PRODUCT EVALUATION AND PROCESS IMPROVEMENT GUIDELINES FOR THE PERSONAL PROTECTIVE EQUIPMENT MANUFACTURERS BASED ON HUMAN FACTORS, NIOSH GUIDELINES AND SYSTEM SAFETY PRINCIPLES

by

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ABSTRACT

Dissertation Title: Product Evaluation and Process Improvement Guidelines for the Personal Protection Equipment Manufacturers based on Human Factors, NIOSH Guidelines and System Safety Principles
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A firefighter's body is usually covered with protective gear during search and rescue operations. Therefore, the natural heat-sensing mechanism of the body is incapable of sensing the ambient temperature, possibly putting firefighters at risk. The Fire-Eye device that attaches to the visor of the head gear is designed to restore situational awareness of the firefighter by showing varying heat intensity through different colored warning indicators in the firefighter's line of sight. Human factors evaluation of the performance of the warnings in the Fire-Eye device was conducted in laboratory-scale (i.e., climatic chamber tests) and in Full-scale (i.e. fire tests in ISO room) environments. The evaluation involved checking the consistency and reliability of different warning indicators by conducting within-device and between-device experiments. A static oven, representing the conductive type of heat; a fire equipment evaluator, with high speed convective flow loop, and a radiant panel, with intense heat flux were used to conduct laboratory-scale tests. The Full-scale fire tests involved three types of fuels: natural gas, heptane, and living room furniture to conduct fire burns. Statistical data analysis was conducted using ANOVA (α= 0.05) for the within-device testing and the between-device testing for the laboratory-scale tests. The data analysis results indicated that there was a significant difference in the performance of the Fire-Eye device among the four laboratory-scale methods for within-device testing as well as between-device testing. ANOVA was also conducted for the comparison of device performance between the laboratory-scale tests and the Full-scale fire tests, indicating that there is a significant difference in the performance of Fire-Eye device between these two testing environments. The results suggest a need to reengineer the device in order to make it more robust in terms of the appropriate status indicators within different fire scenarios.

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LIST OF ACRONYMS

a	Ampere
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
A/D	Analog-to-Digital
Al	Alumel
BFRL	Building Fire Research Code
BTU/ft^3	BTU per cubic feet
cm	Centimeter
Cr	Chromel
^oC	Degrees Centigrade
DAQ	Data Acquisition System
DV	Digital Video
ft	foot/feet
^oF	Degrees Fahrenheit
FE	Fire-Eye device
FE #	Fire-Eye number
FETC	Fire-Eye Thermocouple
FP	Facepiece
FEE	Fire Equipment Evaluator
FT	Front
Ft^3/min	Cubic feet per minute
Gal/min	Gallon per minute
Hg	Mercury
Hz	Hertz
HRR	Heat release rate
kHz	Kilohertz
in	Inch
IE	Inside
ISO	International Standards Organization
kW	Kilowatts
kJ/L	Kilojoules per liter
NFPA	National Fire Protection Association
NG	Natural Gas
Ni	Nickel
NIST	National Institute of Standards and Technology
L/s	Liters per second
L/min	Liters per minutes
min	Minute
m	Meter
mm	Millimeter
m/s	Meters per second
mV	Milli-volt
mAh	Milli Amperes hour

MW	Megawatts
M #	Mask number
MJ/kg	Mega joules per kilogram
MIDAS	MIDAS computerized data collection system
ON	Power on the device
OFF	Power off the device
Pa	Pascal
Rep	Repetition
ROM	Read Only Memory
RP	Radiant Panel
RR	Rear
RTD	Resistance-Temperature Device
s	Second
SO	Static Oven
Test #	Test number
TC	Thermocouple
TC #	Thermocouple number
TI	Temperature Inside
TO	Temperature Outside
UBC	Uniform Building Code
V	Volt
%	Percentage

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SECTION I: LABORATORY-SCALE EXPERIMENTS

1.0 INTRODUCTION

1.0.1 Introduction

Firefighters and first responders often work in adverse fire environments involving high temperatures, high humidity, extreme thermal radiation, and/or smoky conditions. These extreme conditions can cause bodily injury to firefighters and can damage the expensive Nomex turnout gear used by them, (which is now mandated for every firefighter). Also, with advanced personal protective equipment (PPE), firefighters are 'going in deeper' during fires and are staying there longer, while their biological temperature-sensing organ, the outer ear, is covered up by the Nomex hood and other PPE. Largely as a result of Nomex hood use, firefighters no longer have a reliable biological means of determining the ambient temperature around them. Firefighters instead have to depend upon their experience to make a 'best guess' as to when to leave a particular fire environment to avoid thermal injury to themselves or to their equipment. Based on this need of registering the ambient temperature to a firefighter, a simple electronic temperature encoder, known as the "Fire-Eye" device, was invented by a group of firefighters. The Fire-Eye device can be described as a 'personal situation awareness tool' that helps firefighters to make better decisions through providing an accurate indication of the temperature in the workspace surrounding them, and which ultimately seeks to reduce heat-related injuries and damage to equipment.

Due to the fact that ancillary PPE devices and technologies such as the Fire-Eye device cannot be tested to the standards promulgated by entities such as the National Fire Protection Association (NFPA, because such testing must be instituted by the manufacturers of the systems to which a particular device augments, and not the developers of the device), the developers of the Fire-Eye device sought data from NFPA-like testing that would support their efforts to enter the PPE market. Such testing would provide the data needed to verify the developer's internal reports, and from field data collected with representative users. It is hoped that the data herein provides the information needed by Fire-Eye developers such that the device can be marketed to prospective PPE system purchasers.

1.0.2 Heat Transfer Mechanism

There are three mechanisms by which thermal energy is transported: convection, conduction, and radiation. Convection is the transfer of heat by actual movement of the warmed matter or gases in the atmosphere—it is the transfer of heat energy in a gas or liquid by movement of currents. Conduction is the transfer of energy through matter from particle to particle—it is the transfer and distribution of heat energy from atom to atom within a substance. Conduction is most effective in solids, but it can also happen in fluids. Radiation is the transfer of energy by electromagnetic waves that directly transports energy through space—it is one of the fastest and most intense methods of transfer of heat energy. A fire scenario may involve the transfer of heat energy forming any combination of the three mechanisms. Therefore, it is necessary to test the performance of a temperature-warning device in experimental conditions representing each of the three mechanisms. It is also necessary to validate the performance of the device in a dynamic fire environment involving all three types of mechanisms.

