depth at which a heat insult on the outside has no effect on the inside of the insulation can be determined. To put it another way, if a certain heat flux is affecting the outside surface, how thick does the insulation have to be so that the back wall does not experience any effect from the initial heat flux.

The equation for the semi-infinite solid analysis is:

$$\Delta = 4\sqrt{\alpha t} = 4\sqrt{\frac{k}{\rho c_p}} t$$

The semi-infinite solid analysis uses the properties of the insulation being analyzed to determine the thickness that is needed.

<table>
<thead>
<tr>
<th></th>
<th>10min (in.)</th>
<th>20min (in.)</th>
<th>30min (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic Insulation</td>
<td>0.80935941</td>
<td>1.14460705</td>
<td>1.40185162</td>
</tr>
<tr>
<td>Millboard Insulation</td>
<td>0.81754182</td>
<td>1.15617873</td>
<td>1.41602397</td>
</tr>
<tr>
<td>Harsh-Environment Silica Insulation</td>
<td>1.99680395</td>
<td>2.82390722</td>
<td>3.45856589</td>
</tr>
</tbody>
</table>

Table 6: Thickness of insulation from Semi-infinite analysis

The semi-infinite solid analysis is a blunt method thus a more discretized method is needed to find the thickness, weight, and cost of material that is required to protect against the thermal insult.

Finite Difference Method
The finite difference method of calculating the heat transfer, through a solid, works by breaking up the full thickness of the solid and breaking it up into many discretized sections through which to measure the heat transfer. This method provides a more exact way to observer the effects of heat insults over a certain time.

The solid is broken up into N nodes, or control volumes, which the temperature equations act upon. The general energy balance that must be conserved is:

$$\left[ \text{Rate of heat generation inside } CV \right] = \left[ \text{rate of heat conduction into } CV \right] - \left[ \text{rate of heat conduction out of } CV \right]$$

From equation this all of the equations can be derived. For the cabinet considered that there would be no heat generation inside the insulation and assumed a constant heat flux at the front boundary.
and a convective cooling process at the back boundary. Using the equations we can formulate a numerical solution using Microsoft Excel© software.

The heat analysis of the cabinet involved determining the exact specifications required determining what methods of heat transfer would be evident at the boundaries. The method that was chosen included a constant heat flux and convection cooling at the front face and convection applied at the back face.

**The nodal and boundary equations:**
The finite difference method is derived from the one dimensional transient conductive heat transfer equation:

\[
\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}
\]

where \( \alpha \) is the thermal diffusivity, \( \frac{k}{\rho c} \). The environment that the cabinet is exposed in will most likely have a direct heat flux from the fire at the front face of the cabinet with a convective cooling factor accounting for the temperature of the air around the cabinet. The internal layer of the insulation had no heat generation. The back face of the insulation is open to the air inside of the cabinet which is a known surface convection.

\[
q_i'' + h(T_\infty - T_1^p) = k \frac{T_2 - T_1}{\Delta x} \quad \text{(Specified heat flux boundary condition)}
\]

\[
\bar{h}(T_\infty - T_1) + \dot{q}_{c,1} \frac{\Delta x}{2} = -k \frac{T_2 - T_1}{\Delta x} \quad \text{(Known surface convection boundary condition)}
\]

**The nodal and boundary equations:**
The front boundary condition equation is as follows (Kreith, Manglik, & Bohn, 2011):

\[
T_{p+1}^1 = T_p^1 (1 - 2Fo) + 2FoT_m^1 + Fo \left[ \frac{\Delta x}{k} \varepsilon q''_{rad} + Bi(T_\infty - T_p^1) \right]
\]

where the \( T_t \) variable represents the temperature at time \( t = \{1, \ldots, 1, \ldots, n \} \) and thickness \( x = \{1, \ldots, x + 1, \ldots, n\} \). The front boundary is affected by the heat flux from the fire plus a convective cooling factor from the ambient air. To determine the Equation for the internal nodes:

\[
T_{p+1}^n = Fo(T_{p+1}^{n+1} + T_p^{n-1}) + (1 - 2Fo)T_m^i
\]

The internal nodes are calculated from an average of the surrounding nodes, because there is no heat generation in the insulation. For the back boundary condition:

\[
T_{p+1}^n = 2Fo(T_{m+1}^i + BiT_\infty) + (1 - 2Fo - 2BiFo)T_m^i
\]

The back boundary uses the equation for convection to simulate the heat transfer from the insulation to the air inside the cabinet.
**Time Step**

One important aspect of the numerical solution is the time step. If a time step is too large there will be large fluctuations in the solution that do not represent reality. If the time step is set too small then the processing power required for can be large and there is the possibility for round off error.

The process for determining the time step corresponds to the rate of conduction through the solid as compared to its Fourier number. In this case Kreith recommends setting the Fourier number at 0.5 to solve for the timestep, while using a number slightly below the calculated value. Note that the node size $dx$ is being used and that $dt$ should be smaller then $\frac{(dx)^2}{2\alpha}$.

$$dx = \frac{x}{(N-1)}$$

$$Fo = \frac{at}{dx^2} \rightarrow dt < \frac{(dx)^2}{2\alpha}$$

**Initial Conditions**

The initial conditions for the cabinet were set as at time, $t=0$; temperature, $T=T_\infty=298K$. The time step used in the calculation represents the length of time it takes for the heat to transfer through the thickness, $dx$, limited by the insulations properties. To find the time step the Fourier number is set equal to 0.45, to obey $(1 - 2Fo) \geq 0$. The Fourier number $Fo = \frac{a\Delta t}{\Delta x^2}$ where $x$ is the thickness divided by the number of nodes, $a$ is the thermal property of the material and $t$ is the time. To find the time step: $dt = \frac{(dx)^2}{a \cdot \left(\frac{45}{100}\right)}$. The chosen heat fluxes are chosen to display more data at smaller heat fluxes, $1 \frac{KW}{m^2}$ and $5 \frac{KW}{m^2}$, and the extremes $10 \frac{KW}{m^2}$ and $20 \frac{KW}{m^2}$. An emissivity of 0.3 is chosen to account for the steel cabinet casing. The heat transfer coefficients are $30 \frac{KW}{m^2}$ for the convective cooling at the front of the cabinet and $25 \frac{KW}{m^2}$ for the inside of the cabinet.

**End Conditions for Insulation effectiveness:**

The end conditions, used to define the effectiveness of the insulations, are concerned with the temperature after 30 minutes, weight and cost of the insulations chosen. The insulations that were analyzed are: extra high temperature rigid ceramic insulation; high temperature millboard insulation; and harsh-environment silica insulation all of which are rated for use over 1000°F (538°C) (see Table 1).

**Table 7: Insulation Materials and Properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Max Temp (K)</th>
<th>$K$ (W/m*K)</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>1324.816667</td>
<td>0.0493109</td>
<td>304.38</td>
<td>920</td>
</tr>
<tr>
<td>Millboard</td>
<td>1022.038889</td>
<td>0.1426492</td>
<td>945.18</td>
<td>840</td>
</tr>
<tr>
<td>Silica</td>
<td>1366.483333</td>
<td>0.1373659</td>
<td>160.2</td>
<td>800</td>
</tr>
</tbody>
</table>
The numerical solution for these equations is found by using a spreadsheet and applying the marching technique to a specified time, which was chosen to be 30 minutes (1800 seconds). The average time for a typical fire test is about 10 minutes, however a time of 30 minutes was chosen to encompass any longer tests being done.

Weight requirement:
The weight of the cabinet with all instrumentation and insulation is set to remain under 103kg (225lbs) to remain maneuverable by one person and lift-able by two people. The cabinet alone weighs 134lbs (61kg) and the instrumentation is 48lbs (22kg). This allows approximately 20lbs of insulation to be installed.

\[ \text{Weight} = SA \cdot \frac{\text{thickness(in)}}{12\text{in/foot}} \cdot \rho \]

![Graph showing Insulation Weight](image)

**Figure 27:** Weight of Insulation per thickness. The red squares represent the densest insulation, the millboard insulation; the blue diamonds represent the ceramic insulation. The green triangles represent the silica insulation.
The weight criteria, (see Table 8), suggests that the maximum allowable thickness to ensure that the cabinet is mobile is 0.25 inches for the ceramic insulation, 0.125 inches for the millboard insulation and 0.5 inches for the silica insulation. Using such thin insulation will not block nearly the same amount of heat transfer as the higher insulations.

Table 8: Maximum Insulation Thickness due to the weight criteria of the cabinet
Temperature Requirements

The temperature of the backside of the insulation will rise as long as the fire continues to grow. It is assumed that the heat insult consists of a constant heat flux. Once the heat energy is conducted through the insulation, the temperature of the back face of the can be calculated to find the time at which it stays under 45°C (113°F). This temperature was the maximum temperature chosen because it is the temperature at which human skin feels pain (SFPE, 2002). The time temperature curves for each thickness, below, show the times at which the back face of the insulation reaches 45°C (113°F).

![Protection time for specific Heat fluxes](image)

**Figure 28**: Protection time for when the back face of 1.5 inches of Ceramic, Millboard, or Silica Insulation will reach 45°C. 1.5 inches is the thickest insulation studied and the insulation protects the inside of the cabinet for up to 5 kW/m². When the cabinet is experiencing 10 kW/m² the ceramic insulation (red) while the millboard insulation gets to 45°C after 26.4 minutes and the silica (green) reaches 45°C after 4.5 minutes.

The modeled insulation effectiveness is clearly seen as the heat fluxes become higher. Ceramic insulation that is 1.5 inches (see Figure 28) thick protects the cabinet effectively in all fire environments, however when compared to the other insulations it is significantly better at
protecting the cabinet. The decrease in weight (see Figure 29) is over 150lbs for the millboard insulation, 60lbs for ceramic insulation and 30lbs for the silica insulation.

![Protection time for specific Heat fluxes](image)

**Figure 29:** Protection time for when the back face of 0.5 inches of Ceramic, Millboard, or Silica Insulation will reach 45°C (104°F). The insulation universally protects the cabinet when the heat flux is 1kW/m^2. When the heat flux is 5kW/m^2 ceramic insulation protects the cabinet until the end condition, but millboard protects the cabinet for 4.4min and the Silica protects the cabinet for 0.73 minutes. When the cabinet experiences 10kW/m^2 the ceramic insulation (red) decreases to 2.94 minutes, while the millboard insulation gets to 45°C after 2.62 minutes and the silica (green) reaches 45°C after 0.44 minutes. When a fire of 20kW/m^2 is present the protection times continue to decrease, ceramic protecting the cabinet for 1.9 min, millboard for 1.9 and silica for 0.31 min.

Looking at Figure 28, Figure 29, and Figure 30 it is clear that the protection time is dependent upon the thickness and the heat flux calculation. A 66% decrease in the insulation initially has no effect, but when higher heat fluxes are tested the insulation fails to protect the cabinet for more than a few minutes.
Figure 30: Protection time for when the back face of 0.25 inches of Ceramic, Millboard, or Silica Insulation will reach 45°C (104°F). The insulation universally protects the cabinet when the heat flux is 1kW/m². When the heat flux is 5kW/m² ceramic insulation protects the cabinet for 1.2 minutes, but millboard protects the cabinet for 0.38 minutes and the Silica protects the cabinet for 0.2 minutes. When the cabinet experiences 10kW/m² the ceramic insulation (red) decreases to 0.66 minutes, while the millboard insulation gets to 45°C after 0.23 minutes and the silica (green) reaches 45°C after 0.12 minutes. When a fire of 20kW/m² is present the protection times continue to decrease, the ceramic insulation is protecting the cabinet for 0.46 minutes, millboard for 0.2 minutes and silica for 0.1 minutes.

Using the minimum amount of insulation necessary to achieve a total cabinet weight of 103 kg (225 lbs), results in very little additional protection (see Figure 30). From experimental data received the incident heat flux was 2.5kW/m². None of the insulations analyzed are able to protect against the heat flux that would be realized in a testing environment.

The weight requirements reduce the thickness of insulation used, but since 0.25 inches of insulation is inadequate a larger more powerful cooling system is the most cost effective and weight conscience way to increase the protection factor of the cabinet. If the weight requirement permitted the addition of 0.5 in of ceramic insulation a compromise between cost, weight and protection could be achieved.
Finite Difference Results

Three different insulation thickness were tested, 1.5in (38mm), 0.5in (12.7m) and 0.25in (6.4mm). The thicker the insulation the longer the inside face of the insulation would stay below the limit of 318.15K (45°C).

Once the calculations are performed the nodal points can be graphed to make a temperature profile of the insulation (see Figure 31). The insulation acts to stop the flow of heat and therefore builds up heat on the surface this is why the surface can be almost 900K (626.85°C), while the back face is almost 400K (126.85°C)

\[ P = \frac{\text{cost}}{\text{thickness} \times \text{width} \times \text{height}} \]

Figure 31: Temperature Profile

Cost

The cost of the insulations is an indicator of the effectiveness of the insulator. Ceramic is priced higher than the other insulations, but it performs the best.
Figure 32: The price of the insulation. The pricing of the insulation follows the analysis results, with ceramic being the most protective material analyzed. Millboard and Silica being subsequent insulations in both quality of protection and price.
Energy Analysis

An energy analysis was completed to view the amount of energy at the back face of the cabinet over time. To find the energy entering the cabinet the equation below is used. Using the conductive heat transfer equation the energy that is conducted from the rear face of the insulation into the cabinet can be found. See Appendix H: Finite difference method data tables for more detailed charts.

\[
Q = \frac{h_c(T_s - T_\infty)}{A} \rightarrow Q = \frac{20}{m^2 K} \left( \frac{T_{p+1}^n T_{p+1}^n - 298K}{0.74322m^2} \right) \rightarrow Q_0 = 0
\]
**Conclusions**

In total the analysis was done with three insulations tested with 3 different thicknesses and four different heat fluxes. The range of tested insults gives a very good picture of the capabilities and limitations of the insulation.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Insulation</th>
<th>Weight</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.250</td>
<td>Ceramic</td>
<td>14.29</td>
<td>$339.13</td>
</tr>
<tr>
<td>0.500</td>
<td>Ceramic</td>
<td>28.57</td>
<td>$678.26</td>
</tr>
<tr>
<td>1.500</td>
<td>Ceramic</td>
<td>85.72</td>
<td>$1,748.10</td>
</tr>
<tr>
<td>0.125</td>
<td>Millboard</td>
<td>22.18</td>
<td>$118.06</td>
</tr>
<tr>
<td>0.500</td>
<td>Millboard</td>
<td>88.73</td>
<td>$345.82</td>
</tr>
<tr>
<td>1.500</td>
<td>Millboard</td>
<td>266.19</td>
<td>$1,037.45</td>
</tr>
<tr>
<td>0.250</td>
<td>Silica</td>
<td>7.52</td>
<td>$45.20</td>
</tr>
<tr>
<td>0.500</td>
<td>Silica</td>
<td>15.04</td>
<td>$82.14</td>
</tr>
<tr>
<td>1.500</td>
<td>Silica</td>
<td>45.12</td>
<td>$246.43</td>
</tr>
</tbody>
</table>

**Table 9: Insulation options**

To choose an insulation there are several key factors including protection value, cost and weight. To decide the most appropriate insulation for the cabinet, first decide what the maximum heat flux necessary to protect against is.

Following the boundary conditions the minimum thickness of insulation were determined (see Table 10). The minimum amount of insulation will ensure that the cabinet remains at approximately 103 kg (225 lbs), while providing a modicum of protection.

<table>
<thead>
<tr>
<th>Heatflux (kW/m^2)</th>
<th>Insulation Material</th>
<th>Thickness (in.)</th>
<th>Time (min)</th>
<th>Weight (lbs)</th>
<th>Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ceramic</td>
<td>0.250</td>
<td>30.00</td>
<td>14.29</td>
<td>$339.13</td>
</tr>
<tr>
<td>5</td>
<td>Ceramic</td>
<td>0.250</td>
<td>1.18</td>
<td>14.29</td>
<td>$339.13</td>
</tr>
<tr>
<td>10</td>
<td>Ceramic</td>
<td>0.250</td>
<td>0.66</td>
<td>14.29</td>
<td>$339.13</td>
</tr>
<tr>
<td>20</td>
<td>Ceramic</td>
<td>0.250</td>
<td>0.46</td>
<td>14.29</td>
<td>$339.13</td>
</tr>
<tr>
<td>1</td>
<td>Millboard</td>
<td>0.125</td>
<td>30.00</td>
<td>22.18</td>
<td>$118.06</td>
</tr>
<tr>
<td>5</td>
<td>Millboard</td>
<td>0.125</td>
<td>0.38</td>
<td>22.18</td>
<td>$118.06</td>
</tr>
<tr>
<td>10</td>
<td>Millboard</td>
<td>0.125</td>
<td>0.23</td>
<td>22.18</td>
<td>$118.06</td>
</tr>
<tr>
<td>20</td>
<td>Millboard</td>
<td>0.125</td>
<td>0.16</td>
<td>22.18</td>
<td>$118.06</td>
</tr>
<tr>
<td>1</td>
<td>Silica</td>
<td>0.250</td>
<td>30.00</td>
<td>7.52</td>
<td>$45.20</td>
</tr>
<tr>
<td>5</td>
<td>Silica</td>
<td>0.250</td>
<td>0.20</td>
<td>7.52</td>
<td>$45.20</td>
</tr>
<tr>
<td>10</td>
<td>Silica</td>
<td>0.125</td>
<td>0.12</td>
<td>7.52</td>
<td>$45.20</td>
</tr>
<tr>
<td>20</td>
<td>Silica</td>
<td>0.250</td>
<td>0.09</td>
<td>7.52</td>
<td>$45.20</td>
</tr>
</tbody>
</table>

**Table 10: Minimum insulation values and**

G-14
Appendix H: Finite difference method data tables
Finite Difference Results

Results Tables:

<table>
<thead>
<tr>
<th>Q=1kw/m^2; max Insulation; no Weight restriction; no cost restriction</th>
<th>Price/1.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>308.25</td>
<td>1748.095336</td>
<td>85.72265625</td>
<td>30</td>
<td>1.5</td>
</tr>
<tr>
<td>Millboard</td>
<td>303.6</td>
<td>1037.449704</td>
<td>266.1914063</td>
<td>30</td>
<td>1.5</td>
</tr>
<tr>
<td>Silica</td>
<td>99</td>
<td>246.4331897</td>
<td>45.1171875</td>
<td>30</td>
<td>1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q=5kw/m^2; max Insulation; no Weight restriction; no cost restriction</th>
<th>Price/1.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>308.25</td>
<td>1748.095336</td>
<td>85.72265625</td>
<td>30</td>
<td>1.5</td>
</tr>
<tr>
<td>Millboard</td>
<td>303.6</td>
<td>1037.449704</td>
<td>266.1914063</td>
<td>30</td>
<td>1.5</td>
</tr>
<tr>
<td>Silica</td>
<td>99</td>
<td>246.4331897</td>
<td>45.1171875</td>
<td>30</td>
<td>1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q=10kw/m^2; max Insulation; no Weight restriction; no cost restriction</th>
<th>Price/1.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>308.25</td>
<td>1748.095336</td>
<td>85.72265625</td>
<td>30</td>
<td>1.5</td>
</tr>
<tr>
<td>Millboard</td>
<td>303.6</td>
<td>1037.449704</td>
<td>266.1914063</td>
<td>26.3706372</td>
<td>1.5</td>
</tr>
<tr>
<td>Silica</td>
<td>99</td>
<td>246.4331897</td>
<td>45.1171875</td>
<td>4.48087216</td>
<td>1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q=20kw/m^2; max Insulation; no Weight restriction; no cost restriction</th>
<th>Price/0.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>119.6</td>
<td>678.2553191</td>
<td>28.57421875</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>Millboard</td>
<td>101.2</td>
<td>345.816568</td>
<td>88.73046875</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>Silica</td>
<td>33</td>
<td>82.14439655</td>
<td>15.0390625</td>
<td>30</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q=1kw/m^2; Thickness=0.5in; no Weight restriction; no cost restriction</th>
<th>Price/0.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>119.6</td>
<td>678.2553191</td>
<td>28.57421875</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>Millboard</td>
<td>101.2</td>
<td>345.816568</td>
<td>88.73046875</td>
<td>4.36308357</td>
<td>0.5</td>
</tr>
<tr>
<td>Silica</td>
<td>33</td>
<td>82.14439655</td>
<td>15.0390625</td>
<td>0.73272123</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q=5kw/m^2; Thickness=0.5in; no Weight restriction; no cost restriction</th>
<th>Price/0.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>119.6</td>
<td>678.2553191</td>
<td>28.57421875</td>
<td>2.94060471</td>
<td>0.5</td>
</tr>
</tbody>
</table>

H-2
<table>
<thead>
<tr>
<th>Material</th>
<th>Price/0.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millboard</td>
<td>101.2</td>
<td>345.816568</td>
<td>88.73046875</td>
<td>2.61785014</td>
<td>0.5</td>
</tr>
<tr>
<td>Silica</td>
<td>33</td>
<td>82.14439655</td>
<td>15.0390625</td>
<td>0.43748557</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Q=20kw/m^2; Thickness=0.5in; no Weight restriction; no cost restriction
<table>
<thead>
<tr>
<th>Material</th>
<th>Price/1.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>119.6</td>
<td>678.2553191</td>
<td>28.57421875</td>
<td>1.87055133</td>
<td>0.5</td>
</tr>
<tr>
<td>Millboard</td>
<td>101.2</td>
<td>345.816568</td>
<td>88.73046875</td>
<td>1.85731264</td>
<td>0.5</td>
</tr>
<tr>
<td>Silica</td>
<td>33</td>
<td>82.14439655</td>
<td>15.0390625</td>
<td>0.31268141</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Q=1kw/m^2; Minimum; no Weight restriction; no cost restriction
<table>
<thead>
<tr>
<th>Material</th>
<th>Price/1.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>59.8</td>
<td>339.1276596</td>
<td>14.28710938</td>
<td>30</td>
<td>0.25</td>
</tr>
<tr>
<td>Millboard</td>
<td>34.55</td>
<td>118.0628698</td>
<td>22.18261719</td>
<td>30</td>
<td>0.125</td>
</tr>
<tr>
<td>Silica</td>
<td>18.16</td>
<td>45.20431034</td>
<td>7.51953125</td>
<td>30</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Q=5kw/m^2; Minimum; no Weight restriction; no cost restriction
<table>
<thead>
<tr>
<th>Material</th>
<th>Price/1.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>59.8</td>
<td>339.1276596</td>
<td>14.28710938</td>
<td>1.17624188</td>
<td>0.25</td>
</tr>
<tr>
<td>Millboard</td>
<td>34.55</td>
<td>118.0628698</td>
<td>22.18261719</td>
<td>0.38427158</td>
<td>0.125</td>
</tr>
<tr>
<td>Silica</td>
<td>18.16</td>
<td>45.20431034</td>
<td>7.51953125</td>
<td>0.19827759</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Q=10kw/m^2; Minimum; no Weight restriction; no cost restriction
<table>
<thead>
<tr>
<th>Material</th>
<th>Price/1.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>59.8</td>
<td>339.1276596</td>
<td>14.28710938</td>
<td>0.6555098</td>
<td>0.25</td>
</tr>
<tr>
<td>Millboard</td>
<td>34.55</td>
<td>118.0628698</td>
<td>22.18261719</td>
<td>0.23416549</td>
<td>0.125</td>
</tr>
<tr>
<td>Silica</td>
<td>18.16</td>
<td>45.20431034</td>
<td>7.51953125</td>
<td>0.12346219</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Q=20kw/m^2; Minimum; no Weight restriction; no cost restriction
<table>
<thead>
<tr>
<th>Material</th>
<th>Price/1.5&quot;</th>
<th>TotalCost</th>
<th>Weight (lbs)</th>
<th>Time (min)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>59.8</td>
<td>339.1276596</td>
<td>14.28710938</td>
<td>0.4574274</td>
<td>0.25</td>
</tr>
<tr>
<td>Millboard</td>
<td>34.55</td>
<td>118.0628698</td>
<td>22.18261719</td>
<td>0.16211457</td>
<td>0.125</td>
</tr>
<tr>
<td>Silica</td>
<td>18.16</td>
<td>45.20431034</td>
<td>7.51953125</td>
<td>0.08789971</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Results by heatflux:

<table>
<thead>
<tr>
<th>Heatflux (kW/m^2)</th>
<th>Insulation Material</th>
<th>Thickness (in.)</th>
<th>Time (min)</th>
<th>Weight (lbs)</th>
<th>Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Millboard</td>
<td>0.125</td>
<td>30.00</td>
<td>22.18261719</td>
<td>$118.06</td>
</tr>
<tr>
<td>1</td>
<td>Ceramic</td>
<td>0.25</td>
<td>30.00</td>
<td>14.28710938</td>
<td>$339.13</td>
</tr>
<tr>
<td>1</td>
<td>Silica</td>
<td>0.25</td>
<td>30.00</td>
<td>7.51953125</td>
<td>$45.20</td>
</tr>
<tr>
<td>1</td>
<td>Ceramic</td>
<td>0.5</td>
<td>30.00</td>
<td>28.57421875</td>
<td>$678.26</td>
</tr>
<tr>
<td>1</td>
<td>Millboard</td>
<td>0.5</td>
<td>30.00</td>
<td>88.73046875</td>
<td>$345.82</td>
</tr>
<tr>
<td>1</td>
<td>Silica</td>
<td>0.5</td>
<td>30.00</td>
<td>15.0390625</td>
<td>$82.14</td>
</tr>
<tr>
<td>1</td>
<td>Ceramic</td>
<td>1.5</td>
<td>30.00</td>
<td>85.72265625</td>
<td>$1,748.10</td>
</tr>
<tr>
<td>1</td>
<td>Millboard</td>
<td>1.5</td>
<td>30.00</td>
<td>266.1914063</td>
<td>$1,037.45</td>
</tr>
<tr>
<td>1</td>
<td>Silica</td>
<td>1.5</td>
<td>30.00</td>
<td>45.1171875</td>
<td>$246.43</td>
</tr>
<tr>
<td>5</td>
<td>Millboard</td>
<td>0.125</td>
<td>0.38</td>
<td>22.18261719</td>
<td>$118.06</td>
</tr>
<tr>
<td>5</td>
<td>Ceramic</td>
<td>0.25</td>
<td>1.18</td>
<td>14.28710938</td>
<td>$339.13</td>
</tr>
<tr>
<td>5</td>
<td>Silica</td>
<td>0.25</td>
<td>0.20</td>
<td>7.51953125</td>
<td>$45.20</td>
</tr>
<tr>
<td>5</td>
<td>Ceramic</td>
<td>0.5</td>
<td>30.00</td>
<td>28.57421875</td>
<td>$678.26</td>
</tr>
<tr>
<td>5</td>
<td>Millboard</td>
<td>0.5</td>
<td>4.36</td>
<td>88.73046875</td>
<td>$345.82</td>
</tr>
<tr>
<td>5</td>
<td>Silica</td>
<td>0.5</td>
<td>0.73</td>
<td>15.0390625</td>
<td>$82.14</td>
</tr>
<tr>
<td>5</td>
<td>Ceramic</td>
<td>1.5</td>
<td>30.00</td>
<td>85.72265625</td>
<td>$1,748.10</td>
</tr>
<tr>
<td>5</td>
<td>Millboard</td>
<td>1.5</td>
<td>30.00</td>
<td>266.1914063</td>
<td>$1,037.45</td>
</tr>
<tr>
<td>5</td>
<td>Silica</td>
<td>1.5</td>
<td>30.00</td>
<td>45.1171875</td>
<td>$246.43</td>
</tr>
<tr>
<td>10</td>
<td>Millboard</td>
<td>0.125</td>
<td>0.23</td>
<td>22.18261719</td>
<td>$118.06</td>
</tr>
<tr>
<td>10</td>
<td>Ceramic</td>
<td>0.25</td>
<td>0.66</td>
<td>14.28710938</td>
<td>$339.13</td>
</tr>
<tr>
<td>10</td>
<td>Silica</td>
<td>0.25</td>
<td>0.12</td>
<td>7.51953125</td>
<td>$45.20</td>
</tr>
<tr>
<td>10</td>
<td>Ceramic</td>
<td>0.5</td>
<td>2.94</td>
<td>28.57421875</td>
<td>$678.26</td>
</tr>
<tr>
<td>10</td>
<td>Millboard</td>
<td>0.5</td>
<td>2.62</td>
<td>88.73046875</td>
<td>$345.82</td>
</tr>
<tr>
<td>10</td>
<td>Silica</td>
<td>0.5</td>
<td>0.44</td>
<td>15.0390625</td>
<td>$82.14</td>
</tr>
<tr>
<td>10</td>
<td>Ceramic</td>
<td>1.5</td>
<td>30.00</td>
<td>85.72265625</td>
<td>$1,748.10</td>
</tr>
<tr>
<td>10</td>
<td>Millboard</td>
<td>1.5</td>
<td>26.37</td>
<td>266.1914063</td>
<td>$1,037.45</td>
</tr>
<tr>
<td>10</td>
<td>Silica</td>
<td>1.5</td>
<td>4.48</td>
<td>45.1171875</td>
<td>$246.43</td>
</tr>
<tr>
<td>20</td>
<td>Millboard</td>
<td>0.125</td>
<td>0.16</td>
<td>22.18261719</td>
<td>$118.06</td>
</tr>
<tr>
<td>20</td>
<td>Ceramic</td>
<td>0.25</td>
<td>0.46</td>
<td>14.28710938</td>
<td>$339.13</td>
</tr>
<tr>
<td>20</td>
<td>Silica</td>
<td>0.25</td>
<td>0.09</td>
<td>7.51953125</td>
<td>$45.20</td>
</tr>
<tr>
<td>20</td>
<td>Ceramic</td>
<td>0.5</td>
<td>1.87</td>
<td>28.57421875</td>
<td>$678.26</td>
</tr>
<tr>
<td>20</td>
<td>Millboard</td>
<td>0.5</td>
<td>1.86</td>
<td>88.73046875</td>
<td>$345.82</td>
</tr>
<tr>
<td>20</td>
<td>Silica</td>
<td>0.5</td>
<td>0.31</td>
<td>15.0390625</td>
<td>$82.14</td>
</tr>
<tr>
<td>20</td>
<td>Ceramic</td>
<td>1.5</td>
<td>26.47</td>
<td>85.72265625</td>
<td>$1,748.10</td>
</tr>
<tr>
<td>20</td>
<td>Millboard</td>
<td>1.5</td>
<td>16.57</td>
<td>266.1914063</td>
<td>$1,037.45</td>
</tr>
<tr>
<td>20</td>
<td>Silica</td>
<td>1.5</td>
<td>2.79</td>
<td>45.1171875</td>
<td>$246.43</td>
</tr>
</tbody>
</table>
Figure 39: Weight of the Insulation for the thicknesses tested

Figure 40: Insulation Protection with heat flux equal to 20 kw/m^2
Figure 41: Cost of the insulation per thickness:
Protection Time for insulation:

![Protection time for specific Heat fluxes (Ceramic Insulation)](image)

- Ceramic 1.5
- Ceramic 0.5
- Ceramic 0.25
Protection time for specific Heat fluxes (Millboard Insulation)

- Millboard 1.5
- Millboard 0.5
- Millboard 0.125

Heat Flux (kW/m²)

Time (min)
Protection time for specific Heat fluxes
(Silica Insulation)

- Silica 1.5
- Silica 0.5
- Silica 0.25

Heat Flux (kW/m²)

Time (min)
Protection Time for each thickness of insulation

Protection time for specific Heat fluxes
(1.5in insulation)

<table>
<thead>
<tr>
<th>Heat Flux (kW/m²)</th>
<th>Ceramic</th>
<th>Millboard</th>
<th>Silica</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>
Protection time for specific Heat fluxes
(0.5in insulation)

- Ceramic 0.5
- Millboard 0.5
- Silica 0.5

Heat Flux (kW/m$^2$)

Time (min)
Protection time for specific Heat fluxes
(0.25in insulation)

Heat Flux (kW/m²)

Time (min)

Ceramic
Millboard
Silica
Energy Analysis:

Energy through Insulation for Ceramic Insulation

**Energy into Cabinet (Ceramic, 1kw/m^2)**

- Ceramic 1kW 0.25
- Ceramic 1kW 0.5
- Ceramic 1kW 1.5

**Energy into Cabinet (Ceramic, 5kw/m^2)**

- Ceramic 5kW 0.25
- Ceramic 5kW 0.5
- Ceramic 5kW 1.5
Energy into Millboard Insulation

Energy into Cabinet (Millboard, 1kw/m²)

Energy into Cabinet (Millboard, 5kw/m²)
Energy into Cabinet (Millboard, 10kw/m^2)

Energy into Cabinet (Millboard, 20kw/m^2)
Energy into Silica Insulation

Energy into Cabinet (Silica, 1kw/m^2)

Energy into Cabinet (Silica, 5kw/m^2)
Silica 1.50 in

- $h = 25 \text{ W/m}^2\text{K}$
- $L_i = 1.5 \text{ in} = 0.0381 \text{ meters}$
- $T_{i0} = 297 \text{ K}$
- $T_{inf} = 297 \text{ K}$
- $t = 1800 \text{ sec} = 2483.891$
- $q_{tot} = 30 \text{ W/m}^2\text{K}$

- $\alpha = 1.1E-06 \text{ m}^2/\text{s}$
- $\text{Bi} = 6.93403$
- $\text{Fo} = 0.45$
- $\Delta x = 0.00131$
- $\Delta t = 0.72467$

Silica 0.5 in

- $h = 25 \text{ W/m}^2\text{K}$
- $L_i = 0.5 \text{ in} = 0.0127 \text{ meters}$
- $T_{i0} = 297 \text{ K}$
- $T_{inf} = 297 \text{ K}$
- $t = 1800 \text{ sec} = 2235.02$
- $q_{tot} = 30 \text{ W/m}^2\text{K}$

- $\alpha = 1.1E-06 \text{ m}^2/\text{s}$
- $\text{Bi} = 2.31134$
- $\text{Fo} = 0.45$
- $\Delta x = 0.00044$
- $\Delta t = 0.08052$

H-19
### Silica 0.25 in

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>25 W/m$^2$K</td>
</tr>
<tr>
<td>$L_i$</td>
<td>0.25 in 0.00635 meters</td>
</tr>
<tr>
<td>$T_0$</td>
<td>297 K</td>
</tr>
<tr>
<td>$T_{\text{inf}}$</td>
<td>297 K</td>
</tr>
<tr>
<td>time</td>
<td>1800 sec 89420.09</td>
</tr>
<tr>
<td>heat flux</td>
<td>1000 W/m$^2$</td>
</tr>
<tr>
<td>N</td>
<td>30</td>
</tr>
<tr>
<td>$q_{\text{tot}}$</td>
<td>30 W/m$^2$K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constants</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>1.1E-06 m$^2$/s</td>
</tr>
<tr>
<td>Biot</td>
<td>1.15567</td>
</tr>
<tr>
<td>Fourier</td>
<td>0.45</td>
</tr>
<tr>
<td>$dx$</td>
<td>0.00022</td>
</tr>
<tr>
<td>$dt$</td>
<td>0.02013 0.022366</td>
</tr>
</tbody>
</table>

### Millboard 1.50 in

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>25 W/m$^2$K</td>
</tr>
<tr>
<td>$L_i$</td>
<td>1.5 in 0.0381 meters</td>
</tr>
<tr>
<td>$T_0$</td>
<td>297 K</td>
</tr>
<tr>
<td>$T_{\text{inf}}$</td>
<td>297 K</td>
</tr>
<tr>
<td>time</td>
<td>1800 sec 416.3722</td>
</tr>
<tr>
<td>heat flux</td>
<td>1000 W/m$^2$</td>
</tr>
<tr>
<td>N</td>
<td>30</td>
</tr>
<tr>
<td>$h_{\text{tot}}$</td>
<td>30 W/m$^2$K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constants</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>1.8E-07 m$^2$/s</td>
</tr>
<tr>
<td>Biot</td>
<td>6.67722</td>
</tr>
<tr>
<td>Fourier</td>
<td>0.45</td>
</tr>
<tr>
<td>$dx$</td>
<td>0.00131</td>
</tr>
<tr>
<td>$dt$</td>
<td>4.32306 4.803395</td>
</tr>
</tbody>
</table>

H-20
Millboard 0.5 in

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>25 W/m²*K</td>
</tr>
<tr>
<td>$L_i$</td>
<td>0.5 in 0.0127 meters</td>
</tr>
<tr>
<td>$T_0$</td>
<td>297 K</td>
</tr>
<tr>
<td>$T_{\text{inf}}$</td>
<td>297 K</td>
</tr>
<tr>
<td>time</td>
<td>1800 sec 3747.35</td>
</tr>
<tr>
<td>heat flux</td>
<td>1000 W/m²</td>
</tr>
<tr>
<td>$N$</td>
<td>30</td>
</tr>
<tr>
<td>$h_{\text{tot}}$</td>
<td>30 W/m²*K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$1.8 \times 10^{-7}$ m²/s</td>
</tr>
<tr>
<td>Biot</td>
<td>2.22574</td>
</tr>
<tr>
<td>Fourier</td>
<td>0.45</td>
</tr>
<tr>
<td>$dx$</td>
<td>0.00044</td>
</tr>
<tr>
<td>$dt$</td>
<td>0.48034 0.533711</td>
</tr>
</tbody>
</table>