In order to thoroughly validate the performance of the device in keeping with the elements above, it was thought prudent to test the device in laboratory scale experiments utilizing conductive, convective and irradiative devices during the first phase of testing. The second phase of testing involved large-scale, realistic fire scenarios also involving all three above mechanisms of heat transfer, which would help to compare the performance of the device between the two experimental phases.

1.0.3 Fire-Eye Device Description

Fire-Eye uses a green light (the left-most indicator in the wearer's field-of-view) and a red light (the right-most indicator in the wearer's field-of-view) to indicate temperature conditions to the wearer. The temperature is sensed at eye level at the lower tip of the sensor or display unit, and near the center of the facepiece (see Figure 1). The temperature reading takes into account both the temperature of the *environment* and temperature changes related to the *user's protective gear*. The device indicates seven temperature conditions (see Appendix A).

Fire-Eye Development, Inc. has been granted two patents for the Fire-Eye design and has another new patent pending that will include individual physiological characteristics such as the user's heart rate and blood pressure. The manufacturer intends to expand the concept of the Fire-Eye device to a family of new "Personal Situational Awareness" tools that will help to ensure that workers are aware of their surrounding conditions when operating in hazardous environs.

Fire-Eye is compatible with existing firefighting equipment and is designed to be worn on the facepiece of the firefighter. The manufacturer claims that the device warns about the condition of the protective gear when the gear nears its operating limits. The manufacturer claims that the device is "simple to use and understand once the user gets acquainted with the warning indicators." Fire-Eye is self-testing and has a verifiable operation test button to confirm its operability.

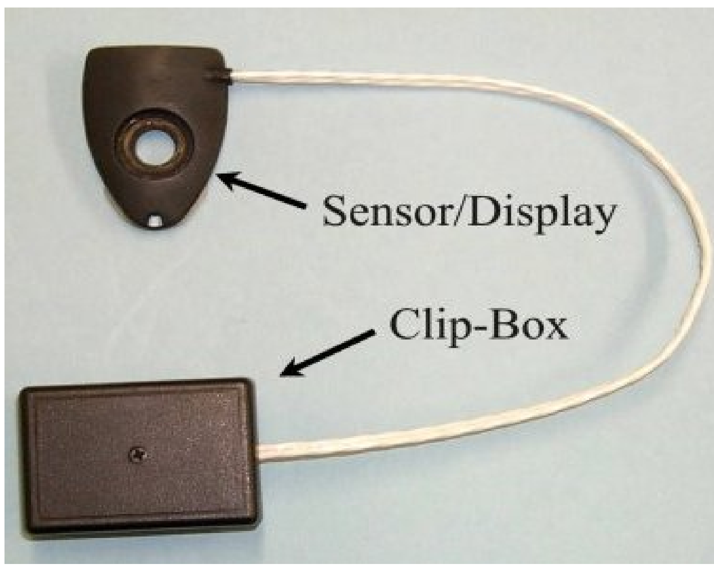


Figure 1. Fire-Eye display device along with the clip-box unit.

The device's calibration can be tested under actual work conditions by depressing a small button provided on the clip-box unit. Fire-Eye maintains a "failsafe design" (both warning lights blink in case of device failure) but does not generate any indications when it malfunctions. The device is able to tolerate operable environments up to 400^o Fahrenheit (F), and is safe for firefighters in extreme situations. The manufacturer claims that the thresholds for the sequence of status indicators were determined with the help of experienced firefighters in real and simulated firefighting scenarios.

Fire-Eye was designed using the Atmel AT90LS4434 processor chip, which has an integrated analog to digital function (A/D). The design uses the Atmel chip to compare a precision reference resistor to a platinum thin-film resistance temperature device (RTD) sensor. The manufacturer suggests that the method of comparison depends only upon the relative resistance of the RTD sensor and the reference resistor. The method of comparison does not depend upon any other factors, such as the battery supply voltage or the temperature of the processor. The sensitivity of the A/D conversion process is approximately one count for each degree-F change, and the repeatability of measurements is approximately +/- 0.5 counts. The embedded software in the processor's flash read only memory (ROM) compares the A/D values to each temperature threshold and controls the intensity and color of indicator lights appropriately. The calculated accuracy of the overall A/D and resistance comparison process yields a result of approximately $\pm 4^{o}$ F, including reference resistor and sensor tolerances.

The manufacturer claims that the overall accuracy of the Fire-Eye device is in the range of $\pm 5^{o}$ F. The reference resistor is a precision metal-film resistor with a 0.1 % accuracy specification with a very low temperature coefficient and is designed for long-term stability. The detailed specification of the reference resistor and Platinum RTD are outlined in Appendix A. As per the claims of the manufacturer, even though the product had been tested previously, systematic documentation of the performance characteristics of the device using specific test procedures in conditions of varying heat was not available. In order to validate the performance of the device independently, the Research Team had to devise a systematic test plan that would simulate all types of heat exposures to which the Fire-Eye device can be exposed to in both laboratory (controlled) and in 'real world' (uncontrolled) live fire scenarios.

1.1 General Fire Statistics

1.1.1 Fire Statistics

In the United States, more people are killed by fires than all other natural disasters combined. On an average every year, there are about 1.9 million fires killing about 4000 people, and injuring about 20,000 more, including about 100 firefighters killed in the active line of duty (USFA, 2006). The statistics from year 2005 continue to show similar trends, reporting 1.6 million fires, injuring over 18,000 civilians, and killing 115 firefighters on line of duty. The damages caused by fires in the year 2005 were estimated to be at $10.7 billion. In 2005, there were an estimated 511,000 structure fires which contributed to approximately 85% of all civilian fire deaths and 85% of civilian injuries. The residential fire problem represented approximately 83% of all fire deaths and 77% of the injuries to civilians in 2005 (USFA, 2005). There are about 30,000 fire departments with 1.1 million firefighters (career: 305,150; volunteer: 795,600) serving actively with them. 80% of the active firefighters are within the age group of 20 through 50 years (NFPA, 2004).

Firefighting is a dangerous profession. Firefighters make quick decisions in high-stress environments, constantly assessing the situation, planning their next set of actions, and coordinating with other team members, often with an incomplete picture of the situation. As one of the firefighter innovator of Fire-Eye device summarized it best: "Firefighting is making a lot of decisions on little information."