Millboard 0.125 in

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>25 W/m²*K</td>
</tr>
<tr>
<td>$L_i$</td>
<td>0.125 in 0.003175 meters</td>
</tr>
<tr>
<td>$T_0$</td>
<td>297 K</td>
</tr>
<tr>
<td>$T_{\text{inf}}$</td>
<td>297 K</td>
</tr>
<tr>
<td>time</td>
<td>1800 sec 59957.6</td>
</tr>
<tr>
<td>heat flux</td>
<td>1000 W/m²</td>
</tr>
<tr>
<td>$N$</td>
<td>30</td>
</tr>
<tr>
<td>$h_{\text{tot}}$</td>
<td>30 W/m²*K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$1.8 \times 10^{-7}$ m²/s</td>
</tr>
<tr>
<td>Biot</td>
<td>0.55643</td>
</tr>
<tr>
<td>Fourier</td>
<td>0.45</td>
</tr>
<tr>
<td>$dx$</td>
<td>0.00011</td>
</tr>
<tr>
<td>$dt$</td>
<td>0.03002 0.033357</td>
</tr>
</tbody>
</table>
Ceramic 1.50 in

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>25</td>
<td>W/m²*K</td>
</tr>
<tr>
<td>Li</td>
<td>1.5</td>
<td>in</td>
</tr>
<tr>
<td>T_0</td>
<td>297</td>
<td>K</td>
</tr>
<tr>
<td>T_inf</td>
<td>297</td>
<td>K</td>
</tr>
<tr>
<td>time</td>
<td>1800</td>
<td>sec</td>
</tr>
<tr>
<td>heat flux</td>
<td>1000</td>
<td>W/m²</td>
</tr>
<tr>
<td>N</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>h_tot</td>
<td>30</td>
<td>W/m²*K</td>
</tr>
</tbody>
</table>

Alpha: 1.8E-07 m²/s
Biot: 19.3162
Fourier: 0.45
dx: 0.00131
dt: 4.41091 4.901008

Ceramic 0.5 in

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>25</td>
<td>W/m²*K</td>
</tr>
<tr>
<td>Li</td>
<td>0.5</td>
<td>in</td>
</tr>
<tr>
<td>T_0</td>
<td>297</td>
<td>K</td>
</tr>
<tr>
<td>T_inf</td>
<td>297</td>
<td>K</td>
</tr>
<tr>
<td>time</td>
<td>1800</td>
<td>sec</td>
</tr>
<tr>
<td>heat flux</td>
<td>1000</td>
<td>W/m²</td>
</tr>
<tr>
<td>N</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>h_tot</td>
<td>30</td>
<td>W/m²*K</td>
</tr>
</tbody>
</table>

Alpha: 1.8E-07 m²/s
Biot: 6.43875
Fourier: 0.45
dx: 0.00044
dt: 0.4901 0.544556

H-22
Ceramic 0.25 inches

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>25 W/m²*K</td>
</tr>
<tr>
<td>$L_i$</td>
<td>0.25 in, 0.00635 meters</td>
</tr>
<tr>
<td>$T_0$</td>
<td>297 K</td>
</tr>
<tr>
<td>$T_{inf}$</td>
<td>297 K</td>
</tr>
<tr>
<td>time</td>
<td>1800 sec, 14690.86</td>
</tr>
<tr>
<td>heat flux</td>
<td>1000 W/m²</td>
</tr>
<tr>
<td>$N$</td>
<td>30</td>
</tr>
<tr>
<td>$h_{tot}$</td>
<td>30 W/m²*K</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1.8E-07 m²/s</td>
</tr>
<tr>
<td>Biot</td>
<td>3.21937</td>
</tr>
<tr>
<td>Fourier</td>
<td>0.45</td>
</tr>
<tr>
<td>$dx$</td>
<td>0.00022</td>
</tr>
<tr>
<td>$dt$</td>
<td>0.12253, 0.136139</td>
</tr>
</tbody>
</table>


- 20kW/m^2

- Time (min)
- Cost (USD)

- Ceramic 0.25in
- Ceramic 0.5in
- Millboard 0.25in
- Millboard 0.5in
- Silica 0.25in
- Silica 1.5in
- Silica 1.5in
Appendix I: Hood detailed design
Hood
The hood is the first part of the system that interacts with any part of the fire. It is designed to collect all of the fire products. The hood must be large enough that none of the fire products will escape, but small enough to prevent excessive entrainment.

Several challenges presented themselves in the design of the hood including the:

- mobility
- size
- construction materials
- modular or fixed (ability to be disassembled)
- number of hoods

Ultimately the decision to have two hoods was a result of the vast differences in the capabilities of each building. Building 3 features open testing that has large ceilings and more space for the hood to be placed.

Design Calculations:
To find the correct size of the hood it is important to analyze the properties of the fire to verify the design. Using the design criteria of a 1-3MW fire we can determine the entrainment rate.


In Section 4.3.1 of “An introduction to fire dynamics”, it tells about the buoyant plume, which fits the purpose of my calculation. The mathematical model of the simple buoyant plume is based on a point source by Heskestad,

\[
\frac{z_0}{D} = -1.02 + 0.083 \frac{\dot{Q}_c^{2/5}}{D}
\]

Where \(z_0\) is the height of the virtual origin point from the fire source, \(\dot{Q}_c\) is the heat release rate of the fire and D is the diameter of the fire on ground. \(z_0=0.96m\).

In the book, the parameter \(\frac{\Delta T_0}{T_\infty}\), which is a qualitatively judgment of the fire plume. If \(\frac{\Delta T_0}{T_\infty} \ll 1\), the plume is considered to be weak. Otherwise, it is strong. \(\Delta T_0\) is the temperature excess over ambient on the axis at height z and \(T_\infty\) is the ambient air temperature. Beyler recommends the following expression for the centerline temperature rise at height z:

\[
\Delta T_0 = 22 \frac{\dot{Q}_c^{2/3}}{z^{5/3}}
\]
In the supposed fire test, $\dot{Q}_c=1000\text{kW}$, $z$ ranges from 3.4m to 4m, and $T_\infty$ is 300K. The calculation shows that $\frac{\Delta T_0}{T_\infty}$ ranges from 1.1 to 1.8, i.e. it is proper to assume the plume is a strong one. Thus, we use the following equation to calculate the mass flow rate by Heskestad:

$$\dot{m}_{\text{ent}} = E \left( \frac{g \rho_\infty^2}{c_p T_\infty} \right)^{1/3} \dot{Q}_c^1 (z - z_0)^{5/3} \left[ 1 + \frac{G \dot{Q}_c^{2/3}}{(g^{1/2} c_p \rho_\infty T_\infty)^{2/3} (z - z_0)^{5/3}} \right]$$

Where $E=0.196$ and $G=2.9$, $\rho_\infty$ is the density of ambient air.

The flame height above the fuel surface $l$ can be calculated with the following equation,

$$l = 0.23 \dot{Q}_c^{2/5} - 1.02D$$

Which is very satisfactory in the range $7 < \frac{\dot{Q}_c^{2/5}}{D} < 700 \text{kW}^{2/5}/\text{m}$. The test area is supposed to be 1ft x 1ft square. The equivalent diameter is 0.344m. So $\frac{\dot{Q}_c^{2/5}}{D} \approx 46$, so we can get $l$ from the above equation. $l=3.29\text{m}$.

The mass flow rate under the flame tip is proportional to $z$.

**Building 3**

The design of the hood was assisted by ASTM E2067, which is the standard practice for full-scale oxygen consumption calorimetry fire tests. The size of the hood needed for a medium scale test offers an opening area of 8 feet x 8 feet (2.4 m x 2.4 m) and depth of 3.3 feet (1m). Depending on the scenario there is a removable skirt on the hood (3.3 feet (1m)) to contain any additional fire products if necessary.

**Materials**

The materials used for the construction of the hood are required to be both chemically and heat resistant to avoid damage from the fire and lightweight to improve maneuverability. Using an aluminum exoskeleton and low gauge galvanized steel sheets allows for a low weight and strong construction.

**Plenum**

The hood attaches to the duct work by means of a plenum. This component is essential for the design because it connects the hood to the duct. The plenum is essential a 3 ft x 3ft x 3ft (1m x 1m x 1m) cube with an opening into the hood and an opening that goes to the duct.

To increase the maneuverability and the mobility of the hood this part is essential for small scale adjustments. The ducting will be coming from different heights and angles depending on the location of the hood; therefore a ball joint like manufactured by Norfab (Norfab, 2012) is necessary to ensure that the duct can attach to the plenum even if it is off of center. The other option is to manufacture something in house.
Hood Mobility

The mobility of the hood in building 3 is imperative to me able to use it in test areas C and E. Unfortunately, the size and weight of the hood limits its mobility. The hood has to be at least 10 feet (3m) off the ground to simulate the height of a typical room. The clearest solution is to put the hood on wheels.

Pallet racks are able to manage heavy loads and they are adjustable to different heights. The approximate weight of the hood is 350.0lbs (160.0kg) plus the weight of the duct (650lbs (300kg)) (TAMBE, 2012) requires the extra heavy duty storage racks (McMaster-Carr (5217T14), 2012) and the Brute Casters (McMaster (2293T32), 2012). These products have been selected not only because of the weight requirements, but also their properties to resist structural damage from the fire; however, it is recommended that a vermiculite fiberglass blanket is used to protect the structure.

Building 2A:
The design of the hood for building 2A differed slightly from the design of the hood for building 3 because of the space limitation for the hood. Test area A is designed to complete residential compartment fires, thus the roof is too low to handle a hood or duct system large enough to collect...
all of the fire products. Placing the hood outside the person door allows for the hood to have enough height to collect the volume of fire products being released.

The width available for the hood in building 2A only allows for a hood width of 5.25 feet (1.6m). While the rest of the design parameters have no size limitations the person door will be 36 inches (0.9m) and the hood is maximized for volume. The final design selected a hood volume of 42 ft$^3$ (1.2 m$^3$). This design keeps the hood large enough to collect the fire products while keeping the weight down.

The design constraints require that the hood is rectangular whereas most hoods are square or round to retain symmetry.

Materials
The hood will be made in house out of the same galvanized steel and extruded aluminum support material as the hood in building 3. The weight is approximately 650 lbs (300kg), which will not be as much of an issue to support because the hood can be attached to the compartment and the building wall.

Plenum
The plenum for hood in test area A does not need to be maneuverable.

Mobility
The hood does not necessarily need to be moved within building 2A, however the hood structure can be disassembled for storage when not in use. To ensure easy assembly and disassembly extruded aluminum will be cut in to the desired dimensions for the hood (listed above) with the steel sheet being bolted to those. The construction of the hood will cause gaps in steel sheets that must be patched with steel or aluminum tape to ensure a smooth surface for the smoke to travel over.

Weight
To calculate the weight of the hood we may first define the area of the material needed.

The existing plenum has dimensions 3ft by 3ft by 3ft with one side missing from the bottom and a circle with a radius of 2ft missing from one of the plates. Inside the plenum there are also 2 plates that scramble flow that are 0.5m by 3ft.

$$A_{plenum} = 5 \times 0.9144m \times 0.9144m - \frac{(0.6096m)^2 \cdot \pi}{4} = 4.7888m^2$$

To find the area of the hood, we must first find the height of each of the plates.

$$\sqrt{(0.72m)^2 + (1m)^2} = 1.2322m$$

To find the area of the trapezoidal shapes:
And assuming all of these have a thickness of 2mm:

$$(4.7888m^2 + 8.47m^2) \times (0.002m) = 0.0265m^3$$

And assuming a density of Steel of 7900kg/m$^3$

$$0.0265m^3 \times 7900\frac{kg}{m^3} = 209.49kg$$

Supporting the entire hood with an extruded aluminum skeleton would add:

$$4 \times 2.44m + 12 \times .9144m + 4 \times 1.427m = 26.441m$$

Which comes just short of 87 feet of skeleton.

And assuming the cross section of the extruded aluminum is 0.8 square inches for the 1.5” x 1.5” extrusions. And with the density of Aluminum as

$$\frac{12 \text{ in}}{ft} \times 87\text{ ft} \times 0.8\text{ in}^2 = 5.8\text{ ft}^2 \quad \rightarrow \quad \frac{169 \text{ lb}}{\text{ft}^3} \times 5.8\text{ ft}^3 = 978\text{ lbs}$$

Converting that to SI we have 443.6kg.

All in total we have 654kg (1442lbs) for the structural members.
Appendix J:  Duct detailed design
Duct
The duct is the next significant portion of the fire products collector. The theoretical fire products collector requires that the fluid flow at the probes section be fully mixed which theoretically happens at an infinite length of duct. ASTM suggests in their design process that typically the measurement of length over diameter of duct is used as a metric with values ranging from 8 to 20 duct diameters (ASTM, 2008).

**Mobility:**
The duct work is 40 feet (12m) long and 24 inches (610mm) wide and weights about 15lbs (6.8kg) for every foot, therefore the duct work is considered stationary. Using sections of duct to move around would take more time then would be convenient.

**Materials**
The materials used in the duct have the same requirements of non-reactivity and heat resistance as the hood has. In addition, at the probes the fire products should be fully mixed and turbulent to ensure the necessary randomness required for comparable data.

**Design Calculations**
To determine the turbulence at a certain length the Reynolds number is used, which is a relationship between the inertial forces and the viscous forces on the fluid. To determine the Reynolds number at a certain diameter of duct use:

\[
Re = \frac{\nu D_h}{V}
\]

, where \(\nu\)=the kinematic viscosity, \(D_h\)=the hydraulic diameter and \(V\)=the velocity (NASA, 2009). When the Reynolds number is calculated to be greater than 4000 the flow is considered turbulent (Engineering Toolbox, 2012). To find the entrance length that a turbulent flow corresponds to the following equation can be used (Engineering Toolbox, 2012):

\[
(E_i)_{turbulent} = 4.4 Re^{1/6}
\]

Using this equation and the Reynolds number for turbulent flow the entrance length number \(\frac{ENTRANCE\ LENTH}{DUCT\ DIAMTER}\) can be found. In turn the entrance length is the entrance length number times the diameter of the duct or:

\[
l_{entrance} = (E_i)_{turbulent} d
\]

An important variable in determining the flow characteristics is the velocity found by using the equation (ASTM, 2008):

\[
\dot{m}_e = 26.54 \frac{Ak_e}{f(Re)} \frac{\Delta P}{T_e}
\]
This equation is used to find the results of the flow rate after the from the tests however the initial flow can be determined using standard values.

**Building 3**

**Size**
The diameter of the duct designed is 24 inches (610mm) and the length of the duct is 40 feet (12m). This size duct is considered to be large enough to manage a 3 MW fire, but calculations are based on the velocity of the flow, which intern depends on the fire and the blower used.

The weight should be minimized to increase the mobility of the system.

**Placement**
The duct will be place on the ceiling of building 3, however the ceiling is X feet (x m) high. To get the duct down to the level of the hood a clevis hanger designed to pivot 15° is capable of lowering the duct about 10 feet (3m) (Erico (179436), 2012). The other option is to design a clevis at Tyco.

An in house clevis or similar would improve the cost of such a device and functionality could be added to the device. Drawing from the design of the clevis, two screws can be placed in the sides of the ducting at each end and attached to the ceiling with hooks to allow maneuverability.

**Connections**
The connection to the plenum is facilitated by the ball joint attached to the plenum. This allows for 20° of freedom increasing the successful attachment of the duct to the hood. All connections should be airtight and gaskets and other means of sealing may need to be used to insure that there is as little leakage as possible.

The end of the duct farthest from the fire will be connected to the probe duct section then the fire products are exhausted to the room. Building 3 contains the WESP which will filter the fire products from the room. Additionally the testing period is typically not long enough to see remixing from the room meaning that even though the fire products are exhausted to the room the time and distance they are from the fire and the hood prevents any mixing.

**Building 2A**

**Length**
The length of the duct in building 2A is the same as in building 3. The diameter of the duct is 24 inches (610mm) and the length of the duct is 40 feet (12m). This size duct is considered to be large enough to manage a 3 MW fire, but calculations are based on the velocity of the flow, which intern depends on the fire and the blower used.

**Placement**
Building 2A is built to test compartment fires and it has a roof that acts as the compartment roof. Figure 43 shows one part of the roof that was identified as a advantageous location for the ducting.
Connections
The duct connects to the plenum on one end and the instrumentation duct section on the other. These connections need to be airtight so that all of the fire products arrive at the probe section, otherwise there will be erroneous data. The Quick-Release Duct Hose Clamps allow the duct section to come together and have an airtight connection (McMaster (53185K61), 2012). The quick release function also allows the clamp to be reused when using the duct in building 3 or building 2A.
Appendix K:   Probe Section
**FPC Data Collection**

All of the probes and sensor are housed in the sensor duct section. All of the gas analyzer and the data acquisition system reside in the cabinet. The data is all filtered into the data acquisition device to be analyzed by computers after the completion of the test (see Figure 44).

![Flowchart showing the sensor and probe data gathered](image)

**Sensor Duct Section**

The sensor duct section gathers all of the information necessary from the combustion gases. As seen in Figure 45 the probe section is approximately 4 feet (1.2m) long and houses the pressure transducer, thermocouples, gas sampling port, the helium-neon laser and the blower. To increase cost effectiveness and decrease the possible variables caused by different probes and sensor the same duct is used in each building.

**Mobility**

The Probe section is designed to be fully mobile and recommended to be used in each building. It will be approximately 4 feet (1.2m) long and the same 24 inches (610mm) in diameter as the other ducting (see Figure 45).
Transducers

**Bidirectional Probe**
The bidirectional probe was designed by McCaffrey and Heskestad to negate the problem of soot clogging their pitot tubes (McCaffrey & Heskestad, 1976). The pressure in the section is used to determine the mass flow rate and using the temperature data.

The pressure transducer needs to be the first item in the probe sensor duct because it is critical to get accurate pressure data. The rest of the transducers, sensor and sample lines are not affected as much by disturbance in the flow profile (ASTM E2067, 2008).

**Helium-Neon Laser**
The helium neon laser is measure the smoke obscuration of the fire products. The smoke obscuration is defined as the reduction of light transmission by smoke, as measured by light attenuation (ASTM E2067, 2008). Using the appendix of ASTM E2067 there is a method of taking the light obscuration data from the laser and finding the total smoke released by the fire. (ASTM E2067, 2008). The standards have very clear advice on how to set up the laser device (see Figure 46: Laser Smoke Measurement System).

Helium-neon lasers are manufactured by Thorlabs, who offers multiple power and mounting configurations (Thorlabs, 2012). The specific laser chosen is a red helium-neon laser that operates at a central wavelength of 632.8 nm and has an output power of 2.0mW (see Figure 47).
ASTM E2067 recommends that Chromel-Alumel type K thermocouples, with a wire diameter of 24AWG (0.51mm). The Chromel-Alumel type K thermocouples are capable of measuring continuous temperatures of 2012°F (1100°C). To ensure accurate point temperatures the thermocouples should be insulated.

Omega engineering is a manufacturing and distribution company with vast experience with probes and sensors. The k type thermocouples are identified by a brown outer insulation and the positive node as a yellow wire and the negative node as a red wire (see Figure 48) (Omega Engineering, 2012).

There needs to be a thermocouple at the pressure transducer and near the neon laser (see Figure 45 Above). The location of the thermocouples is significant because the equations used to find the mass flow rate and the smoke obscuration value, both need temperature data.

Sampling
Mechanical Systems

Gas Sampling Probe
The gas sampling probe is used to collect the combustion gases in the duct. These sensors are made and designed by the United Sensor Corp who make the probes able to withstand temperatures of 2000°F (1100°C) (United Sensor, 2012). To find statistically relevant data the probe is design to be installed at the centerline of the duct. From ASTM E2067 the probe should be made from polytetrafluoroethylene or stainless steel. To ensure effective operation of the device it must be checked every test to ensure that nothing has blocked the sampling hole.

Blower
The blower is used to assist the gases and fire products up through the hood and the duct. The gases of a fire already have enough buoyancy to travel to the hood, but the fan increases consistency and to aid in the evacuation of the duct.

Motors follow the National Electrical Manufacturers Association (NEMA) standards. There are many different classifications of motors including drip-proof, Totally enclosed air over (TEAO), totally enclosed non-ventilated (TENV), totally enclosed fan cooled (TEFC) or totally enclosed, hostile and severe environment (Engineering Toolbox, 2012).

The blower needed is approximately a 6500CFM blower that attaches to 24 inch diameter duct. Because of the size and protection from high temperatures and particulates in the air it is McMaster has several including a high output direct drive duct fan and a belt drive duct fan (McMaster (1927K36), 2012). However this fan is very expensive and an alternative could be made in house for cheaper and with better compatibility with system requirements.

Instruments
Gas Analyzer
The gas analyzer is the device which gives the percent of the gases that are collected through the gas sampling probe. The collection and analysis of the gasses is the main purpose for building a fire products collector is to use this gas analysis method to find the heat release rate.

The sequence of the gas train as determined by ASTM E2067 is:

1. Sampling Probe
2. Soot Filter
3. Cold Trap
4. Gas Path Pump
5. Vent Valve
6. Plastic Trying Column
7. Carbon Dioxide Removal Column
8. Flow Controller
9. Gas Analyzer
Gas Analyzer Filters
The moisture is filtered mostly by a cold trap which requires a cooling unit to function. Any moisture that makes it through the cold trap is filtered by a cylinder filled with a dessicate. To assist the flow of the combustion gases into the analysis system, a gas pump is also necessary. Finally, the sometimes present acids are filtered by a cylinder filled with another substance.

Future Expansion
After consultation with an advisor it was made clear that future expansion of this device was a concern. This kind of expansion could include more gas analyzers, a hydrocarbon analyzer and possibly an infrared sensor for further analysis. As a reference for the possibility of this machine, a Fire Propagation Apparatus (FPA) was observed. An FPA has a hydrocarbon analyzer, as well as all of the instruments mentioned in the previous paragraph. It was deemed prudent to include this instrument as a necessity for further expansion.
Appendix L:   Cabinet design
Cabinet Design

Cabinet Mobility
The next problem was the mobility. The entire challenge of this project was to make this entire system mobile and flexible to situations where fire testing is required. Mobility could be achieved in a number of ways but the method must be practical.

![Figure 49: Examples of protected connectors for an attachment of the cone calorimeter](image)

Cabinet Materials
Many materials were evaluated for constructing the cabinet, amongst which were plastics and metals. For the application in mind the materials are considered for a worst case scenario where a sprinkler being activated would cause heavy mixing within the smoke layer of a room and cause the smoke layer to engulf the cabinet. For a scenario like this, regardless of their ability to insulate, many plastics would be unreliable. Most metals used in fabrication of structural members, pipes and fasteners have a relatively high melting point. For dealing with thermal insults from a fire, this would be ideal. However, some metals are very good conductors of heat and electricity alike. This requires consideration as an outer case that conducts a lot of heat will not deter heat well and can radiate to the instruments.

The materials from which the cabinet would be built from required much deliberation. The materials for the shell and supporting structure were selected based on what the cabinet needed to endure from the environment of a fire test. As previously iterated, the cabinet will have to endure the presence of smoke, water and heat to some degree. Something that cannot be understated is the importance of a solution that is practical to the requirements of the solution, but also cost-effective.

Insults

Effects of Smoke Toxicity
The presence of smoke can mean a combination of different chemicals is interacting with the cabinet. Depending of the fire reactants and the burning characteristics of the fire hazard chemicals
like CO and HCN can be present. Irritants such as acrolein (CH$_2$=CH-CHO), from wood, and hydrochloric acid (HCl), from polyvinyl chloride, can also be encountered (Drysdale, 2011). To survive agents of corrosion for any prolonged period of time the cabinet shell material would have to be chemically inert.

Effects of Soot
Soot will cause mechanical components to fail as, like dust, it embeds itself in fans and other moving and electrical components and causes inefficiency, friction or insufficient contact over time. With these considerations in mind, it was determined it would be prudent to make the electrical connections outside of the box protected or airtight.

Effects of water
With water present in the environment, the cabinet must be waterproof. The need, for a dry environment inside the cabinet, indicates that the cabinet cannot be made of a material that is porous or absorbent. If water is exposed to any of the electrical components, they will short circuit and become irreparable.

In the fire environment the heat of the fire causes water in the vicinity to evaporate, increasing the humidity to levels that the gas analyzers are not capable of operating at. This is a greater concern because condensed liquid in the cabinet may collect in harmless levels at low temperatures, but when exposed to the heat of the fire the box heats up and evaporates the air, causing a source of error in the gas analysis. This could be monitored remotely during a test with a wireless weather station or similar product (Amazon, 2012).

Effects of heat
With consideration to heat, the materials selected need a high heat tolerance. The cabinet is not intended to continuously endure a flame hitting it, but it will be able to withstand a typical fire from a reasonable distance away. Another concern about the level of heat present was how well a material would dissipate or heat. Materials with very high conductivity should be avoided.

Heat, as with any kind of component, may cause certain materials to react with their surroundings in an unintended fashion, or cause materials to fail mechanically.

Materials

Copper & Aluminum
Metals that were chosen as heat conducting metals were Copper and Aluminum. Aluminum is a less conductive metal but it is less expensive than Copper, however when the application requires some ductility, like the case of tubing or wire, copper is incredibly convenient.

Wood
With the previous paragraphs in mind, a couple of materials were ruled out as candidates. Wood is an organic material and could get attacked by mold as well as being somewhat absorbent. Plastics are typically not made to withstand fire, which also becomes a concern even when the possibility of direct contact is minor. This still leaves the possibility of a metal case.
Steel

For a box that is meant to dissipate heat, away from the instruments, a very conductive metal would be ideal. After some deliberation the metal that was chosen as a heat deterrent metal, was 304 Stainless steel. Stainless steel is a broad term used for alloys of steel that have some significant presence of Chromium to protect it from corrosion. Chromium has the ability to passivate, or create a thin layer of oxidized metal that remains at its surface protecting it from further oxidation. This property is ideal for shielding something from hydrochloric acid (HCl), which is sometimes present as a product when burning plastics.

The chosen material was galvanized steel. Galvanized steel, low manganese steels in general, have a low thermal conductivity compared to metals such as copper or gold. Along with being much cheaper than gold galvanized steel is also considerably cheaper than other more specialized steels such as stainless steel. Lastly galvanized steel is very available commercially and thus may be obtained from a variety of vendors.

Case Design

With consideration to the supporting structure of the cabinet the main concern was the structure’s strength. The cabinet was built out of a modular industrial erector set as done with many other things in Tyco’s Cranston site.

Design a.: Sealed Case Cabinet

The idea of a sealed case was probably one of the most important the team had. A major part of the threat within the fire tests at the Cranston facility was the soot content of the smoke. As with any kind of small particles in the air, soot poses an ever growing threat to any kind of machinery, electrical or mechanical. Soot deposits itself in areas between moving components or in connectors of electrical components. As a result extra friction or lack of contact, lead to undesired operation or accelerated failure, both should be avoided.

Design b.: Double Layer Cabinet

One of the simpler ideas of the design team was to have a box within a box. The outer box would serve to protect the instrumentation from thermal radiation, thermal convection and soot. Meanwhile the inner layer would serve as a heat sink for the components that might produce heat within the machine. The space between the two cases would serve as a “third layer” considering the insulating properties of air in small spaces.

Cake Dome

The design incorporated an outside case that would not be attached, but just placed over another case. The outer case would be a shield from corrosion and attacks from the environment, be they chemical, thermal or water. The inner case would be a sealed case with water lines running over its surface to dissipate heat emitted by the outside case, and heat created by the components inside the inner case.

The outer case, and the air between it and the inner case, would serve as a protective layer of insulation but more importantly it would serve as a defense in the case of the sealing mechanism of
the inner case failing. As the outer case would be the one exposed to the environment the material it would be made of would have to be heat resistant, somewhat insulating and corrosion resistant. As previously mentioned, 304 Stainless steel would be the perfect candidate due to its cost, availability and ability to perform in all of those categories.

The inner case would have to be built also to be somewhat resistant to heat corrosion and water but with a different philosophy in mind. Since the components inside of the case would produce some heat of themselves, the case around them would need to be able to soak in heat relatively quickly to dissipate it. This could be done by constructing the box of a conductive metal. A suitable option for this was Aluminum due to its resistance to corrosion and heat conduction capacity. To dissipate heat away from the system, the idea of running water lines made of copper around the inner box, like the cooling plates of the cone calorimeter, seemed very attractive. This would provide a way to dissipate heat from the air between the two cases and the heat from the inside case. If the idea of running the sample gas lines along the copper lines were to be implemented, that would be another use.

**Design c.: Sectioned sealed cabinet**

Design of the cabinet with input and output flows that protect against smoke, soot and water is necessary in the addition of any cooling system. This design was specifically created to hold a mechanical cooling unit in one insulated compartment and hold the instrumentation in a separate insulated compartment.

**Design d.: Single-wall pressure-positive cabinet**

Keeping the majority of design a. this design implements a low power mechanical system. A mechanical device would be installed in the wall of the cabinet not facing the fire. Cuts in the cabinet wall would allow access to ambient air, which would be filtered and a covering would be added to protect against the water insult above.

**Cabinet Temperature Control**

**Water Cooling**

Perhaps the most complicated, and most effective, idea to dissipate heat was a water cooled box. Water cooling, as seen in computers, cars and all sorts of other machinery, takes advantage of the large heat capacity and abundant supply of water and uses it to absorb heat away from components. Every building that fire tests are performed have some kind of water connection that would provide more than enough water for the cabinet to remain cool.

The design team was given proof of this idea’s merit when the group watched a fire test using the cone calorimeter (see Figure 50). To protect the sample from being ignited as the cone preheats, there are cooling plates that can be retracted by the operator. The cone's cooling plates have water lines running through them to dissipate the heat. Despite the cone's temperature being at 700°F (371°C), the bottom part of the cooling plate was cool enough to touch.
Application to Design a.

It was considered that copper tubing with water running through it be placed on the inside wall of the cabinet. This would block all heat entering the cabinet either through radiation or convection, while supplying a source of cooling for the instruments inside. The problem with the design was the risk it presented. If one of the tubes carrying the water burst the instrumentation would be irreparable.

Application to Design b.

In the double layered case the water could be passed through the space between the outer and inner case through a high conductivity tube to absorb heat as quickly as possible. This would ensure any heat possibly created by the inside components would be conducted through inside case and into the water and also from the outside case into the water. In this design the gas sample line could benefit from the cooling properties of the water. The draw backs of this design were the complications foreseen in reaching the gas analyzer.

Refrigeration

Refrigeration was the next cooling method considered. In order for this idea to be viable a new cabinet idea was formulated that would insulate the refrigeration system from the instrumentation. Breaking the cabinet into two compartments, one compartment holds the instrumentation and the other compartment holds the refrigeration system. This negates the instrumentations exposure to the exhaust from the refrigerator. By isolating each the refrigerator can be free to interact with the outside environment, having a small insulated hole to blow in the cold air.

Refrigeration Cycle

A refrigeration cycle works by using a fluid and running it through the cycle seen in Figure 51. Starting at the condenser changes the vapor form of the fluid to a liquid, which releases heat to the...
environment. The liquid, under pressure, goes through an expansion valve to decrease the pressure and decrease the temperature of the fluid. That fluid is then put through an evaporator, which causes the fluid to draw in heat energy from the surroundings in an endothermic reaction. The fan can then use this reaction to disperse the cooler air. The final step in the cycle is to re-pressurize the fluid.

![Diagram of Single stage vapor compression refrigeration](image)

**Figure 51: Single stage vapor compression refrigeration (Pepper, 2006)**

**Design c.: Sectioned sealed cabinet**

The drawback to adding the refrigeration system to the cabinet is the exposure to the fire environment. There needs to be an air intake into the compressor and air outtake from the instrumentation section to decrease any effects of pressure buildup. However adding a filtered opening to the compressor would solve any problems with soot, smoke and water. Adding a louvered vent to the bottom of the cabinet would allow air to escape from the instrumentation section while allowing no soot, smoke or water in. Using a louvered exit from the instrumentation section means the pressure inside can be calibrated to remain positive barring any physical insults from entering.

**Marine Air Conditioners**

Marine air conditioners are usually used on boats and ships and they use water as the means of heat exchange because it is plentiful and free. Some of these air conditioners exhaust heat by means of exchanging heat with the air. However these specific marine air conditioners exchange heat with the sea water to cool the condenser. As previously mentioned there are water connections in the test areas, meaning that there is an adequate supply of water for heat exchange.

Water cooled refrigeration systems use a different kind of exchanger as a condenser. These “shell and tube” heat exchangers pass a tube of a liquid or gas through a sealed case of another similar medium. The advantage of using water as the method for heat conduction is that the temperature of the environment has little to no effect on the refrigeration unit.
Implementation

Air conditioners are not designed to be used in enclosed spaces, like the cabinet. Using duct hoses, ambient air can be drawn from outside the cabinet through a filter and guided directly to the intake of the air conditioner. In the same way, the cool outflow can be directed into the instrumentation section of the cabinet and the hot exhaust can be emitted by a filtered louvered exit. The duct hose is sealed to all the entrances of the air conditioner by an airtight seal.

Holes in the cabinet wall allow access to ambient air, but also are open to the soot and smoke mixed in the ambient air. To negate the effects of smoke and the airborne particulates carbon filters are installed at every entrance and exit. The filters are classified as MERV 7 and will remove the particulates greater than 10 microns. The intake filters in the air conditioner will remove any remaining insults from the air. The air conditioner’s dehumidifier works in parallel with the air cooling system to remove up to 12 liters/24 hour from the air (American Comfort, 2012).

All inflows and outflows would be designated to the side of the cabinet facing away from the fire to pull the lowest temperature air possible.

Air Cooling

Fans

Another cooling method that was considered is to use fans or a blower to cool the system with the circulation of air, creating forced convection over the instruments. To protect against the smoke and soot particulate filters would be installed in front of the fans.

Design d.: Single-wall pressure-positive cabinet

A separate design incorporating fans into the cabinet was devised. The design needs to protect the instruments from smoke, soot and water. The design would be to install fans on the side of the cabinet facing away from the fire to reduce the amount of convective heat. Filters would negate the effects of the smoke and the soot. To negate the effects of water a dryer duct vent with a downward facing design would keep water out of the cabinet.
<table>
<thead>
<tr>
<th>Water Cooling</th>
<th>Insulation</th>
<th>Fans</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Cons</strong></td>
<td><strong>Pros</strong></td>
</tr>
<tr>
<td>Highest heat dissipation capacity</td>
<td>Complicated</td>
<td>Inexpensive</td>
</tr>
<tr>
<td>Can also cool sample</td>
<td>Expensive</td>
<td>Simple</td>
</tr>
<tr>
<td>Abundant and inexpensive coolant</td>
<td>Possibly high maintenance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Added weight of water lines</td>
<td></td>
</tr>
</tbody>
</table>

**Insulation**

The idea of insulating the inside of the box was considered to protect the inside of the cabinet from the fire environment. The insulation acts as a time barrier that depends on the properties of the insulation and the thickness of installed. Insulation is also an inexpensive way to protecting the cabinet from the heat insult. Insulation allows the cabinet to remain a closed system during the fire tests. Further analysis of the insulation will be explored in the analysis section of the paper.

To determine the amount of insulation on the box we first need to determine the heat transfer from the fire to the cabinet and how that heat conducts through the box. Initially to determine whether any insulation is needed we can do a semi-infinite calculation to show what of sheet steel would be sufficient to keep the inside of the cabinet below the maximum operable temperature of the gas analyzers.
Area Calculation

Since some of the inside area of the plates are taken up by the meeting point of the plates and the structural members inside of the cabinet the area that the insulation will take up will be the compliment of that.

\[ A_{\text{insulation}} = (L_{\text{plate}} - L_{\text{skeleton}}) \times (W_{\text{plate}} - W_{\text{skeleton}}) \]

For the top and bottom;

\[(1.2m - 0.0762m) \times (0.6m - 0.076m) = 0.589m^2\]

For a total area of 2.6 square meters.

For the end plates;

\[(0.6m - 0.0762m) \times (0.6m - 0.0762m) = 0.325m^2\]

For a total area of 0.650 square meters.

For a total insulation surface area of 3.25 square meters.
Volume calculation

The same area formulas can be applied to the calculations for the volume of the insulation. The only dimension that must be added here is the thickness.

\[ V_{\text{insulation}} = \tau_{\text{insulation}} (L_{\text{plate}} - L_{\text{skeleton}}) \times (W_{\text{plate}} - W_{\text{skeleton}}) \]

For the 6.35cm (0.25in) thick insulation.

\[ V_{\text{insulation}} = 0.00635m \times (3.25m^2) = 0.0206m^3 \]

For the 12.7cm (0.5in) thick insulation

\[ V_{\text{insulation}} = 0.0127m \times (3.25m^2) = 0.0414m^3 \]

For the 38.1cm (1.5in) thick insulation

\[ V_{\text{insulation}} = 0.0381m \times (3.25m^2) = 0.124m^3 \]

<table>
<thead>
<tr>
<th>Cabinet Dimensions</th>
<th>mm</th>
<th>m</th>
<th>ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1200</td>
<td>1.2</td>
<td>3.937007874</td>
</tr>
<tr>
<td>Width</td>
<td>550</td>
<td>0.55</td>
<td>1.804461942</td>
</tr>
<tr>
<td>Height</td>
<td>600</td>
<td>0.6</td>
<td>1.968503937</td>
</tr>
<tr>
<td>Aluminum thickness</td>
<td>38.1</td>
<td>0.0381</td>
<td>0.125</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface Area</th>
<th>mm²</th>
<th>m²</th>
<th>ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sides</td>
<td>2738558.64</td>
<td>2.73855864</td>
<td>29.47759987</td>
</tr>
<tr>
<td>Ends</td>
<td>0.53245644</td>
<td>5.731313421</td>
<td></td>
</tr>
<tr>
<td>Top&amp;Bottom</td>
<td>0.24817644</td>
<td>2.671348968</td>
<td></td>
</tr>
<tr>
<td>surface area</td>
<td>2.73855864</td>
<td>29.47759987</td>
<td></td>
</tr>
</tbody>
</table>
**Semi-Infinite Method Analysis**

After determining that the sheet steel was not sufficient to protect the cabinet from the estimated heat flow the next step was to use a semi-infinite solution. Using the semi-infinite solution the depth at which a heat insult on the outside has no effect on the inside of the insulation. To put it another way, if a certain heat flux is affecting the outside surface, how thick does the insulation have to be so that the back wall does not experience any effect from the initial heat flux.