1.1.2 Task Analysis of Firefighting Activity

The fire brigade responds to emergencies. According to Bretschneider, Brattke, and Rein (2006), the firefighting operation can be classified into three main tasks: emergency medical services, technical services and fighting fires.

a) *Task 1 - Fighting Fires*: Fighting fires roughly involves 8 to 15% of total operations. Fighting fires is the oldest and most honored task of a fire brigade. Fire brigades encounter hazardous conditions when fighting fires. The main tasks of a firefighter during fire include the search and rescue of victims and the "inside attack," which means extinguishing the fire from inside the building. When firefighters go inside a burning building, they are confronted with high temperatures, high humidity, toxic gases, vapors and dense smoke. Therefore, a SCBA and a breathing mask are worn to protect against smoke inhalation and toxic fumes. In order to not lose the orientation in the structure, the general procedure during fire interventions is to shuffle through the structure with one hand against the wall due to dense smoke. Because of high heat and dense smoke in the upper part of the room, the firefighters sometimes have to crawl. Due to such circumstances, searching for victims might need a lot more time. Further risks for the firefighters could arise from falling objects, breaking structures and unstable floors. Fire operations are extremely dangerous, physically demanding and stressful for the firefighters because of the hazardous operating conditions (Bretschneider, Brattke, and Rein, 2006).

b) *Task 2 - Technical Services:* Technical services involve 5 to 20% of all operations. They include the recovery of vehicles after traffic accidents, extraction of victims of the accidents, the disposal of storm and flood damage, and nuclear biological chemical (NBC) or hazardous materials (HAZMAT) removal. During NBC operations, the firefighters have to wear a SCBA and a chemical suit, in addition to standard protective clothing, due to the presence of toxic gases, vapors and chemicals (Bretschneider, Brattke, and Rein, 2006).

c) *Task 3 - Emergency Medical Service (EMS):* EMS involves about 60-70% of a firefighter's job. They are a part of a firefighter's job only in countries such as the USA, France, Japan and Germany. EMS includes rescue operations and medical care of the injured and sick people. When involved in EMS, the firefighters are not confronted with especially hazardous surrounding conditions. Therefore, *typically* the standard protective clothing other than SCBA and breathing mask is sufficient in such circumstances (Bretschneider, Brattke, and Rein, 2006).

1.2 Physiological Parameters of Firefighters

Extensive research is being carried out related to fire and firefighters. One of the most important research areas is related to the physiological parameters of the firefighter and the impact of the fire on them. Conventionally, human factors and ergonomics deals with the aspects of human capability and limitations based on the physiology of human body. Therefore, this research is an integral part of human factors engineering as well as fire research.

There is no doubt that the range of services provided by firefighters continues to expand. Along with battling structural fires, the local fire department is also responsible for mitigating hazardous materials incidents, performing technical rescues, and providing emergency medical services as stated earlier. The threat of terrorist incidents increases the fire department's responsibility, as firefighters must be taught to recognize the signs of chemical or biological attack, and the proper response to such scenarios.

According to Holcombe (1981), while fighting structural fires, firefighters are not only exposed to one thermal hazard but two: burns and heat stress. A firefighter's core body temperature is affected by the external heat as well as the workload, but in very different ways. Heat from the environment has to first get through the ensemble and the skin before it may influence the core temperature, whereas the workload provokes the heat flux from the core temperature in the opposite direction. The workload first increases the core temperature before the excessive heat is transmitted to the skin. When the outside temperature is more than the skin temperature, then the skin can only get rid of excessive heat by evaporation of sweat on the skin surface (Rossi, 2003). The evaporative cooling should further compensate for the heat storage due to the external heat.

1.2.1 Firefighter Burns and Injuries

The US firefighting statistics (Karter and Leblanc, 1995) show that 52% of the injuries actually occur while battling a fire, and only 10% of these injuries are burns. There are substantial lethal accidents as well. The statistics mentioned earlier show that, on average, more than 100 firefighters die in the active line of duty every year. Makinen (1991) estimates that about 80-90% of injuries are due to the human failures of *misrepresentation* or *misinterpretation* of the fire situation. Wenzel and Piekarski (1982) depicted that the firefighter's concentration is greatly reduced as soon as the core temperature increases and the number of mistakes made by him also increase in proportion. Schopper – Jochum et al., (1997) suggested that the core temperature of fully equipped firefighters can increase, even at moderate temperatures, and it can be assumed that a great number of injuries are due to overheating of the body.

Holcombe and Hoschke (1986) have identified several possible main factors responsible for burns in the firefighters. The first factor is the *incident heat flux intensity* and the way it varies during the firefighter's exposure. The second factor is the *duration of exposure* (including the time it takes for the temperature of the garment to fall below that which causes injury after the source is removed). The third factor is the *level of total insulation* between the fire source and the skin. The fourth factor is the *extent of degradation of the garment materials* during exposure. The fifth factor is the *condensation on the skin of any vapor or pyrolysis products* released as the temperature of the fabric increases. In some studies, the behavior of the skin when exposed to intensive heat sources has been analyzed with experimental animals. It has been shown that the body acts as a heat sink in such circumstances (Rossi, 2003).

Firefighters are also subjected to the effects of shiftwork and to the demands (physical and mental) and dangers of their profession. All of the earlier-mentioned factors can contribute to their injuries. Glazner (1996) tried to identify factors involved in injuries to firefighters relating to the timing, frequency, types, and places of occurrence of injuries in three different municipal fire departments. The findings suggest that the most frequent injuries involved inhalation of hazardous materials and lacerations. Ninety-two percent of the injuries occurred at the fire scene, and their causes were related to firefighting duties, such as rescue, extinguishment and overhaul. Even though only 54% of the fire alarms nationwide occurred from 12:00 to 16:00 and from 18:00 to 24:00 (42% of a 24 hour day), 68% of the injuries sustained by firefighters occurred during these time periods. As per Glazner (1996), firefighters were more likely to be injured per alarm, at meal time or on the night shift. The researcher also found that serious injuries were more prevalent during standardly-accepted meal times. The timing of the highest frequencies of injuries indicates that, due to the shift work nature of firefighting, both disruption of eating patterns and fatigue increases the risk of work-related injury to firefighters. Glazner (1996) suggests that by understanding the contribution of factors, especially the human ones, such as altered metabolism (due to disruption) and fatigue (due to time elapsed since awakening, alteration/disruption of sleep-wake pattern etc.), interventions can be developed to reduce the injuries to firefighters.

1.2.2 Conditions Encountered while Firefighting

In fire situations, heat exposure is mostly due to radiation (80%) but convection and conduction can also occur (Krasny, 1986). The radiant heat intensity can reach to 40 kW/m^2 during domestic fires and even more than 200 kW/m^2 during large fuelled and uncontrolled fires (Schoppee et al., 1986). The flame temperature usually reaches 800 to 1100 ^oC during fires and the heat is radiated at wavelength of 1 to 6 µm, the maximum being at about 2 µm (Abbott and Schulman, 1976). The heat load experienced by the firefighter depends on the distance of the firefighter from the fire. The intensity of a fire is also dependent on the smoke and the hot gases that emerge from a fire. Any kind of screen between the fire and the firefighter reduces the effect of radiation heat from the firefighter.

Hosche (1981) has classified the exposure conditions of firefighters into three categories:

- *Routine conditions:* Generally conditions equivalent to a hot summer day where the temperature rises to 60 ^oC. These conditions are applicable to firefighters who are operating hoses or fighting fires from a distance.

- *Hazardous conditions:* Typically those conditions that would be encountered outside a burning building by the firefighters. The more severe conditions of this category are applicable to firefighters who are *first* into a burning building. A turnout uniform is necessary to provide adequate burn protection and to minimize the thermal stress endured by the firefighter.
- *Emergency conditions:* These are encountered in very close proximity to the fire. These conditions are not encountered by civilian firefighters in most cases. The worst case would be a "flashover" fire or fire condition generated around a crashed aircraft when the fuel is burning fiercely. Hosche (1981) suggests the use of special equipment for these high levels of heat flux and temperature.

Unfortunately, these classifications do not specify where and how these temperatures have been measured. A study conducted by Lawson (1997) has shown that very high heat fluxes may also occur with low temperatures during certain fires. Therefore, a fire with low temperature can also be very hazardous and destructive if it generates high heat flux. High heat fluxes can also occur outside the burning structures or buildings, even though the surrounding temperatures are quite low.

Firefighters are frequently exposed to smoke that is generated due to the combustion of various materials in a fire incident. The thermal decomposition or combustion of every combustible material produces a "fire affluent" atmosphere which in sufficiently high concentrations, presents toxic hazards to the exposed population. There are both physiological and psychological effects associated with exposure to fire and its effluents which may impact the safe escape of occupants. Hartzell (2001) has described a list of physiological effects which include varying degrees of impaired judgment, disorientation, decreased ability to perform aerobic work, loss of motor coordination, and unconsciousness. Collectively, these effects physically impair, and may even prevent, the escape of occupants. The psychological effects that impact upon escape depend upon an occupant's perceived tenability associated with various courses of action. Whether or not escape is attempted, as well as the choice of a route, involves a firefighter's perception of relative risks. Overall, these psychological effects of exposure to fire and smoke are difficult to evaluate and do not readily lend themselves to an engineering assessment. Hartzell (2001) has provided a methodology for calculating the effluent toxicity component of a fire hazard analysis in terms of the status of exposed occupants at discrete time intervals, allowing for a continuous assessment of their ability to escape safely without experiencing or developing serious health effects. The methodology considers the effects of asphyxiant toxicants, carbon monoxide (CO) and hydrogen cyanide (HCN), as well as the effects of both sensory/upper respiratory and pulmonary irritation. The asphyxiants are toxicants causing hypoxia (a decrease in oxygen supplied to or utilized by body tissue), resulting in the depression of central nervous system leading to loss of consciousness and ultimately death (Hartzell, 1997).

1.2.3 Body Temperature of Firefighters

Wenzel and Piekarski (1982) have described the human metabolism mechanism. During every physical activity, the body produces a certain amount of heat: between 80 W while sleeping and over 1000 W during working. Therefore, it can be estimated that firefighters will at least produce about 300-500 W of heat during their work. The surplus energy can be transferred to the environment by three means: respiration, release of dry heat (radiation, convection and conduction) and evaporative heat through the skin. When the ambient temperature is over 35 ^{o}C, evaporation is the only way to cool the body. Evaporative cooling is a very efficient way of heat dissipation.

Apart from the studies on human metabolism, much work has also been done on the load of the firefighter's equipment on the body (Smith et al., 2001). For instance, the weight of the equipment set of 24 kg reduces the performance of the wearer by 25% (Louhevaara et al., 1995). Lotens (1983) showed that the size of the clothing and the number of textile layers also increases the energy consumption of the wearer, and thus the required heat loss. As the maximum core temperatures allowed during firefighting work are known, maximum work times could be theoretically defined for each type of work situation. But this is easier said than done, since the work conditions for firefighters can quickly and radically change, and their core temperature still rises for several minutes even if the work has been completed (Duncan et al., 1979). Moreover, certain factors such as psychological stress on duty are not at all accounted for. The studies that are performed in laboratories are typically conducted for the sake of repeatability and there is very limited research data that exists regarding the stress in fire situations (Rossi, 2003).

1.2.4 Protective Clothing and its Micro-Environment

Firefighters are required to wear some kind of protective gear, depending upon the type of situation they are exposed to. Protective clothing (PC) of any type covering the body produces a micro-environment between itself and the body. This micro-environment is continuously affected by both metabolic heat production and the surrounding ambient temperature. When the PC is impermeable and insulative as in case of firefighters, and ambient temperatures are not extremely hot, this micro-environment can very quickly become elevated well above ambient temperature due to the impact of restricted heat loss. Therefore, a firefighter is actually being exposed to a heat stress which is underestimated by ambient temperature measures alone. Kenny (1987) determined that the heat stress produced by the micro-environment under the impermeable PC was equivalent to a 10.6^{o}C Wet Bulb Globe Temperature (WBGT) increase above ambient temperature. Even though different measuring methodologies were used by Kenney (1987) and Bishop et al. (2000), the latter was in an agreement with the currently accepted adjustment of 10^{o}C WBGT for ambient temperatures ~ 18 ^{o}C. However, the efforts related to the direct measurement and assessment of the micro-environment is still very limited. Bishop et al. (2000) were one of the pioneers to provide one of the few *direct* measurements of micro-environment within an impermeable PC using temperature and humidity sensors. Their work suggested that, at higher ambient temperatures, the difference between ambient and micro-environments was considerably decreased to a mean value of 5 ^{o}C. The study conducted by Muir, Bishop and Kozusko (2001) also indicated that an adjustment of only 5 ^{o}C WBGT may be present between the micro-climate temperature and higher ambient temperatures. A range of WBGT adjustments dependent upon the ambient temperature, the clothing type, and metabolic rate appears to be the most accurate means to ensure firefighter's safety, while maximizing productivity in PC.

Although people often perceive the role of firefighters as fighting fires, only a small percentage of their time is devoted to this task (Lusa et al., 1994). When away from their base, firefighters spend considerably more time performing other duties such as walking, running, lifting and pushing while attending road traffic accidents, rescue incidents, and even false alarms. At all times during the course of their duties, firefighters are required to wear PC (excluding breathing apparatus) and while the energy cost of various routine firefighting activities has been reported (Davis et. al., 1982), little attention has been directed at the energy cost and thermoregulatory changes that occur while working in 'fire kit' in a non-fire environment.