The equation for the semi-infinite solid analysis is:

\[ \Delta = 4\sqrt{\alpha t} = 4 \sqrt{\frac{k}{\rho c_p}} t \]

The semi-infinite solid analysis uses the properties of the material being used to determine the thickness that is needed.

<table>
<thead>
<tr>
<th>Material</th>
<th>10min (in.)</th>
<th>20min (in.)</th>
<th>30min (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic Insulation</td>
<td>0.80935941</td>
<td>1.14460705</td>
<td>1.40185162</td>
</tr>
<tr>
<td>Millboard Insulation</td>
<td>0.81754182</td>
<td>1.15617873</td>
<td>1.41602397</td>
</tr>
<tr>
<td>Harsh-Environment Silica Insulation</td>
<td>1.99680395</td>
<td>2.82390722</td>
<td>3.45856589</td>
</tr>
</tbody>
</table>

Table 11: Table show thickness of insulation needed using Semi-Infinite Solid analysis

The semi-infinite solid analysis is a blunt method and a more discretized method is needed to have a more detailed of what thickness, weight, and cost of material is needed to protect against a certain heat flux.

**Finite Difference Method Analysis**

The finite difference method of heat transfer works by breaking up the full thickness of the solid and breaking it up into many discretized sections through which to measure the heat transfer. This method provides a more exact method at which to observer the effects of heat insults over a certain time.

The solid is broken up into N nodes, or control volumes, which the temperature equations act upon. The general energy balance that must be conserved is:

\[
\frac{\text{Rate of heat generation inside CV}}{\text{inside CV}} = \frac{\text{rate of heat conduction}}{\text{into CV}} - \frac{\text{rate of heat conduction}}{\text{out CV}}
\]

From equation this all of the equations can be derived. For the cabinet considered that there would be no heat generation inside the insulation and assumed a constant heat flux at the front boundary and a convective cooling process at the back boundary. Using the equations we can formulate a numerical solution using Microsoft Excel software.

The nodal and boundary equations:

**Finite Difference Method**
The finite difference method is derived from the one dimensional transient conductive heat transfer equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

where $\alpha$ is the thermal diffusivity, $\frac{k}{\rho c}$. The environment that the cabinet is exposed in will most likely have a direct heat flux from the fire at the front face of the cabinet with a convective cooling factor accounting for the temperature of the air around the cabinet. The internal layer of the insulation had no heat generation. The back face of the insulation is open to the air inside of the cabinet which is a known surface convection.

$$q''_i + h(T_\infty - T^i_p) = k \frac{T_2 - T_1}{\Delta x} \quad \text{(Specified heat flux boundary condition)}$$

$$\bar{h}(T_\infty - T_1) + \dot{q}_{c,1} \frac{\Delta X}{2} = -k \frac{T_2 - T_1}{\Delta x} \quad \text{(Known surface convection boundary condition)}$$

The nodal and boundary equations:
The front boundary condition equation is as follows (Kreith, Manglik, & Bohn, 2011):

$$T^{i+1}_p = T^i_p (1 - 2Fo) + 2FoT^i_m + Fo \left[ \frac{\Delta x}{k} \epsilon q''_{rad} + B\ell (T_\infty - T^i_p) \right]$$

where the $T^i_x$ variable represents the temperature at time $t = \{1, ..., i, ..., i + 1 \}$ and thickness $x = \{1, ..., x + 1, ..., n\}$. The front boundary is affected by the heat flux from the fire plus a convective cooling factor from the ambient air. To determine the Equation for the internal nodes:

$$T^{n+1}_p = Fo\left(T^{n+1}_p + T^{n-1}_p\right) + (1 - 2Fo)T^i_p$$

The internal nodes are calculated from an average of the surrounding nodes, because there is no heat generation in the insulation. For the back boundary condition:

$$T^{n+1}_p = 2Fo\left(T^{i+1}_m + B\ell T_\infty\right) + (1 - 2Fo - 2Bifo)T^i_m$$

The back boundary uses the equation for convection to simulate the heat transfer from the insulation to the air inside the cabinet.

Initial Conditions
The initial conditions for the cabinet were set as at time, $t=0$; temperature, $T=T_\infty=298K$. The time step used in the calculation represents the length of time it takes for the heat to transfer through the thickness, $dx$, limited by the insulations properties. To find the time step the Fourier number is set equal to 0.45, to obey $(1 - 2Fo) \geq 0$. The Fourier number $Fo = \frac{a\Delta t}{\Delta x^2}$ where $x$ is the thickness divided by the number of nodes, $a$ is the thermal property of the material and $t$ is the time. To find the time step: $dt = \frac{(dx)^2}{a} \cdot \left(\frac{45}{100}\right)$. The chosen heat fluxes are chosen to display more data at smaller
heat fluxes, $1 \frac{kw}{m^2}$ and $5 \frac{kw}{m^2}$, and the extremes $10 \frac{kw}{m^2}$ and $20 \frac{kw}{m^2}$. An emissivity of 0.3 is chosen to account for the steel cabinet casing. The heat transfer coefficients are $30 \frac{kw}{m^2}$ for the convective cooling at the front of the cabinet and $25 \frac{kw}{m^2}$ for the inside of the cabinet. See Appendix L: Cabinet design for additional details.

**End Conditions for Insulation effectiveness:**

The end conditions, used to define the effectiveness of the insulations, are concerned with the temperature after 30 minutes, weight and cost of the insulations chosen. The insulations that were analyzed are: extra high temperature rigid ceramic insulation; high temperature millboard insulation; and harsh-environment silica insulation all of which are rated for use over 1000°F (538°C) (see Table 1).

**Table 12: Insulation Materials and Properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Max Temp (K)</th>
<th>K (W/m*K)</th>
<th>Density (kg/m^3)</th>
<th>Specific Heat (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>1324.816667</td>
<td>0.0493109</td>
<td>304.38</td>
<td>920</td>
</tr>
<tr>
<td>Millboard</td>
<td>1022.038889</td>
<td>0.1426492</td>
<td>945.18</td>
<td>840</td>
</tr>
<tr>
<td>Silica</td>
<td>1366.483333</td>
<td>0.1373659</td>
<td>160.2</td>
<td>800</td>
</tr>
</tbody>
</table>
Cabinet Water and Smoke Protection

The water insult is considered to be from the sprinklers above the cabinet and it was not anticipated that the cabinet would ever be partially or totally submerged in water. To counter the water insult from the sprinkler would be a drip edge on the top plate of the cabinet. This would require very little extra material to be purchased.

Structural Analysis

In the evaluation of the structural integrity of the cabinet's skeleton some assumptions were made to simulate a plausible worst case scenario. The first assumption is that the cabinet does not deform. The second assumption is that the bolts fail in shear. A shear failure is more likely than tension or compression as even materials, such as steel, tend to fail about twice as quickly in shear. Tension failures will also be considered unlikely as the cabinet is not being subjected to any pulling force. Lastly a repeated loading study is also unnecessary as the cabinet will not have any large spinning or oscillating components exerting a load on its members. Provided the assumptions made for this calculation, the structure has a safety factor of over ten.

It will also be assumed that all loading takes place parallel to one axis to ensure the most possible strain on one member. As the yield criteria, Tresca's criteria for yielding was chosen. (http://www.doitpoms.ac.uk/tlplib/metal-forming-1/yield_criteria.php)

With the previously mentioned assumptions and for a box with a weight of 300 lbs, the safety factor is greater than ten. It cannot be understated that most of the choices for this calculation have been conservative.

Detailed Design

An idea to circumvent the problem of having the cabinet limited to only two accessible plates was to make all side panels removable. In practice however this would complicate the design. To have all the plates be independent would mean each one of them would require a different cooling line. If this did not add a considerable amount of cost to materials, this would definitely complicate maintenance and repair.
As the final steps of the design come, a team member once again consulted with a technician about the design. The idea of having one welded, thin metal box seemed impractical due to the problem of storing a fragile structure. Instead, the idea of having a metal box that was easily disassembled was proposed. Due to some of its dimensions, the box could prove cumbersome in some spaces, having something that could be dismantled and reassembled seemed very practical. This design idea somewhat compromises the ability of the box to stay water tight but the real problem is not to have the box be able to float, as much as it is to have the box survive splashes and dousing from possible fire suppression. This could be accomplished by the geometry of the box and extruded aluminum structure alone. The inner box would have to be more complicated as the instrumentation would need to be protected from smoke.

**Design Selection**

The final design selection was based on criteria of mobility, ease of operation and cost effectiveness. The design choices that best reflect the selection criteria are a sealed case, lined with insulation as to protect against the heat insult and a drip edge to protect against the water insult.

The sealed case would be the main countermeasure against smoke. The insulation would be the main defense against the heat flux, whether it be convective or radiative, it would delay the inside wall of the case from getting hot quickly. To help against the water a drip edge would be installed on the top of the case. The drip edge would require almost no additional materials.
Appendix M:  Cooling System
Air Conditioner

The cooling system recommended is the American Comfort ACW100. This cooling system offers the optimal combination of low weight, small size, cooling capability and cost effectiveness that is necessary. The weight of the device is 26.5lbs (12kg) with the dimensions being 14in (355mm)x23 in (585mm)x 9 in (230m), with the cooling capability of 240 watts (American Comfort, 2012). This system can increase the protection time of the cabinet from 1min to 30min depending on the severity of the heat flux hitting the cabinet.

![American Comfort 1000BTU personal Air Conditioner](image)

Figure 52: American Comfort 1000BTU personal Air Conditioner

Implementation

Air conditioners are not designed to be used in enclosed spaces, like the cabinet. Using duct hoses, ambient air can be drawn from outside the cabinet through a filter and guided directly to the intake of the air conditioner. In the same way, the cool outflow can be directed into the instrumentation section of the cabinet and the hot exhaust can be emitted by a filtered louvered exit. The duct hose is sealed to all the entrances of the air conditioner by an airtight seal.

Holes in the cabinet wall allow access to ambient air, but also are open to the soot and smoke mixed in the ambient air. To negate the effects of smoke and the airborne particulates carbon filters are installed at every entrance and exit. The filters are classified as MERV 7 and will remove the particulates greater than 10 microns. The intake filters in the air conditioner will remove any
remaining insults from the air. The air conditioner’s dehumidifier works in parallel with the air cooling system to remove up to 12 liters/24 hour from the air (American Comfort, 2012).

All inflows and outflows would be designated to the side of the cabinet facing away from the fire to pull the lowest temperature air possible.
Appendix N: Scientific Presentation Slides
Design of Mobile Fire Products Collector

August 15, 2012

Andre da Vitoria, Drew Martin, Yongbin Ji, Lei Zhang

Global Team

Andre da Vitoria
- Senior WRI
- BSc/MSc
- IEFFPE

Drew Martin
- Senior WRI
- BSc MEng
- IEFFPE

Yongbin Ji
- Senior SJTU
- MSc

Lei Zhang
- Senior SJTU
- ME

Agenda

- Background
- System Design
  - Hood Design
  - Duct Design
  - Cabinet Design
  - Testing
  - Location Case Studies
- Cost-Benefit Analysis
- Recommendations and Conclusions
Project Objectives

- TFPP’s criteria
  - Mobile
  - Able to evaluate HRR from 3MW Fires
  - Survive fire test environments
  - Operate in the same space as other infrastructure
    - Must not interfere with other operations
- Cost Benefit Analysis
  - Will evaluate the cost of the system
  - Future input for a CER

Agenda

- Background
- System Design
  - Hood Design
  - Duct Design
  - Cabinet Design
  - Testing
  - Location Case Studies
- Cost-Benefit Analysis
- Recommendations and Conclusions

Fire Products Collector System

- Hood
  - A means of collection of the smoke
- Duct
  - Carries smoke from fire to be analyzed
  - Necessary for gas sampling as part of the calorimetry process
- Cabinet
  - Houses and protects instrumentation
  - Prototyped as part of our project
The need for a Fire Products Collector

- Allows calculation of Heat Release Rate
  - Critical parameter in sprinkler design
- Further our understanding of room fire growth
  - Understand the repeatability of test fires
- Validate fire models
  - Fire models allow for inexpensive means to simulate laboratory fire tests
  - Streamline sprinkler development
    - Lower cost
    - Increased safety

Need for Mobility

- Multiple fire testing areas located in two separate buildings
  - Five unique testing areas and two demo cells, as shown below
- Test areas A, C, and E are the best areas for calorimetry

Small, Medium and Large Scale Calorimeters

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test samples</td>
<td>Test small samples for material properties (Avg=0.01m²)</td>
<td>Test furniture &amp; full size rooms (Avg=10m²)</td>
<td>Test furniture &amp; full size rooms (Avg=100m²)</td>
</tr>
<tr>
<td>Study material</td>
<td>Study material properties</td>
<td>Used in fire modeling, study room geometries</td>
<td>Used to study room and building fires and verify models</td>
</tr>
<tr>
<td>Cone Calorimeter</td>
<td>Cone Calorimeter, Fire Propagation Apparatus</td>
<td>Test burns that involve a piece of furniture or an entire room</td>
<td>Test burns that involve entire rooms or buildings</td>
</tr>
</tbody>
</table>
Oxygen Consumption Calorimetry

- Oxygen consumption calorimetry can be used to measure the power output of a fire
  - There is a constant heat release per unit mass of Oxygen consumed for most organic materials
    - 13.1 MJ/kg \( \text{O}_2 \)
    - Accurate to within +/- 5%
- Measure
  - Mass flow of gas in duct
  - Mass Concentration of soot, CO, CO\(_2\), and \( \text{O}_2 \)

\[
q = C \frac{S_0}{T_s}
\]

\[
\frac{X_{CO}(1 - X_{CO} - X_{O}_2)}{X_{CO}(1 - X_{CO} - X_{O}_2)}
\]

\[
Q(t) = \left[ \frac{X_{CO}(1 - X_{CO} - X_{O}_2)}{2} \times \frac{N_{CO}}{N_{CO}} \times \frac{M_{CO}}{M_{CO}} \times (1 - X_{O}_2(t)) \times X_{O}_2(t) \right]
\]

**Agenda**

- Background
- System Design
  - Hood Design
  - Duct Design
  - Cabinet Design
  - Testing
  - Location Case Studies
- Cost-Benefit Analysis
- Recommendations and Conclusions
Hood Design - Concept

- Criteria
  - Must to be large enough to prevent leakage of products
  - Small enough to prevent excessive entrainment
- Hood design in Building 3 uses size recommended by ASTM E2067 for medium scale fire
  - Moved and supported by racks
  - Building 2A needs a modified design due to its limited space

Hood Design - Mobility

- Racks adjustable from 3-4.5m(10’-15’) to support hood and extra ducting
- Wheels to move into location
- Able to be disassembled for easy storage
- Fabricate at Tyco
  - Needs a custom rack design

Hood Design - Analysis

- Space Limitations
  - Special considerations were given to test area A

Network Diagram
Agenda

- Background
- System Design
  - Hood Design
  - Duct Design
  - Cabinet Design
  - Testing
- Location Case Studies
- Cost-Benefit Analysis
- Recommendations and Conclusions

Mobile Sampling Duct - Concept

- Detachable, mobile, plug and play section of duct where fire data is gathered
- Minimized length for mobility
- Able to use in all test areas previously defined
- Gas sampling duct components
  - Blower
  - Gas sampling ports
  - Thermocouple
  - Bi-directional probe

Mobile Sampling Duct - Components

- Necessary measurement Instruments
  - Thermocouples (temperature)
  - Gas Sampling port
  - Smoke obscuration measurement system
  - Bi-directional Probe (velocity)
  - Blower
Entrainment Rate of a 1MW Pool Fire

\[ \text{Entrainment Rate, Fire Plume (kg/s)} \]
\[ \text{Mass flow blower (kg/s)} \]

\[ m_{\text{ent}} = \left[ \frac{g y_{\text{ref}}}{c_{\text{p}T_{\text{ref}}}^2} \right]^{1/3} Q_{\text{f}}^{1/3} (z - z_0)^{2/3} \left[ 1 + \frac{G Q_{\text{f}}^{1/3}}{(g^{1/2} c_{\text{p}T_{\text{ref}}})^{2/3}(z - z_0)^{3/2}} \right] \]

Height above fire (m)

Mass Flow Rate (kg/s)

Duct Analysis

- Entrance Length
  - Reynolds number
    \[ Re = \frac{v * D_h}{\nu} \]
  - Entrance Length
    \[ E_i(Tubulent) = 4.4 \times Re^{1/6} \]

Re=Reynolds number
laminar when \( Re < 2300 \)
transient when \( 2300 < Re < 4000 \)
turbulent when \( 4000 < Re \)
\( v=\)velocity [m/s]
\( D_h=\)hydraulic diameter [m]
\( \nu=\)kinematic viscosity [m²/s]

Duct Entrance Length

Entrance Length (m)
Max Duct Length (ft)
Duct Diameter (m)

Agenda

- Background
- System Design
  - Hood Design
  - Duct Design
  - Cabinet Design
    - Testing
  - Location Case Studies
- Cost-Benefit Analysis
- Recommendations and Conclusions

Cabinet Design - Concept

- Mobile Cabinet containing analysis equipment
  - Gas analyzer (and protective equipment)
    - Moisture disposal
    - Particulate filters
    - Data Acquisition (DAQ)
    - Gas pump
    - Space for future expansion
    - Hydrocarbon analyzer

Cabinet Design - Instrumentation

- Gas Analyzer($O_2$, $CO$, $CO_2$)
  - Servomex 4100
- Data Acquisition System (DAQ)
  - Collect all the sensors’ information
  - NI cDAQ 9178
- Moisture Removal
  - Moisture will lead to inaccurate results and equipment damage
Cabinet Design - Specifications

- Cabinet must withstand daily use within the Cranston site
- Relocation requirements
  - Must be small enough to be transported into any evaluated test area within the Cranston site
  - Maximum two person relocation
  - Weight must remain under 200 lbs
    - actual design is 194 lbs, with all instrumentation
  - Must survive transport by forklift
    - 6 fasteners for each corner

Cabinet Design - Specifications (cont.)