Advances in fabric and material technology protect the firefighter from environmental heat which can be tolerated for short periods at > 200 ^oC (Foster and Roberts, 1994). However, many investigators have shown that firefighter clothing is not only effective in keeping external heat out, but also in preventing a subject's internally generated heat from escaping (White and Hodous, 1988). It has been suggested by Kamon and Belding (1971) that a rise in core temperature is related to a rise in heart rate (HR) in a variety of environmental conditions. Perceived exertion is recognized to play an important role in estimating the exercise intensity of given task (Eston, 1996). Ratings of Perceived Exertion (RPE) increase linearly with exercise intensity and is most closely correlated with HR and oxygen consumption (VO_2). With some experience of various levels of exercise intensity, more participants are able to numerically define their effort perception on a scale of 1-10 (Borg, 1982). More recently, Moran et al., (1998) suggested a physiological strain index (PSI) to evaluate heat strain on a scale of 1-10 in which HR was also related to core temperature (where 1 = little or no heat strain, and 10 = very high heat strain). Baker et al., (2000) tried to explore the relationship between cardio-respiratory and thermoregulation in subjects exercising at various intensities and for different periods in protective clothing. The testing was carried out in a temperate environment of 21 +/- 1.5 ^oC and a relative humidity of 55% +/- 5%. The results of the study showed that walking (12 min) at a moderate intensity in PC in a temperate environment can involve ~ 75% of maximal oxygen consumption. Further, when the work intensity was of extended duration (~ 60 minutes) it was perceived as 'strong' and a 'high' heat strain was imposed on the participants in PC. If the intensity or duration exceeds those imposed in this study then the core temperature might rise to dangerous levels unless the symptoms and signs of heat stress are recognized (Baker et al., 2000).

A research study conducted by Davis et al., (1982) was one of the first studies to address the relationship between physical performance measures and simulated firefighting tasks. Since during 1980, many fire departments have initiated job-related performance testing and have incorporated physical fitness testing as a criterion for job performance (Rafilson, 1995). Davis et al., (1982) demonstrated that a firefighter's work capacity could be predicted from a combination of field and laboratory test results. They found that the dependent variables such as grip strength, sit-ups, standing long jump, oxygen pulse and heart rate were good predictors of physical work capacity. Williford et al., (1999) has further endorsed the findings of Davis et al., (1982) in validating the relationship between physical fitness and physical performance. The investigation by Williford et al., (1999) has shown that activities that increase or maintain muscular strength, muscular endurance, cardio-respiratory fitness, or decrease the % of body fat are important when related to job performance.

1.2.5 Fire Drills and Simulated Fire Exercises

It is well known that a combination of physical activity, heavy clothing, and/or thermal stress results in increased physiological and psychological stress (Smith et al., 1995). In the early 1990's little was known about the impact of thermoregulatory demands on cardiovascular and psychological responses of firefighters during firefighting activities. Smith et al., (1997) examined selected responses to a training drill in different thermal environments. Male firefighters were randomly assigned to perform a simulated ceiling overhaul task for 16 min in either a neutral (13.7 ^{o}C) or hot (89.6 ^{o}C) conditions while wearing firefighter gear. The researchers assessed physiological and psychological measures before beginning the test, after 8 min, and after 16 min of firefighting activity, and following a 10 min recovery period. The variables assessed included heart rate (HR), tympanic temperature (T_{tymp}), lactate level (LAC), blood glucose level, rating of perceived exertion (RPE), perceptions of respiration, thermal sensations (TS) and state anxiety (SA). The researchers reported significant increase for HR, T_{tymp}, LAC, RPE, and SA, with the increases being much greater following work in the hot condition. The findings of the study suggest that the addition of live fire scenarios (a common situation for firefighters) contributes to increased cardiovascular and psychological strain at a standardized workload.

Smith and Petruzzello (1998) also conducted another study to examine selected physiological and psychological responses to strenuous live-fire drills in different configurations of protective firefighting gear. The researchers used career firefighters to perform three sets of firefighting drills in a training structure that contained live fires in two different configurations of firefighting gear on separate days. The participants wore: (a) the NFPA 1500 (1987) standard configuration, and (b) a hip-boot configuration of the firefighting gear. The researchers found that the perceptions of effort and thermal sensation were greater in the NFPA 1500 gear. The data also suggested that performing strenuous firefighting drills in the current NFPA 1500 standard configuration results in longer performance time, greater thermal strain, and greater perception of effort and thermal sensation.

In order to reduce the heat stress of wearing firefighting protective clothing, New York City Fire Department (FDNY) replaced the long pants under the protective overpants with shorts. In the year 2004, the Toronto Fire Service was also considering a similar option for their firefighters. The studies conducted by Malley et al., (1999) and Prezant et al., (2000) have also provided support for the decision taken by FDNY. McLellan and Selkirk (2004) also systematically studied the effects of heat stress while wearing long pants or shorts under firefighting protective clothing. The results from this study also endorsed replacing the duty uniform long pants that are worn under the protective overpants with shorts, endorsing that such a change will reduce the cardiovascular and thermal strain during exercise that lasts in excess of 60 minutes.

Eglin et al., (2004) conducted another study involving firefighter instructors in the firefighting training schools. The results showed that even though firefighter instructors undertake less physical activity than their students, the longer duration of exposure coupled with the inability to dissipate heat while wearing PC can result in considerable physiological strain. This situation may be further complicated by prior dehydration. The study also concluded that the additional effort required to rescue a collapsed firefighter may over-exert an instructor who is already hot and dehydrated.

There have been numerous studies investigating the physiological responses of firefighters in real or simulated firefighting activities. Such studies have reported that firefighting activity results in near maximal heart rate (Smith et al., 1996, Smith and Petruzello 1998), decrease in stroke volume (Smith et al., 2001), increase in oxygen consumption as well as core temperature (Smith and Petruzello 1998, Smith et al., 2001), increase in blood lactate levels and increases in psychological distress (Smith et al., 1996, Smith and Petruzello 1998). Despite the number of studies that have been conducted on the physiological effects of firefighting, there are no data related to the hormonal and immunological responses to firefighting activities. Since firefighters are also first responders in many circumstances, they are exposed to people with the potential to transmit illness/disease to them. Although this is an unavoidable occupational hazard, the characterization of hormonal and immunological responses to firefighting activity is a necessary step in understanding the magnitude of physiological disruption associated with firefighting (Smith et al., 2005). Smith et al., (2005) measured various immunological, endocrine and self-report variables in order to better describe the overall stress in firefighting and if firefighting resulted in indices of immunosuppression. The results from the study indicated that firefighting induces hormonal and immunologic changes that are complex and can differ greatly depending on the timing of measurement.