- Fire test environment requirements
  - Inside temperature not above 100 F during UL 1628 Fires
    - Insulation
- Fire Test environment
  - Must withstand water exposure from hose and sprinklers during tests
    - Drip edge
  - Must withstand contamination by fire products
    - Aluminum tape
  - Must withstand corrosion by smoke agents
    - Material selection

Cabinet Design - Heat Transfer Analysis

- Experimental data used to model insulation needs
- Insulation constraints
  - Must not exceed 3.81 cm (1.5") in thickness
  - Must not discharge fibers or particulates into equipment
  - Must be inert material
Cabinet Design - Heat Transfer Analysis

- Semi-infinite solid analysis
  - Interior boundary condition:
    \[ T(x \rightarrow \infty, t) = T_i \]
  - Useful idealization for practical problems
- Penetration depth
  - Within a certain time, transient heat conduction can be regarded not to influence the interior condition
  \[ \delta_p = 2\sqrt{\frac{k}{\rho C_t}} \]

Cabinet Design - Heat Transfer Analysis

Insulation in Cabinet

Cabinet Analysis - Structural Failure

- Assumptions
  - Shear failure
    - Evenly distributed shear force on one plane of one joint
  - Uniform material
  - Failure occurs on two screws on same plane
    - Minor diameter
  - Outside plates offer no structural support
  - All loading on one plane
  - No deformation
Cabinet Analysis - Structural Failure

- Tresca’s criterion for yielding of ductile materials
  \[ |\sigma_1| \geq \sigma_y, |\sigma_2| \geq \sigma_y \text{ or } |\sigma_1 - \sigma_2| \geq \sigma_y \]
  \[ \sigma_1 = \frac{1}{2} (\sigma_1 + \sigma_2) + \frac{\sqrt{3}}{2} \left( \sigma_2 - \sigma_1 \right)^2 + \frac{1}{2} \]
- After calculating maximum stress
  \[ \text{Shear Yield Str.} = 0.58 \cdot \text{Tensile Yield Str.} \]
  \[ \tau = \frac{F}{A} \]

Agenda

- Background
- System Design
  - Hood Design
  - Duct Design
  - Cabinet Design
    - Testing
      - Location Case Studies
- Cost-Benefit Analysis
- Recommendations and Conclusions

Testing Setup

- Verify design and protect instruments from fire insults
- Collaborated with previously planned fire tests
  - UL 1626 room fire represents realistic worst case scenario
- Instruments used
  - Thermocouples
  - Heat flux gauge

N-12
Testing Results

Temperatures on Cabinet @ 15°

Testing Results - Maximum Temperature

- Took part in 8 tests thus far
- UL 1626 Fire

Testing Results

Heat Flux on Cabinet @ 15°
Agenda

- Background
- System Design
  - Hood Design
  - Duct Design
  - Cabinet Design
  - Testing
- Location Case Studies
- Cost-Benefit Analysis
- Recommendations and Conclusions

Test Area A - Case Study

- Concept
  - Stationary duct left in place on roof
  - Detachable sampling duct
  - Removable, maneuverable hood
- Structural Constraints
  - Duct length 13 m (43')
  - Duct diameter 0.7 m (28’)
  - Length of hood 1.6 m (5')
Test Area A - Dimensions

- Duct
  - 0.6m (24") duct diameter
  - 12m (40’) duct length
  - I/D=40/2=20 duct diameters
- Hood
  - 1.58m(5.2’) x 1.8m(5.9’) x 1m(3.3’)
  - Maneuverable within 1.8m (6’)
- Plenum
  - 0.9m(3’) x 0.9m(3’) x 0.9m(3’)

Building 3 Case Study

- Test Bays C and E are best suited for Calorimetry
- Single duct system will connect to WESP in test areas C or E
  - Only move Hood, sampling section and connection ducting
  - WESP flow rate 10,000 ACFM with 0.6m (2’) connections
Building 3 – Test Bay C, D and E System Concept

- Permanent ducting on the ceiling of test area C, D and E
- Switch duct sampling section and hood to test between test bay C and E
- Fabricate rack for hood, ducting and sample section on site

Building 3 – Test Bay C, D and E Design

Plan View

Elevation View

Demo Cell Case Study
Demo Cell Case Study

- Demo cells were built as a closed system for viewing
  - Air intake from roof
  - Empty into the Wet Electro-Static Precipitator (WESP)
- Perfect setting for fire tests
  - Collection system in place
  - Few modifications needed
    - Duct and sampling sections
- Not part of the engineering department

Building 3 – Test Bay F Constraints

- WESP connection available
- Current setup
  - Test setup currently takes up a lot of space
- Fires conducted here are too big for the calorimeter designed

Agenda

- Background
- System Design
  - Hood Design
  - Duct Design
  - Cabinet Design
  - Testing
- Location Case Studies
- Cost-Benefit Analysis
  - Recommendations and Conclusions
Total Cost

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Cost Low</th>
<th>Cost High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabinet</td>
<td>$907</td>
<td>$907</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>$28,996</td>
<td>$33,660</td>
</tr>
<tr>
<td>Ducting*</td>
<td>$2,456</td>
<td>$2,456</td>
</tr>
<tr>
<td>Hoods*</td>
<td>$2,173</td>
<td>$2,340</td>
</tr>
</tbody>
</table>

* Indicates material cost

Total System Cost

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$34,533</td>
<td>$39,362</td>
</tr>
</tbody>
</table>

Total Cost

- One mobile system versus 3 stationary systems
  - Mobile system
    - Estimated average cost ~ $37,000
  - Three stationary systems
    - Three sets of instrumentation
    - Three cabinets
    - Area A system remains the same
      - One hood and duct
    - Independent systems for area C and E
      - Two hoods and two ducts
    - Approximate total ~ $111,000

Agenda

- Background
- System Design
  - Hood Design
  - Duct Design
  - Cabinet Design
    - Testing
  - Location Case Studies
- Cost-Benefit Analysis
- Recommendations and Conclusions
Completed Project Objectives

- Mobile system with single cabinet and sampling section
- Ability to collect data on fires up to 3MW, including HRR
- Testing confirmed safety of cabinet from heat insult
  - Highest temperature in cabinet was 87 F
- Design minimizes the space it takes up
  - Duct is permanently on the ceiling
  - Sampling section, cabinet and hood are removable from the test areas
- Minimized Cost
  - Design and product price comparison

Future Work

- Paint cabinet
- Addition of hydrocarbon analyzer
- Demo cells have the possibility to be test areas with our system at a low cost
- Case study of maintenance costs of three systems versus operation and maintenance costs of mobile system
- Submission of a CER
Acknowledgements

- Thanks to all the helpful and supportive employees at Tyco for their time and expertise and thanks especially to
  - George Oliver
  - Paul Piccolomini
  - Melissa Avila
  - Zach Magnone
  - Chad Goyette
  - Prof. Nick Dembsey
  - Prof. Weizhe Wang
  - Roger Wilkins
  - Sean Cutting
Design of Mobile Fire Products Collector

August 7, 2012

Andre da Vitoria, Drew Martin, Yongbin Ji, Lei Zhang

Global Team

Andre da Vitoria
-Senior WPI
-5yr BS/MS
-ME/FPE

Yongbin Ji
-Senior SJTU
-ME

Drew Martin
-Senior WPI
-5yr BS/MS
-ME/FPE

Lei Zhang
-Senior SJTU
-ME

Project Objectives

- Mobile Fire Products Collector
  - Design system
  - Prototype Cabinet
  - Test Cabinet

- Cost Benefit Analysis
  - Will evaluate the cost of the system
  - Future input for a CER
Schedule

- We will finish our project by Wednesday, August 15, 2012

<table>
<thead>
<tr>
<th>Week</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabinet Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cabinet Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Writing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The need for a Fire Products Collector

- Allows calculation of Heat Release Rate
  - Critical parameter in sprinkler design
- Further our understanding of room fire propagation
  - Understand the repeatability of test fires
- Build and validate fire models
  - Fire models allow inexpensive, efficient means to test fires
  - Streamline development process

Need for Mobility

- Multiple fire testing areas located in two separate buildings
  - Five unique testing areas, as shown below in Cranston site plan
- Different fire tests are done in each test area
  - From large scale room fires to medium scale fires
Existing Calorimeters in Cranston

- Cranston’s small scale cone calorimeter
  - Used for bench scale testing of 100mm x 100mm samples
  - Does not have the capability to test large fires
- Uses oxygen consumption calorimetry to measure the power output of the fire
  - Yields highly accurate results of heat release rate

Fire Products Collector System

- Hood
  - A means of collection of the smoke
- Duct
  - Carries smoke from fire to be analyzed
  - Necessary for gas sampling as part of the calorimetry process
- Cabinet
  - Houses and protects instrumentation
  - Prototyped as part of our project

System Design Concepts

- Cranston has five different fire testing areas that require different ducting solutions
- Mobile part of system on rack
Mobile Design Specifications

- Small Size
  - To fit into each of the testing areas

- Easy to Maneuver
  - Max two person maneuverability
  - Low weight, high durability wheels

- Designed to Withstand
  - Heat and radiation resistant
  - Smoke and water resistant
  - Corrosion resistance

Cabinet Prototype

- Materials
  - Extruded aluminum skeleton
  - Steel outer shell

- Construction
  - Hands on engineering!

Testing Setup

- Verify design and protect instruments from fire insults

- Collaborated with previously planned fire tests
  - UL 1636 room fire, used to test sprinkler activation represents realistic worst case scenario

- Instruments used
  - Thermocouples
  - Heat flux gauge will be used in future tests
Testing Results

Global Team: Benefits & Challenges

- Cross-cultural collaboration
  - One American, one Brazilian and two Chinese team members
- Benefits
  - Multiple approaches to problem solving
  - Increased adaptability
- Challenges
  - Engaging in effective communication
Student Team

- Student Activities
  - Living Together
  - Grocery Shopping
  - Cooking
  - Bowling with SLT
  - Wrentham Outlets
  - Red Sox
  - Tyco Golf Outing (8/17)
  - Student Trips

Student Trips

- New York City
- 3rd Beach, Newport, RI

Benefits

- Tyco
  - Work with new talent on real projects
  - Continue support and collaboration with global universities
  - Enhance TFP’s capabilities
- Students
  - Work with a world leader in fire and security products
  - Collaborate with engineers and technicians
  - Experience a real working environment
Acknowledgements

- Thanks to all the helpful and supportive employees at Tyco for their time and expertise and thanks especially to
- George Oliver
- Paul Piccolomini
- Melissa Avila
- Zach Magnone
- Chad Goyette
- Prof. Nick Dembsey
- Prof. Weizhe Wang
- Roger Wilkins
- Sean Cutting
Appendix P: Instrumentation Data Sheets
Helium Neon Laser Data Sheet:

HNL020R, HNL020L, HNL050R, HNL050L

Red HeNe Laser System

User Guide
MEDTHERM 64 SERIES heat flux transducers and infrared radiometers have been proven in thousands of applications for over thirty years - in ground and flight aerospace testing, fire testing, heat flux standards for flammability testing, heat transfer research, materials development, and furnace development.

NIST traceable comparison calibrations to ISO/IEC 17025 are referenced both to blackbodies as standard sources and MEDTHERM Kendall Absolute Cavity (ECR) Radiometers as standard detectors.

- LINEAR OUTPUT
- OUTPUT DIRECTLY PROPORTIONAL TO HEAT TRANSFER RATE
- ACCURATE, RUGGED, RELIABLE
- UNCOOLED MODELS, WATER COOLED MODELS, GAS PURGED MODELS
- RADIOMETER AND LIMITED VIEW ACCESSORIES
- MEASURE TOTAL HEAT FLUX
- MEASURE RADIANT HEAT FLUX
DAQ Data Sheet

NI CompactDAQ
USB Data Acquisition Systems

- Mix sensor measurements with analog and digital I/O in the same instrument
- Access new, non-analog I/O modules at different rates with multiple timing engines
- Run up to seven I/O tasks simultaneously
- Windows XP support
- Hi-Speed USB communication with NI Signal Streaming Technology
- LabVIEW SignalExpress LE data logging software included
- Four 32-bit general purpose counters built into chassis (access through digital module or BNC triggers)
- BNC trigger connections on the cDAQ-9178 for up to 8 GHz clocks and triggers

Overview
The NI-DAQ 9178 is an eight-slot NI CompactDAQ chassis designed for small, portable, mixed-measurement test systems. Combine the cDAQ-9178 with up to eight NI C Series I/O modules for a custom analog input, analog output, digital I/O, and counter/timer measurement system.

Modules are available for a variety of sensor measurements including thermocouples, RTDs, strain gauges, load and pressure transducers, torque cells, accelerometers, flow meters, and microphones. NI CompactDAQ systems combine sensor measurements with voltage, current, and digital signals to create custom, mixed-measurement systems with a single, simple USB cable back to the PC, laptop, or network.

The cDAQ-9178 has four 32-bit general purpose counters built in. You can access these counters through an installed, hardware-timed digital module such as the NI-9401 or NI-9422 for applications that involve quadrature encoders, PWM, event counting, pulse train generation, and period or frequency measurement.

Use the two built-in BNC connections to share clocks or triggers up to 1 MHz.

The cDAQ-9178 chassis is shipped with the following:
- A/DC converter that plugs directly into the chassis
- USB cable with a thumbscrew lock for strain relief

Power cord sold separately.

The NI-DAQmx driver shipped with every chassis includes the following:
- LabVIEW, LabWindows/CVI, and Measurement Studio
- .NET API for LabVIEW and Measurement Studio
- .NET API for LabVIEW and Measurement Studio
- Example programs for all supported languages
- NI Measurement & Automation Explorer (MAX) for system configuration and test

Comparison Tables

<table>
<thead>
<tr>
<th>Model</th>
<th>Slots</th>
<th>Counters</th>
<th>Number of Simultaneous Tasks</th>
<th>Number of AI Timing Engines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Servomex 4100 Gas Analyzer

The Servomex 4100 analyser is specifically designed to meet the control and product quality monitoring needs of industrial gas producers and users.

- Purpose designed for industrial gas producers and users
- Easy to set up and operate
- Low maintenance
- Extremely stable and reliable sensors
- Can measure up to four gas streams simultaneously
- External analogue input facility
- RS232 serial data output

**Specification**

<table>
<thead>
<tr>
<th>Gases Measured</th>
<th>O₂ (purity)</th>
<th>O₂ (trace)</th>
<th>CO₂ (trace)</th>
<th>N₂O (trace)</th>
<th>CH₄ (trace)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERFORMANCE</td>
<td>Paramagnetic</td>
<td>Zirconia</td>
<td>Infrared</td>
<td>Infrared</td>
<td>Infrared</td>
</tr>
<tr>
<td>Range</td>
<td>0-100% O₂</td>
<td>0-210,000 ppm</td>
<td>0-10 ppm</td>
<td>0-50 ppm</td>
<td>0-50 ppm</td>
</tr>
<tr>
<td>Linearity</td>
<td>&lt;0.05% O₂</td>
<td>&lt;0.1 ppm</td>
<td>0.1 ppm</td>
<td>0.1 ppm</td>
<td>0.1 ppm</td>
</tr>
<tr>
<td>Repeatability</td>
<td>&lt;0.01% O₂</td>
<td>&lt;0.1 ppm</td>
<td>0.1 ppm</td>
<td>0.1 ppm</td>
<td>0.1 ppm</td>
</tr>
<tr>
<td>Response time</td>
<td>12 sec</td>
<td>15 sec</td>
<td>20 sec</td>
<td>20 sec</td>
<td>20 sec</td>
</tr>
<tr>
<td>at sample flow</td>
<td>2000 ml/min</td>
<td>2000 ml/min</td>
<td>2000 ml/min</td>
<td>2000 ml/min</td>
<td>2000 ml/min</td>
</tr>
<tr>
<td>Zero drift/week</td>
<td>0.01% O₂</td>
<td>&lt;1% of reading</td>
<td>0.2 ppm</td>
<td>1 ppm</td>
<td>1 ppm</td>
</tr>
<tr>
<td>Span drift/week</td>
<td>0.02% O₂</td>
<td>2% of reading</td>
<td>2% of reading</td>
<td>2% of reading</td>
<td>2% of reading</td>
</tr>
</tbody>
</table>

Other measurements are available on request

**SIGNAL INPUTS/OUTPUTS**

- Analogue outputs: Two isolated 4-20mA/0-20mA as standard. Additional outputs may be added
- analogue outputs: Freely selectable over the measurement range  
- Serial output: Two floating 4-20mA/0-20mA as standard with data valid contacts
- Alarms: Single ASCII data logging and analyser status output (RS232), User configurable, 2400 to 19200 baud
- PHYSICAL:
  - Dimensions: 430mm x 420mm (19") x Short Chassis depth 470mm (18.6") or Long Chassis depth 600mm (23.6") x 133mm (5U) nominal
  - Weight: Typical 22Kg (48.4lb)

1 or 1% of reading, whichever is greater
2 derived figure, dependent on calibration gases
3 inherently linear, value dependent on calibration gases
4 In range 0-100ppm
5 for a change of 2-10ppm O₂
6 for flow driven sample systems or pressure driven sample systems
7 for 8 psig input
8 whenever is greater

Servomex
Operating Environment
Temperature:
  Operating: 5°C to 40°C/41°F to 104°F
  Storage: -20°C to 60°C/-4°F to 140°F
Atmospheric Pressure:
  11 to 18psi/79 to 124 kPa
  (for operation up to 2000m altitude)
Warm Up Time
  typically 1 hour from ambient (20°C/68°F)
Relative Humidity:
  10-90% RH, non-condensing

Sample Gas
Temperature: 5°C to 40°C/41°F to 104°F
Dew Point: 5°C/41°F below minimum ambient
Condition: Oil free, non-corrosive, non-condensing, non-foamable
Particulates: Filtered to 2µm
Vent: Vent to atmosphere
Sample Pressure: nominal 60 psi (±3 psi), 364 kPa (±21 kPa)
Sample inlet connections:
  Zirconia and Ox infrared
  Sensors: 1/8” OD male
  Paramagnetic Sensors: 1/8” NPT female
  Calibration gas ports for
  auxiliary options: 1/8” NPT female
Sample outlet connections: 1/4” NPT female for all sensor types
  (Note: Pressure driven option uses internal restrictors to provide proper
  flow to the sensor. Additional flow is bypassed around the sensor)

Power Supply
85 to 132 VAC, 47 to 62 Hz (550 VA) maximum
170 to 264 VAC, 47 to 62 Hz (550 VA) maximum

Sample Wetted Materials

<table>
<thead>
<tr>
<th>Sample Wetted</th>
<th>C (Purity)</th>
<th>C (Trace)</th>
<th>H₂</th>
<th>N₂</th>
<th>CH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Stainless Steel (316)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Borosilicate Glass</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Platinum</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Platinum, Inconel, and Alloys</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Stainless Steel (310)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Aluminum</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Viton Blended Zirconia</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Nickel wire</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Steel, Glass</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Gold</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ceric Fluoride</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Nickel</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Pressure Driven Option
Polyethylene

Flowmeter Option
Borosilicate Glass

Capillary

Analysis Option
Aluminum

Injection Port

Internal Filter Option
Polyethylene

Glass Filters

External Filter Option
Stainless Steel (316)

Long Chassis: 608mm/23.7”
Short Chassis: 476 mm/18.8”
Clearance 76.2mm/3.0”
## EC Directive Compliance


It conforms to the following harmonised European standards for product safety and electromagnetic compatibility:

- **EN 61010-1**: Safety requirements for electrical equipment for measurement, control and laboratory use.
- **EN 61326-1**: Electrical equipment for measurement, control and laboratory use - EMC requirements (All induced errors are less than the intrinsic error, with the exception of: O₂ purity <0.05% O₂, O₂ trace <2% of reading).

This product is rated for installation Category F in accordance with EC 654.

This product is rated for "Pollution Degree 2" in accordance with EC 654.

### Performance Specification Continued

<table>
<thead>
<tr>
<th>Gases Measured</th>
<th>O₂ (purity)</th>
<th>O₂ (trace)</th>
<th>CO₂ (trace)</th>
<th>N₂O (trace)</th>
<th>CH₄ (trace)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology:</td>
<td>Paramagnetic (PM) transducer</td>
<td>Zirconia (Zr) transducer</td>
<td>Infrared (IR) transducer</td>
<td>Infrared (IR) transducer</td>
<td>Infrared (IR) transducer</td>
</tr>
<tr>
<td>Minimum recommended output range:</td>
<td>0.05% O₂</td>
<td>&lt;0.01% O₂</td>
<td>0-10 ppm(v) CO₂</td>
<td>0-10 ppm(v) CH₄</td>
<td></td>
</tr>
<tr>
<td>Output fluctuation (peak to peak noise):</td>
<td>No effects</td>
<td>The following have an effect of:&lt;0.1 ppm(v) O₂, &lt;0.5 ppm(v) CH₄, or &lt;0.1 ppm(v) CO</td>
<td>0-10 ppm(v) N₂O</td>
<td>0-10 ppm(v) CH₄</td>
<td></td>
</tr>
<tr>
<td>Cross sensitivity (p/n set on nitrogen):</td>
<td>&lt;0.003% of reading</td>
<td>No effect</td>
<td>1% of reading or 0.1 ppm(v)</td>
<td>1% of reading or 0.5 ppm(v)</td>
<td></td>
</tr>
<tr>
<td>Ambient pressure coefficient: (per 1% change in ambient pressure)</td>
<td>0.2% of reading or 0.02% O₂</td>
<td>&lt;1% of reading or 0.2 ppm(v) O₂</td>
<td>0.5% of reading</td>
<td>0.5% of reading</td>
<td></td>
</tr>
<tr>
<td>Ambient temperature coefficient: (per 10°C/18°F)</td>
<td>&lt;0.1% O₂</td>
<td>&lt;0.15% of reading or 0.1 ppm(v) O₂</td>
<td>1 ppm(v) N₂O</td>
<td>1 ppm(v) CH₄</td>
<td></td>
</tr>
<tr>
<td>Sample pressure effect (for 2-8 psi)</td>
<td>&lt;0.1% O₂</td>
<td>&lt;0.15 ppm(v) or 0.2% of reading</td>
<td>1% of reading or 0.25 ppm(v) CO₂</td>
<td>1% of reading or 0.5 ppm(v) CH₄</td>
<td></td>
</tr>
<tr>
<td>Sample flow effect</td>
<td>&lt;0.1% O₂</td>
<td>0-150 ppm(v) or 0-2% of reading</td>
<td>0.5 to 2.5L/min</td>
<td>1.5 to 2.5L/min</td>
<td></td>
</tr>
<tr>
<td>For flow rate:</td>
<td>100-250 ml/min</td>
<td>200-500 ml/min</td>
<td>1.5 to 2.5L/min</td>
<td>1.5 to 2.5L/min</td>
<td></td>
</tr>
</tbody>
</table>

1 whichever is the greater 2 In range 99 - 100 ppm(v) 3 In range 99 - 100%
Appendix Q: Calorimetry Standards
ASTM E 603: Room Fire tests

Designation: E603 – 07

Standard Guide for
Room Fire Experiments

This standard is issued under the fixed designation E603; the number immediately following the designation indicates the year of
original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A
superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

This guide has been written to assist those planning to conduct full-scale compartment fire
experiments. There are many issues that should be resolved before such an experimental program is
initiated, and this guide is written with the objective of identifying some of these issues and presenting
considerations that will affect each choice of procedure.

This guide deals with any or all stages of fire growth in a compartment. Whether it is a single-
or multi-room experiment, observations can be made from ignition to flashover or beyond full-scale
involvement.

One major reason for conducting research on room fires is to learn about the room fire
buildup process so the results of standard fire test methods can be related to performance in full-scale room
fires, allowing the further refinement of these test methods or development of new ones.

Another reason concerns computer fire modeling. Full-scale tests can generate data needed for
modeling. Comparisons of modeling with full-scale test results can serve to validate the model.

The various results among room fire tests reflect different experimental conditions. The intent of this
guide is to identify these conditions and discuss their effects so meaningful comparisons can be made
among the room fire experiments conducted by various organizations.

1. Scope

1.1 This guide addresses means of conducting full-scale fire
experiments that evaluate the fire-test response characteristics
of materials, products, or assemblies under actual fire
conditions.

1.2 It is intended as a guide for the design of the experiment
and for the use and interpretation of its results. The guide is
also useful for establishing laboratory conditions that simulate
a given set of fire conditions to the greatest extent possible.

1.3 This guide allows users to obtain fire-test-response
characteristics of materials, products, or assemblies, which are
useful for describing or appraising their fire performance
under actual fire conditions.

1.3.1 The results of experiments conducted in accordance
with this guide are also useful elements for making regulatory
decisions regarding fire safety requirements. The use for
regulatory purposes of data obtained from experiments con-
ducted using this guide requires that certain conditions and
criteria be specified by the regulatory authority.

1.4 The rationale for conducting room fire experiments in
accordance with this guide is shown in 1.5-1.8

1.5 Room fire experiments are a means of generating input
data for computer fire models and for providing output data
with which to compare modeling results.

1.6 One of the major reasons for conducting room fire
experiments is as an experimental means of assessing the
potential fire hazard associated with the use of a material or
product in a particular application. This should be borne in
mind when designing nonstandard experiments.

1.7 A rationale for conducting room fire experiments is the
case when smaller-scale fire tests inadequately represent end-
use applications.

1.8 A further rationale for conducting room fire experiments
is to verify the results obtained with smaller scale tests, to
understand the scaling parameters for such tests.

1.9 Room fire tests can be placed into four main categories:
reconstruction, simulation, research, and standardization.

1.10 This standard is used to measure and describe the
response of materials, products, or assemblies to heat and
flame under controlled conditions, but does not by itself

Copyright © ASTM International, 100 Barr Harbor Dr., P.O. Box C70, West Conshohocken, Pennsylvania 19428-2955, United States

Copyright by ASTM Int'l (all rights reserved); Sun Apr 1 10:31:28 EDT 2012
Downloaded Print by
Worcester Polytechnic Inst pursuant to License Agreement. No further reproductions authorized.

Q-2
ASTM E 1623: Medium scale fire

Designation: E1623 – 11

An American National Standard

Standard Test Method for
Determination of Fire and Thermal Parameters of Materials,
Products, and Systems Using an Intermediate Scale
Calorimeter (ICAL)1

This standard is issued under the fixed designation E1623; the number immediately following the designation indicates the year of
original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A
superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This fire-test-response standard assesses the response of materials, products, and assemblies to controlled levels of
radiant heat exposure with or without an external ignitor.

1.2 The fire-test-response characteristics determined by this
test method include the ignitability, heat release rates, mass
loss rates, visible smoke development, and gas release of
materials, products, and assemblies under well ventilated
conditions.

1.3 This test method is also suitable for determining many of
the parameters or values needed as input for computer fire
models. Examples of these values include effective heat of
combustion, surface temperature, ignition temperature, and
emissivity.

1.4 This test method is also intended to provide information
about other fire parameters such as thermal conductivity,
specific heat, radiative and convective heat transfer coeffi-
cients, flame radiation factor, air entrainment rates, flame
temperatures, minimum surface temperatures for upward and
downward flame spread, heat of gasification, nondimensional
heat of gasification (O) and the flame spread parameter (see
Test Method E1321). While some studies have indicated that
this test method is suitable for determining these fire para-
meters, insufficient testing and research have been done to justify
inclusion of the corresponding testing and calculating pro-
cedures.

1.5 The heat release rate is determined by the principle of
oxygen consumption calorimetry, via measurement of the
oxygen consumption as determined by the oxygen concen-
tration and flow rate in the exhaust product stream (exhaust duct).
The procedure is specified in 11.1. Smoke development is
quantified by measuring the obscuration of light by the
combustion product stream (exhaust duct).

1.6 Specimens are exposed to a constant heating flux in the
range of 0 to 50 kW/m² in a vertical orientation. Hot wires
are used to ignite the combustible vapors from the specimen during
the ignition and heat release tests. The assessment of the
parameters associated with flame spread requires the use of line
burners instead of hot wire igniters.

1.6.1 Heat release measurements at low heat flux levels (<
10 kW/m²) require special considerations as described in
Section A1.1.6.

1.7 This test method has been developed for evaluations,
design, or research and development of materials, products, or
assemblies, for mathematical fire modeling, or for research and
development. The specimen shall be tested in thicknesses and
configurations representative of actual end product or system
uses.

1.8 Limitations of the test method are listed in Section 5.5.
1.9 The values stated in SI units are to be regarded as
standard. No other units of measurement are included in this
standard.

1.10 This standard is used to measure and describe the
response of materials, products, or assemblies to heat and
flame under controlled conditions, but does not by itself
incorporate all factors required for fire hazard or fire risk
assessment of the materials, products, or assemblies under
actual fire conditions.

1.11 Fire testing is inherently hazardous. Adequate safe-
guards for personnel and property shall be employed in
conducting these tests. Specific information about hazards is
given in Section 7.

1.12 This standard does not purport to address all of the
safety concerns, if any, associated with its use. It is the
responsibility of the user of this standard to establish appro-
priate safety and health practices and determine the ap-
pliability of regulatory limitations prior to use.

---

1This test method is under the jurisdiction of ASTM Committee E05 on Fire
Standards and is the direct responsibility of Subcommittee E05.21 on Smoke and
Combustion Products.

approved in 1994. Last previous edition approved in 2009 as E1623 – 08. DOI:
10.1520/E1623-11

The boldface numbers given in parentheses refer to the list of references at the
end of this standard.
Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA)

This standard is issued under the fixed designation E2058; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This fire-test-response standard determines and quantifies synthetic polymer material flammability characteristics, related to the propensity of materials to support fire propagation, by means of a fire propagation apparatus (FPA). Material flammability characteristics that are quantified include time to ignition (t_{50}), chemical (\dot{Q}_{chem}), and convective (\dot{Q}_c) heat release rates, mass loss rate (m) and effective heat of combustion (EHC).

1.2 The following test methods, capable of being performed separately and independently, are included herein:

1.2.1 Ignition Test, to determine t_{50} for a horizontal specimen;

1.2.2 Combustion Test, to determine \dot{Q}_{chem}, \dot{Q}_c, m, and EHC from burning of a horizontal specimen; and,

1.2.3 Fire Propagation Test, to determine \dot{Q}_{chem} from burning of a vertical specimen.

1.3 Distinguishing features of the FPA include tungsten-irradiated graphite external, isolated heaters to provide a radiant flux of up to 65 kW/m² to the test specimen, which remains constant whether the surface regresses or expands; provision for combustion or upward fire propagation in prescribed flows of normal air, air enriched with up to 40% oxygen, air oxygen-irradiated, pure nitrogen mixtures or exhaust product flows generated during upward fire propagation on a vertical test specimen 0.305 m high.

1.4 The FPA is used to evaluate the flammability of synthetic polymer materials and products. It is also designed to obtain the transient response of such materials and products to prescribed heat fluxes in specified inert or oxidizing environments and to obtain laboratory measurements of generation rates of fire products (CO, CO₂, and, if desired, gaseous hydrocarbons) for use in fire safety engineering.

1.5 Ignition of the specimen is by means of a pilot flame at a prescribed location with respect to the specimen surface.

1.6 The Fire Propagation test of vertical specimens is not suitable for materials that, on heating, melt sufficiently to form a liquid pool.

1.7 Values stated are in SI units. Values in parentheses are for information only.

1.8 This standard is used to measure and describe the response of materials, products, or assemblies to heat and flame under controlled conditions, but does not by itself incorporate all factors required for fire hazard or fire risk assessment of the materials, products or assemblies under actual fire conditions.

1.9 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. Specific hazard statements, see Section 7.

2. Referenced Documents

2.1 ASTM Standards:

E176 Terminology of Fire Standards
E321 Test Method for Determining Material Ignition and Flame Spread Properties
E1623 Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter (ICAL)

3. Terminology

3.1 Definitions—For definitions of terms used in these test methods, refer to Terminology E176.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 fire propagation, m—increase in the exposed surface area of the specimen that is actively involved in flaming combustion.
Standard Practice for
Full-Scale Oxygen Consumption Calorimetry Fire Tests

This standard is issued under the fixed designation E2067; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice deals with methods to construct, calibrate, and use full scale oxygen consumption calorimeters to help minimize testing result discrepancies between laboratories.

1.2 The methodology described herein is used in a number of ASTM test methods, in a variety of unstandardized test methods, and for research purposes. This practice will facilitate coordination of generic requirements, which are not specific to the item under test.

1.3 The principal fire-test-response characteristics obtained from the test methods using this technique are those associated with heat release from the specimen tested, as a function of time. Other fire-test-response characteristics also are determined.

1.4 This practice is intended to apply to the conduction of different types of tests, including both tests in which the objective is to assess the comparative fire performance of products releasing low amounts of heat or smoke and some in which the objective is to assess whether flashover will occur.

1.5 This practice does not provide pass/fail criteria that can be used as a regulatory tool, nor does it describe a test method for any material or product.

1.6 For use of the SI system of units in referee decisions, see IEEE/ASTM SI-10. The units given in parentheses are provided for information only.

1.7 This standard is used to measure and describe the response of materials, products, or assemblies to heat and flame under controlled conditions, but does not by itself incorporate all factors required for fire hazard or fire risk assessment of the materials, products, or assemblies under actual fire conditions.

Note 1—This is the standard caveat described in section F2.2.2.1 of the Form and Style for ASTM Standards manual for fire-test-response standards. In actual fact, this practice does not provide quantitative measures.

1.8 Fire testing of products and materials is inherently hazardous, and adequate safeguards for personnel and property shall be employed in conducting these tests. Fire testing involves hazardous materials, operations, and equipment. See also Section 7.

1.9 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:

D5424 Test Method for Smoke Obscuration of Insulating Materials Contained in Electrical or Optical Fiber Cables When Burning in a Vertical Cable Tray Configuration

D5537 Test Method for Heat Release, Flame Spread, Smoke Obscuration, and Mass Loss Testing of Insulating Materials Contained in Electrical or Optical Fiber Cables When Burning in a Vertical Cable Tray Configuration

D6113 Test Method for Using a Cone Calorimeter to Determine Fire-Test-Response Characteristics of Insulating Materials Contained in Electrical or Optical Fiber Cables

E84 Test Method for Surface Burning Characteristics of Building Materials

E175 Terminology of Fire Standards

E509 Guide for Room Fire Experiments


E1354 Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter

E1474 Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter

E1537 Test Method for Fire Testing of Upholstered Furniture
Appendix R: Price List of System Components
## Instrumentation

<table>
<thead>
<tr>
<th>Component</th>
<th>Product</th>
<th>Price (+attachment)</th>
<th>Low Cost</th>
<th>High Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas Analyzer</strong></td>
<td>Servomex 4100 4 Gas analyzer</td>
<td>$21,406</td>
<td>$21,406</td>
<td>$24,500</td>
</tr>
<tr>
<td></td>
<td>Signal Group 9128MGA</td>
<td>$24,500</td>
<td>$24,500</td>
<td>$24,500</td>
</tr>
<tr>
<td><strong>Data Acquisition</strong></td>
<td>NI cDAQ-9188 (Ethernet)</td>
<td>$1,399(+339-1299)</td>
<td>$1,438</td>
<td>$2,698</td>
</tr>
<tr>
<td></td>
<td>NI cDAQ-9178 (USB)</td>
<td>$1,099(+339-1299)</td>
<td>$1,438</td>
<td>$2,698</td>
</tr>
<tr>
<td></td>
<td>Agilent 34972A (USB/Ethernet)</td>
<td>$1883(+??)</td>
<td>$1,438</td>
<td>$2,698</td>
</tr>
<tr>
<td><strong>Vacuum Pump</strong></td>
<td>Air Dimensions B081-FP-AA1</td>
<td>$398(+34)</td>
<td>$398</td>
<td>$432</td>
</tr>
<tr>
<td><strong>Dessicant Filter</strong></td>
<td><a href="#">Drierite 27068</a></td>
<td>$109.33(+25.25)</td>
<td>$109.33</td>
<td>$134.58</td>
</tr>
<tr>
<td><strong>Particulate Filters</strong></td>
<td>Whatman Hepa Filter (10 pack)</td>
<td>$80.69</td>
<td>$80.69</td>
<td>$80.69</td>
</tr>
<tr>
<td></td>
<td>United Filtration 710NL</td>
<td>$41.00(110.00)</td>
<td>$151</td>
<td>$151</td>
</tr>
<tr>
<td><strong>Blower</strong></td>
<td>Dayton Blower, 22 1/4 In</td>
<td>$3264(+29)</td>
<td>$3,293</td>
<td>$3,293</td>
</tr>
<tr>
<td><strong>Laser</strong></td>
<td>Newport Green HeNe Laser</td>
<td>$2060.40(+89-339)</td>
<td>$2,149.40</td>
<td>$2,399.40</td>
</tr>
</tbody>
</table>

Low Total : 29024.33  
High Total : 33688.67
<table>
<thead>
<tr>
<th>Description</th>
<th>Ordered</th>
<th>Unit Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>47065T102 Aluminum Inch T-Slotted Framing System, Four-Slot Single, 1-1/2&quot; Hollow Extrusion, 8' Length</td>
<td>5</td>
<td>51.36</td>
</tr>
<tr>
<td>8943K27 Galvanized Low-Carbon Steel Sheet, .046&quot; Thick, 48&quot; X 48&quot;</td>
<td>2</td>
<td>69</td>
</tr>
<tr>
<td>8943K17 Galvanized Low-Carbon Steel Sheet, .046&quot; Thick, 24&quot; X 48&quot;</td>
<td>1</td>
<td>44.32</td>
</tr>
<tr>
<td>47065T224 Aluminum Inch T-Slotted Framing System, 90 Degree Bracket, Single, 2-Hole, for 1-1/2&quot; Extrusion</td>
<td>28</td>
<td>4.06</td>
</tr>
<tr>
<td>47065T163 Aluminum Inch T-Slotted Framing System, Panel Hinge, for 1-1/2&quot; Extrusion</td>
<td>2</td>
<td>14.59</td>
</tr>
<tr>
<td>47065T57 Aluminum Inch T-Slotted Framing System, Slide-Bolt Extrusion Latch, for 1&quot; &amp; 1-1/2&quot; Extrusion</td>
<td>1</td>
<td>20.95</td>
</tr>
<tr>
<td>47065T327 Aluminum Inch T-Slotted Framing System, Drop-in Fastener with Spring-Loaded Ball, for 1-1/2&quot;</td>
<td>50</td>
<td>1.21</td>
</tr>
<tr>
<td>47065T97 Standard Zinc-Plated Steel End-Feed Fastener, for 1-1/2&quot;, Aluminum Inch T-Slotted Framing System, packs of 4</td>
<td>18</td>
<td>2.71</td>
</tr>
<tr>
<td>91306A385 Zinc-Plated Steel Button Head Socket Cap Screw, 5/16&quot;-18 Thread, 1/2&quot; Length, packs of 25</td>
<td>2</td>
<td>37.61</td>
</tr>
<tr>
<td>91306A601 Zinc-Plated Steel Button Head Socket Cap Screw, 5/16&quot;-18 Thread, 3/8&quot; Length, packs of 25</td>
<td>2</td>
<td>37.61</td>
</tr>
<tr>
<td>90133A036 Neoprene Rubber Washer, 5/16&quot; Screw Size, 9/16&quot; OD, .093&quot; Thick, packs of 100</td>
<td>1</td>
<td>906.82</td>
</tr>
<tr>
<td>TOTAL 4 Wheels</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td>Item Code</td>
<td>Description</td>
<td>Quantity</td>
</tr>
<tr>
<td>------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>47065T102</td>
<td>Aluminum Inch T-Slotted Framing System, Four-Slot Single, 1-1/2&quot; Hollow Extrusion, 8' Length</td>
<td>24</td>
</tr>
<tr>
<td>5217T17</td>
<td>Extra-Heavy Duty Pallet Racks, 10 ft</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><a href="http://www.metalsdepot.com/catalog_cart_view.php?msg=">Link</a></td>
<td></td>
</tr>
<tr>
<td>47065T224</td>
<td>Aluminum Inch T-Slotted Framing System, 90 Degree Bracket, Single, 2-Hole, for 1-1/2&quot; Extrusion</td>
<td>72</td>
</tr>
<tr>
<td>47065T97</td>
<td>Standard Zinc-Plated Steel End-Feed Fastener, for 1-1/2&quot;, Aluminum Inch T-Slotted Framing System, packs of 4</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td></td>
</tr>
</tbody>
</table>

**Duct**

<table>
<thead>
<tr>
<th>Item Code</th>
<th>Description</th>
<th>Quantity</th>
<th>Unit Price</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><a href="http://www.metalsdepot.com/catalog_cart_view.php?msg=">Link</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47065T102</td>
<td>14 GA. (.075+/-) thick T304 Stainless Steel Sheet - Dull Mill Finish</td>
<td>10</td>
<td>$408</td>
<td>$4080</td>
</tr>
</tbody>
</table>
Appendix S: List of Materials Components Considered
Gas Analyzer

Servopro 4100 Gas Analyser

The 4100 is designed to meet the process control and product qualification needs of industrial gas producers and users.