1.3 Human Factors Issues Associated with Fire-Eye Device

The Fire-Eye device is a thermal sensor attached to the head gear of the firefighter. The warnings displayed by the device, the location of the device and the human physiology lead to the identification of several human factors and ergonomics issues. The most important of the issues identified are the importance and the process of warnings, the color of the warning indicators, issues related to the physiological characteristics of the eye, the location of the warning device and the situational awareness related to the fire scenario in which it is used. The earlier issues of the location of the device and the human physiology have been addressed in prior research related to some other products or systems. Therefore, an attempt has been made to discuss the traditional human factors knowledge base associated with the use of such technology.

1.3.1 Warnings

Extensive research has been done in forming the framework for warnings in Human Factors area. The basic tenet of Human Factors is that safety should be ensured through appropriate design of the system. If a potential hazard in a system cannot be "designed out," then it must be guarded against. If guarding against the hazard is not possible or there is an uncertainty about a hazard, then a warning system should be developed and installed. The main purpose of a warning is to alert attention to a potentially dangerous situation. Sanders and McCormick (1993) have suggested that "at a minimum, a warning must involve the following fundamental elements:

Signal word: to convey the gravity of the risk, such as, 'danger', 'warning,' 'caution';

Hazard: the nature of the hazard;

Consequence: what is likely to happen if the warning is not heeded?

Instructions: appropriate behavior to reduce or eliminate hazard" (pp. 683)

The warning literature has great breadth and the research related to warnings has been continuing since late 70's. Rodgers et al., (2000) conducted an extensive review of the warning literature and developed an organizational framework for human factors professionals. The framework has yielded general principles about the variables that influence various aspects of the warning process, a resource for warning developers, and a guide to facilitate effective analysis of warnings. The researchers classified the influence variables into *person variables* and *warning variables*. *Person variables* refer to the factors that are specific to the individuals interacting with the warning system, such as age, gender; cognitive variables such as familiarity, and symbol comprehension; and personality variables such as risk taking style and perception of control. Warning variables refer to the characteristics of the warning itself or the context in which the warning appears. These include physical characteristics such as color, layout, type and style, as well as more abstract characteristics such as tone, explicitness, or interactivity (Rodgers et al., 2000).

Even though these influential variables affecting warnings were identified by the researchers, it is also important to differentiate the exact components of the warning process. Rodgers et al., (2000) identified four broad components of a warning process:

a) Notice the warning – attention is required to notice the warning;
b) Encode the warning – the external existent information is converted into some internal representation through reading words, processing symbols, etc.;
c) Comprehend the warning – understand the meaning of the warning;
d) Comply with the warning – behavior is in accordance with the warning

Different conceptualizations of the warning process have also been suggested by other researchers but the earlier warning process suggested by Rodgers et al., (2000) is an effective overall representation of a warning process. As per Laughery (2006), warnings are safety communications, and they are intended to communicate information about safety issues or problems. The researcher suggests that there are four perspectives from which the purpose of warnings can be addressed. These perspectives are referred to as *safer world*, *provide information*, *influence behavior*, and *reminder*.

Laughery (2006) has summarized two models for all of the theoretical efforts regarding warnings: Communications (C) theory and Human Information Processing (HIP) theory. The typical, basic communication model has four components:

1. *Source* – The designer, originator, sender of the warning message.
2. *Medium* – How the message is presented or displayed.
3. *Message* – The content of the warning.
4. *Receiver* – The target audience of the warning.

The HIP theory is a model consisting of stages through which warning information flows. The stages begin with a source continued with a channel leading to attention, comprehension, attitudes, beliefs, motivation terminated with behavior. At each stage the information is processed and, if successful, "flows" to the next stage. Processing failure at any stage can block the flow and result in the warning not being effective. Wogalter et al., (1999) combined the C and HIP models into a single theoretical framework for warnings (C-HIP). Models such as C-HIP have been useful in organizing research literature as well as in diagnosing warning failures.

Substantial warning research has also been conducted in the area of automation, since warnings are the integral component in user interfaces and workstations in all domains of life. Human factors professionals have been actively involved in the specification of warning signals and their integration into the overall user interface. However, this requires a clear understanding of the user's reactions to the warnings (Maltz and Meyer, 2001). People do respond to every warning they observe. But people also often cease to respond to warnings if the frequency of nonvalid warnings is high (Sorkin, 1988) – a phenomenon referred to as the "cry-wolf effect" by Breznitz (1983). Automated system operators have also been found to respond more slowly to warnings of low predictive value (Getty, Swets, Pickett, and Gonthier, 1995). Alternatively, people may also rely too strongly on warnings and may fail to attend to additional information that indicates the possible existence of problem. This phenomenon is similar to the misuse of automation (Parasuraman & Riley, 1997) and the finding of automation bias (Mosier, Skitka, Heers, & Burdick, 1998). When people perform a task with low attentional demands, observing the warnings does not diminish the resources that can be invested in task performance. In contrast, when the task is demanding, users might increase their reliance on warnings if they are valid or ignore them entirely if they are nonvalid. This correlated with the studies that show complacency and over-reliance on automation mainly when people have to perform multiple concurrent tasks that generate high workload (Parasuraman, Molloy, and Singh, 1993). Maltz and Meyer (2001) conducted a study regarding the use of warnings in attentionally demanding tasks and suggested that the existence of a warning system may create an impression that the warning relieves the user of part of the responsibility of hazard detection, thereby allowing the user to take greater risks. The researchers also advise the system designers indicating that when a system poses great cognitive demands for the user, warnings will be certainly useful and will be attended only if they are highly valid.

The Fire-Eye device designed for firefighters is a system which is used in highly demanding situations and is a small subsystem in a broad firefighting scenario. The firefighters are required to devote attention to complex tasks and even perform multiple tasks simultaneously while potentially receiving and responding to the device warnings. When this is so, the results from the study by Masha and Meyer (2001) show that low validity warnings are likely to be ignored, whereas highly valid warnings will be attended. An operator's response to a warning system should depend upon the diagnostic properties of the system, but it may also be affected by warning system presentation. A more-salient warning that attracts attention may lead to a stronger response than a less-salient one.

Meyer (2001) suggests that a hazard warning is in most cases equivalent to an instruction to perform a certain action, and the person who receives this instruction can choose to comply with it or to disregard it. Thus, *compliance* refers to the operator's responding as if there is actually a malfunction in the system when the system indicates the possibility of malfunction. *Reliance* refers to the operator assuming that the system is in a safe state when the indicators say so. Meyer (2001) concluded that an operator's reliance on and compliance with a warning system are strongly situation dependent.

The firefighting profession involves working in a dynamic situation with multiple tasks being performed at the same time in emergency situations. Therefore, a warning system for firefighters needs to be dynamic, explicit and consistent. Laughery (2006) describes dynamic warnings as more attention demanding than are static warnings. Further, when a warning display is static over time, it is subject to habituation, i.e., it may no longer be noticed or processed. Dynamic warnings reduce the problem of habituation since the content changes over time. The Fire-Eye device uses a dynamic warning system to warn the firefighters, since the bi-colored warning changes it status slowly or instantaneously based on the ambient temperature at that particular time.

Behavioral and Psychological Aspects of Warnings

Laughery (2006) suggests that warnings must be designed to be noticed and encoded and to provide the information needed for users to make informed decisions about compliance. The factors that research has shown to be most influential in determining whether or not the warnings are successful can be placed into two categories: 1) design parameters of the warning, and 2) characteristics of the target audience and situation.

Design parameters that are the most significant to warning success include format factors such as size, location, color/context, signal words and the use of pictorials. Content factors that are important are explicit information regarding hazards, consequences and instructions. Some of the most significant target audience and situation factors are that a *priori* perception of hazards and consequences, familiarity, modeling, and cost of compliance (Laughery, 2006).

People's *a priori* perceptions of hazards associated with a product or environment are important determinants of whether or not they will look for and read warnings. Wogalter et al., (1991) have shown that the greater the level of perceived hazard, the more likely people will look for, read, and encode warning information. In the case of firefighters, the situation is always risky and the victims as well as their own life are at stake; therefore, the warnings conveyed to the firefighters can make a life-saving difference.

Compliance decisions in terms of warnings can be viewed as including a cost-benefit tradeoff analysis. People may not comply with a warning if the cost of compliance is perceived to outweigh the benefits. Costs may take the form of money, time, effort, and so on. Benefits of compliance might include avoiding accidents and injuries, negative health effects, and property damage. Research shows that compliance is more likely when the directed behavior is relatively easy, i.e. the cost of the compliance is low (Wogalter et al., 1989, Dingus et al., 1991).

Laughery and Smith (2006) suggest that clear, unambiguous presentations would reduce the cognitive load to process the information and would decrease misunderstandings that might result in incorrect procedures being performed. The explicitness of content information has emerged as an important factor in warning effectiveness. Laughery and Smith (2006) have viewed and summarized a number of studies dealing with this topic. As per Laughery and Smith (2006), explicitness is defined as information that is specific, detailed, is clearly stated, and leaves little or nothing implied. It can be said that explicitness influences compliance. Explicit information should be especially significant when consequences are more severe and such information certainly enables people to better understand and carry out important actions.

The effects of familiarity on compliance are somewhat complex. It seems that the effect interacts with the nature of the experiences people have had with a product or environment. (Wogalter et al., 1995). Wogalter et al., (1995) indicate that greater familiarity leads to lower levels of compliance with warnings. The idea that "familiarity breeds contempt" may be involved in the sense that greater familiarity leads to lower levels of perceived threat that, in turn, results in noncompliance.

Wogalter, Magurno, Rashid and Klein (1998) studied the influence of time stress and location on behavioral warning compliance. Stress has been shown to affect perceptual processing and decision making in various domains, including emergency management. Wogalter et al., (1998) found that compliance with the warning (wearing of the protective equipment) was significantly higher among participants who were under low stress and exposed to the within-instructions warning in the first experiment. In the second experiment, the stress manipulation was separated into two factors: time pressure (absence vs. presence) and social monitoring (absence vs. presence). The results showed that time pressure significantly reduced compliance compared with its absence, but social monitoring produced a small but non-significant compliance enhancement. The study went on to confirm the warning location effect as well, which showed that placing the warning in a location where participants are known to look produces higher compliance than placing it in a location that participants are less likely to look. The reason for this location effect was not apparently justified but it was estimated to be due to perceived relevance or the narrowing of attention and cognition (Wogalter et al., 1998).

The research in this area would be advanced by measuring what participants actually look at. Objective measurement of eye movement and scanning behavior would help to clarify this issue.

According to Wogalter et al., (1998), while designing warnings it is important to consider the environment, the individuals who will be in that environment, and the levels of stress experienced by them in that situation. Stress levels are affected by other aspects of people's lives which vary from individual to individual and across time. In situations where certain environmental stressors are unavoidable or expected, strategies such as training people on relevant tasks, enhancing their coping skills, and using well-designed warnings may help to reduce accidents and injury (Wogalter et al., 1998).

The study conducted by Wogalter and Mayhorn (2005) describes how existing and future technology can be applied to warnings and risk communication to improve information accessibility and to provide cognitive support. The cognitive support refers to the assistive aspects of technology that enhance the mental capabilities (and avoid limitations) of users. As described earlier, Rodgers et al., (2000) have modeled a user's interaction with a warning which involves four broad components: *notice, encode, comprehend,* and *comply*. This review by Rodgers (2000) is focused on visual and auditory warnings, since the use of the 'other' senses (smell, taste, and touch) in warnings is relatively rare. Wogalter and Mayhorn (2005) concluded that future technology-based warning systems promise to provide improved access to safety information and cognitive support for each of the components of the warning process. Specifically, the goal of improving user safety through higher quality risk-related decisions can be accomplished by capitalizing on the interactive capabilities of technology and its ability to personalize warning information through dynamic modification of content.

Yechiam, Erev, and Barron (2006) conducted a study to notice the effect of experience on using a safety device. The study concluded that human sensitivity to a negative low-probability outcome appears to be affected by the explicitness of the presentation and the availability of personal experience. This pattern can lead to maladaptive behavior. One example is the investment in safety devices and a failure to use them. Nevertheless, this pattern can lead to desirable outcomes, such as overcoming fear or aversive stimuli. The current analysis by Yechiam et al., (2006) suggests that a better understanding of this pattern can be used to derive constructive methods to facilitate safety.

1.3.2 Human Vision and Use of Color in Warnings

According to Pokorny, Smith, Verrient, & Pinkers (1979), approximately 8% of males and 0.5% of females in the population have congenital red-green color blindedness. One fourth of these men cannot see red light (Allen, 1970). Golden yellow is the most easily visible color for both normal and color-deficient groups under all testing conditions (Lahr and Heinsen, 1959). These color-deficient people have reduced ability to discriminate redness-greenness throughout the full gamut of colors. Most significantly, from a view point of safety, the problems include the red, orange, yellow, and yellow-green parts of the visible spectrum. The human visual system is most sensitive to the band of colors between the wavelengths of 510 nm and 570 nm, which encompasses greenish-yellow (or lime-yellow) and yellow (Southall, 1961). The normal dark-adapted human-eye is red blind. The bright-adapted eye is red weak (Southall, 1961).