- Easy to set up and operate
- Low maintenance
- Extremely stable and reliable sensors
- Can measure up to four gases simultaneously
- External analogue input facilities
- RS232 / RS485 serial data output
- Modbus TM communications

Technology Used

Oxygen purity measurement – Servomex’ unique paramagnetic cell, which offers a fast, linear, accurate, highly stable and selective response in a non-depleting rugged package.

Oxygen at trace levels – Servomex’ unique zirconic cell, which offers an accurate and stable measurement in a design that gives a fast response and exceptionally long service life.

Carbon monoxide, carbon dioxide, nitrous oxide, methane at trace levels – Single beam gas filter correlation photometric technology, which gives a highly stable, sensitive and selective measurement.

Carbon monoxide, carbon dioxide, Methane at % levels – Single beam, single wavelength infrared technology, which gives a highly stable, sensitive and selective measurement.

Moisture at trace levels – externally fitted ceramic impedance dew point transmitter.

Features

- Simultaneously measures up to 4 gas streams
- Paramagnetic sensor with temperature control and pressure compensation for ultimate performance
- Independent autocalibration of all measurements up to 8 isolated analogue outputs and up to 12 relays with follow or freeze option
- Alarm, fault and calibration history log
- Bench top, panel or 19” rack mount

Typical Applications

- Product purity on air separation plant
- Process control on air separation plant
- Monitoring the trace CO₂ on scrubbed air inlet to air separation process
- Bottling/filling plant applications

Price : 21406
Data Acquisition

NI cDAQ 9188

**NI CompactDAQ 8-Slot Ethernet Chassis**

- Choose from more than 50 hot-swappable I/O modules with integrated signal conditioning
- Measure up to 256 channels of electrical, physical, mechanical, or acoustic signals
- Run up to seven hardware-timed analog I/O, digital I/O, or counter/timer operations simultaneously
- Stream continuous waveform measurements with patented NI Signal Streaming technology
- Simplify setup with zero configuration networking and a built-in Web-based configuration utility
- Measure in minutes with NI-DAQmx software and automatic code generation using the DAQ Assistant


Price: 1399
NI CompactDAQ 8-Slot USB Chassis

- Choose from more than 50 hot-swappable I/O modules with integrated signal conditioning
- Four general-purpose 32-bit counter/timers built into chassis (access through digital module)
- Run up to 7 hardware-timed analog I/O, digital I/O, or counter/timer operations simultaneously
- Stream continuous waveform measurements with patented NI Signal Streaming technology
- Built-in BNC connections for external clocks and triggers (up to 1 MHz)
- Measure in minutes with NI-DAQmx software and automatic code generation using the DAQ Assistant


Price : 1099
NI cDAQ 9211

4-Channel, 14 S/s, 24-Bit, ±80 mV Thermocouple Input Module

- 4 thermocouple or ±80 mV analog inputs
- 24-bit resolution, 50/00 Hz noise rejection
- Hot-swappable operation
- -40 to 70 °C operating range
- NIST-traceable calibration

Price: 339

34972A LXI Data Acquisition / Data Logger Switch Unit


Key Features & Specifications
- 3-slot LXI data acquisition unit with 6 ½-digit DMM (22-bit) and 8 plug-in modules to choose from
- Measures 11 different input signals including temperature with thermocouples, RTDs and thermistors; DC/AC volts or current; 2- or 4-wire resistance; frequency and period
- Accepts all 34970A switch and control plug-in modules, and is backward compatible with the 34970A SCPI command set
- 1Gbit LAN and USB 2.0 for easy connectivity to the PC
- USB memory port for data storage or transfer
- Graphical Web interface for easy set up and control
- Free BenchLink data logger software to create tests without programming

Description
The Agilent 34972A Data Acquisition / Data Logger Switch Unit consists of a 3-slot mainframe with a built-in 6 ½ digit DMM and 8 different switch & control modules. This product features built-in LAN and USB interfaces so you can easily connect to a PC or laptop without needing to purchase additional IO cards or converter interfaces. The intuitive graphical Web Interface offers easy remote control over the network with per channel measurement configuration, data logging and data monitoring. With the 34972A, there is no computer required for field applications. Use a USB flash drive to upload data logging configurations from BenchLink Data Logger into the 34972A and to transfer large data sets back to the computer. Simply connect the USB stick to your PC when you return and easily import into a spreadsheet or other applications for data analysis.

The 34972A can accept any of the 34970A plug-in modules. With a simple address change the 34972A is easily integrated into an existing test with no wiring or hardware changes. The plug-in modules also feature on-board screw terminals and relay closure count so you can create a compact data logger, full-featured data acquisition system or low-cost switching unit that is easy to connect, configure and use on the bench, on a network or in field applications.

Plug-In Module Product Comparison

The included BenchLink Data Logger software provides a familiar Microsoft® Windows® interface for test configuration and real-time data display and analysis. Setup and make measurements quickly, export data or use the built-in graphs to log your results. Download free BenchLink Data Logger software. Or, use the 34830A BenchLink Data Logger Pro that adds advanced data logging and decision making for your more complex data acquisition tasks. Download free BenchLink Data Logger software.
Vacuum Pump
Air Dimensions B081-FP-AA1

Price: 398
Gas Train Protection

Desiccant Air Filters
http://www.mcmaster.com/#catalog/118/966/=kbshet

5164K76

High-Pressure Chemical Resistant—Offer excellent resistance to synthetic compressor lubricants, hydrocarbons, solvents, acids, and other chemicals. All have clay desiccant to remove not only moisture, but also oil and oil vapor. They also have a built-in filter to capture particles down to 0.3 microns. Body is polyurethane. Bowl is transparent so you can view the desiccant, which darkens when saturated. Dryers lower inlet air dew point by 20% and can be mounted vertically and horizontally. Max. pressure is 250 psi. Max. temperature is 180° F.

Pipe size 1/2 model has a two-piece housing with built-in mounting bracket. Desiccant can be replaced but not reactivated. Inlet and outlet connections are NPT male.

Price : 199
Whatman HEPA-VENT Disposable Filters

Whatman HEPA-VENT Disposable Filters, Whatman Filter Dispos HEPA-VENT PK10 is a reliable and dependable addition to the Whatman Filters family of products. Combining top-notch and uncompromising quality with an affordable price, the Whatman HEPA-VENT Disposable Filters, Whatman Filter Dispos HEPA-VENT PK10 6723-5000/ 28137-860 can fulfill your laboratory needs while still offering a great value for the money.

Product Category Description:

Ideal for venting incubators, ovens and lyophilizers. Retains 99.97% of all particles greater than or equal to 0.3µm. Glass microfiber filter media is laminated on both sides with a monofilament and treated to be mildly hydrophobic. Filter features high flow rates with low pressures. Polypropylene housing is 1.8L x 2.1dia.". Stepped barb connectors on both ends. (Whatman 6723-5000)

http://www.opticsplanet.com/whatman-hepa-vent-disposable-filters-whatman-6723-5000.html?gclid=CJGV1t7-67MCFU-d4AodYCwA1Q&ef_id=ULMKCAAAF4M8Sh@p:20121126061952:s

Price : 90
Nylon Housing Particulate Filter

Nylon housings are an economical choice for sample systems as well as low pressure compressed air. A wide variety of filter elements are available to meet the most demanding applications. Each housing is available with 3 drain options; 1/8” NPT, Manual Twist Drain or No Drain. For liquid filtration we recommend using a version with no drain.

Price : 41

http://www.unitedfiltration.com/nylonhousings1.html
Blower

Dayton Blower 22 ¼ In

Blower, Forward Curve, Belt Drive, Unassembled, Wheel Diameter 22 1/4 Inches, Shaft Diameter 1 3/16 inch, Airflow @ 0.375/0.500 /0.750 Inch Static Pressure 6650/6030/4630 CFM, Blower Speed 412 RPM, Includes 1 1/2 HP 115/230 Volt 1 Phase Motor, Drives And Weatherproof Drive Cover, Height 44 Inches, Width 44 Inches, Depth 38 Inches, Inlet Diameter 23 7/8 Inches, Outlet Height 24 Inches, Outlet Width 17 3/8 Inches, Maximum Inlet Air Temperature 250 Degrees F, CW Rotation Viewed From Drive Side

Grainger Item #
7C896

Price (ea.)
$3,251.00

Brand
DAYTON

Mfr. Model #
7C896

UNSPSC #
40101601

Ship Qty
1

Sell Qty (Will-Call)
1

Ship Weight (lbs.)
433.2

Availability
Ready to Ship

Catalog Page No.
4331

Country of Origin
USA

(Country of Origin is subject to change.)

| Item Type | Blower Type | Wheel Dia. (in.) | CFM @ 0.125-in. | CFM @ 0.250-in. | CFM @ 0.375-in. | CFM @ 0.560-in. | CFM @ 0.750-in. | dBA @ 6 Feet | Max. Inlet Temp. (Deg. F) | Max. Ambient Temp. (F) | Voltage | Phase | Hz | Full Load Amps | Motor HP | Motor RPM | Motor Enclosure | Motor Frame | Motor Type | Shaft Dia. (in.) | Height (in.) | Width (in.) | Depth (in.) | Inlet Dia. (in.) | Discharge Height (in.) | Discharge Width (in.) | Wheel Width (in.) | Blower RPM | Rotation | Bearing Type | Wheel Material | Housing Material | Housing Finish | Footnotes | Includes |
|-----------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------------|-----------------|---------------------|-----------------|---------|-------|--------------|---------|----------|----------------|-----------|----------|-------------|------------|-----------|----------------|--------------|-------------|-----------|----------|---------|-------------|--------------|----------------|-------------|-----------|----------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|-------------|-------------|----------|--------|--------|-------------|--------------|------------- |
Smoke Opacity Laser

Green HeNe Laser, 543 nm, 2.0 mW

http://search.newport.com/?x2=sku&q2=R-30972

The R-30972 Green HeNe Laser generates a randomly polarized output of 2.0 mW (minimum) at 543 nm. Longitudinal mode frequency is approximately 303 MHz. Utilizing enhanced designs and superior optical components these HeNe lasers deliver unsurpassed operational stability and lifetimes. The mirror quality and performances are optimized to result in the highest quality HeNe lasers available in the market. These high-performance lasers are supported by a one-year warranty and are available off-the-shelf. CE compliant, Class 3R. The power supply is included.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td>R-30972</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>543 nm</td>
</tr>
<tr>
<td><strong>Output Power</strong></td>
<td>2.0 mW</td>
</tr>
<tr>
<td><strong>Beam Diameter (1/e²)</strong></td>
<td>0.83 mm</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>Random</td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>1.0 %</td>
</tr>
<tr>
<td><strong>Spatial Mode</strong></td>
<td>TEM00</td>
</tr>
<tr>
<td><strong>Longitudinal Mode</strong></td>
<td>303 MHz</td>
</tr>
<tr>
<td><strong>Beam Divergence Full Angle</strong></td>
<td>0.84 mrad</td>
</tr>
<tr>
<td><strong>Power Requirements</strong></td>
<td>120/240 VAC, 50/60 Hz</td>
</tr>
<tr>
<td><strong>Suggested Laser Mount</strong></td>
<td>ULM or ULM-TILT</td>
</tr>
<tr>
<td><strong>Laser Head Size</strong></td>
<td>21.00 L x 1.75 D in.</td>
</tr>
<tr>
<td><strong>Beam Drift, Long Term</strong></td>
<td>&lt;0.05 mrad</td>
</tr>
<tr>
<td><strong>CDRH Class</strong></td>
<td>IIIa</td>
</tr>
<tr>
<td><strong>CE Certified</strong></td>
<td>Yes</td>
</tr>
</tbody>
</table>

Price: 2090
Structure

Screws

Zinc-Plated Steel Button Head Socket Cap Screw, 5/16"-18 Thread, 1/2" Length, packs of 25

91306A385

Zinc-Plated Steel Button Head Socket Cap Screw, 5/16"-18 Thread, 1/2" Length, packs of 25

Price: 6.82 per package
Zinc-Plated Steel Button Head Socket Cap Screw, 5/16"-18 Thread, 1/2" Length, packs of 25

91306A601

Zinc-Plated Steel Button Head Socket Cap Screw, 5/16"-18 Thread, 3/8" Length, packs of 25

Price: 6.86 per package
Washers

*Neoprene Rubber Washer, 5/16" Screw Size, 9/16" OD, .093" Thick, packs of 100*

<table>
<thead>
<tr>
<th>Neoprene Rubber Washer, 5/16&quot; Screw Size, 9/16&quot; OD, .093&quot; Thick, packs of 100</th>
<th>1 pack</th>
</tr>
</thead>
<tbody>
<tr>
<td>90133A036</td>
<td></td>
</tr>
</tbody>
</table>

Price: 10.48 per package
Members

*Aluminum Inch T-Slotted Framing System, Four-Slot Single, 1-1/2" Hollow Extrusion, 8' Length*

| 47065T102 | Aluminum Inch T-Slotted Framing System, Four-Slot Single, 1-1/2" Hollow Extrusion, 8' Length | 5 each |

Price: 61.31
Plates

*Galvanized Low-Carbon Steel Sheet, .046" Thick, 48" X 48"

| 8943K27 | Galvanized Low-Carbon Steel Sheet, .046" Thick, 48" X 48" | 2 each |

Price: 69.00
Galvanized Low-Carbon Steel Sheet, .046” Thick, 24” X 48”

8943K17

Galvanized Low-Carbon Steel Sheet, .046” Thick, 24” X 48”

1 each

Price : 69.00
Brackets

*Aluminum Inch T-Slotted Framing System, 90 Degree Bracket, Single, 2-Hole, for 1-1/2" Extrusion*

28 each

Price: 6.06 each
Hinges

*Aluminum Inch T-Slotted Framing System, Panel Hinge, for 1-1/2" Extrusion*

| 47065T163 | Aluminum Inch T-Slotted Framing System, Panel Hinge, for 1-1/2" Extrusion | 2 | each |

Panel Hinge

Price: 19.45
Latch

Aluminum Inch T-Slotted Framing System, Slide-Bolt Extrusion Latch, for 1" & 1-1/2" Extrusion

**47065T57**

Aluminum Inch T-Slotted Framing System, Slide-Bolt Extrusion Latch, for 1" & 1-1/2" Extrusion

1 each

---

Slide-Bolt Extrusion Latch

Price : 20.95
Other Fasteners

*Aluminum Inch T-Slotted Framing System, Drop-in Fastener with Spring-Loaded Ball, for 1-1/2"*

![Image](image-url)

**47065T327**

Aluminum Inch T-Slotted Framing System, Drop-in Fastener with Spring-Loaded Ball, for 1-1/2"

| 50 | each |

Price: 1.21 each
Standard Zinc-Plated Steel End-Feed Fastener, for 1-1/2", Aluminum Inch T-Slotted Framing System, packs of 4

Price: 2.71

47065T97

18 packs
Appendix T: Cabinet Instructional Recommendations
The Solution to the problem given was solved with only convection and radiation in mind from the fire. Direct contact should be avoided. The previous statement implies any kind of contact with the fire itself or hot surfaces within the fire environment. Avoiding direct contact would reduce the input of heat, possibly, dramatically as conduction is a method of heat transfer that can be easily avoided.

As with any sensitive equipment the instrumentation cabinet should be calibrated daily. Frequent calibration will ensure the validity of the data as well as the integrity of judgments made from data obtained by the device being calibrated.

When not in use, the cabinet should be stored in a dry place where the temperature does not exceed 100 degrees on any given day. Storing it in a dry and somewhat cool place will ensure the equipment inside the instrument cabinet is not damaged.

As with any galvanized products the coating will usually wear away over time due to abrasion or chemical abuse. To counteract the loss of the zinc coating of the outside plates, the cabinet should be painted so no metal from the outside plates is visible.

Due to the prototype instrumentation cabinet not being built with precision instruments, the outside plates do not meet perfectly. The imperfections in these junctions mean the box needs to be sealed as smoke and water might creep in to damage the instruments. The solution found by the design team was to seal these junctions with Aluminum tape and to replace the tape at least weekly to ensure the integrity of the seal. However effective the aluminum tape was for the setting the cabinet was exposed to, a better method could be procured. Along with a better seal for the cabinet, a system to keep pressure positive inside the box, relative to ambient conditions, should be implemented. The positive pressure would ensure that even in the scenario of a leak, the instrumentation would not be compromised.
Bibliography


Norfab. (2012). Ball Joint.