As per Von Kries (1899), red-green color vision deficiencies are subdivided into a number of categories. People with *dichromasy* lack one of the three normal receptors as compared to color-normal population. As a consequence, their ability to discriminate colors is two dimensional rather than three. The two forms of dichromasy are *protanopia* and *deuteranopia*, lacking the long wavelength (i.e., red receptor) or the middle-wavelength (i.e., green receptor,) respectively. Their ability to discriminate a red, yellow, and yellow green signal code on the basis of color is absent, and they must rely on the usual brightness hierarchy that yellow is brighter than yellow green, which is brighter than red. Protanopia and deuteranopia each constitute about 1% of males. Deuteranopia and deuteranomaly are collectively referred to as *deutan color deficiencies*, and protanopia and protanomaly are collectively referred to as *protan color deficiencies* (Atchison, Pedersen, Dain and Wood, 2003).

Laboratory and field trials conducted by Vingrys and Cole (1988) have conclusively indicated that congenital color deficients make more color confusions than do normal controls. In addition, congenital color deficients, particularly protans, have significantly longer reaction times to red signals than do color normals, both in the field. (Pokorny et al., 1979) and in laboratory (Pun, Brown, and Lui, 1986).

While it is important to study the physiological parameters of the human eye recognizing the warning signal and color, it is also important to study the way the warning information is conveyed. Substantial research has been conducted in the area of display format and the spatial dimension of the warning's location and their integration. Wickens and Carswell (1995) and Carswell and Wickens (1996) described the *proximity compatibility* principle, which suggests that when tasks require information sources to be integrated, they are better supported by displays that integrate display components representing the required information. Low proximity displays are those in which elements that are spaced close to each other, are part of configuration, or form an object. Low-proximity tasks require a separate consideration of variables, whereas high proximity tasks require the integration of variables. Display integration can be achieved through increased spatial proximity or by combining display components into a single object. Such displays may enhance performance when processing multiple properties of a single object required (e.g., determining whether an object is a threat based on its location, identity, and information about how certain that identity is) (Wickens and Carswell, 1995). Continuous information about system variables is usually presented through analog (i.e., spatial) displays. Warning systems generate, in most cases, discrete outputs that are often displayed as color coding of lights and indicators. The joint use of color and size (a spatial variable) in a single object can facilitate parallel processing of the two variables at a perceptual level that will help both focused attention and integration (Kahneman and Treisman, 1984).

An effect of color-vision deficiency on reaction times and accuracy of identification of traffic light signals have been studied by Atchison et al. (2003), proving that color deficients have longer response times and make more mistakes than do color normals when responding to signals. Atchison et al (2003) also found that for color deficient's, response times to red lights increased with increase in severity of color deficiency, with deutans performing worse than protans of similar severity: response times of deutanoropes and protanopes were 53% and 35% longer than those of color normals. For green lights, response times for all groups were similar.

O'Brien, Cole, Maddocks, and Forbes (2002) have suggested that system designers should be cautious in using color as the sole or principal means of attracting attention to information displays when there are color-deficient persons in the user group. They should ensure that other object attributes – such as size, edge definition, brightness, and background simplicity provide adequate conspicuity to the warning signal.

Previous research has indicated that different colors have different hazard connotations, and tailoring safety information helps the user to effectively deal with the situation (Wogalter et al., 1998; Smith-Jackson and Wogalter, 2000). Red, the color used by the Homeland Security Advisory System as well as the Fire-Eye manufacturer to indicate the highest level of danger, is typically perceived to be more hazardous or urgent than are other colors. Thus, in applications, the color displayed in a warning could be changed to reflect the current level of danger as is the case in the Fire-Eye device. Similarly, voice and sound modifications can also produce different levels of perceived urgency (Hollander and Wogalter 2000) but are effective in only quiet environments.

Manton and Hughes (1990) found that more effort was required to search and acquire information from monochrome displays than from redundantly color coded displays. The advantage of color-coded displays was greater at high information levels. This implies that the use of color is even more effective in dynamic displays than in static displays. Color is of major importance in tasks that involve visual synthesis and spatial organization (Derefeldt, 1995), and in tasks that involve saccadic movements of eye in a dynamic situation.

Derefeldt et al., (1999) summarized the importance of color based on extensive previous research in various tasks as well as in dynamic systems. The authors suggest that color might be an effective code when used as a cue or alerting signal, as a method for locating and grouping similar items or separating items, as a method for increasing symbol visibility, and for improving learning of visual material, decreasing work load at high information levels, decreasing errors, generating faster response times. Overall, research related to the significance of color has proved that color enhances decision making as well as performance, especially in complex presentations of information (Post, 1992; Post, 1997; Hughes and Creed, 1994).

1.3.3 Head Mounted Displays

As discussed earlier, the location of the warning is an important aspect in warning design in dynamic scenarios. Firefighters and emergency responders are covered with protective gear while conducting firefighting or response activities; therefore, they can only attend to a visual warning which is directly in their line of sight. As a result of this, manufacturers of PPE are introducing useful devices for firefighters with head mounted displays (HMDs) in which the information is conveyed to them through a Head-Up Display (HUD) or Head-Down Display (HDD). However, HUD is most prominently used in PPE for emergency responders. HUD has the potential to increase firefighter's safety and make their work more efficient without interfering with their primary task of fighting a fire. Some of the typical devices in which HUDs are installed include display of thermal imaging data to locate a fire victim or fellow firefighter, or tactical information, such as maps or navigational information. The HUD warning system has also been used in the Fire-Eye device. The Fire-Eye device utilizes the location of the head visor to indicate various warning indicators, directly in the line of sight of the firefighter.

Traditionally, HMDs have been described as the display devices which project digital information from a video source or a wearable computer directly in front of user's eyes. The first HMD was developed in 1968 for military applications (Melzer and Moffitt, 1997), but today they are being used in many diverse application areas, such as medical devices during surgery, engineering and science, 3D games and entertainment, etc. Each application area has specific HMD requirement and benefits. In the case of industrial applications, HMDs need to be integrated into the user's work equipment or environment. For firefighters, the main requirements for HMDs are robustness, ease of use, and integration with masks and helmets (Bretschneider, Brattke, and Rein, 2006). HMDs have the potential to increase the safety of the firefighters and the effectiveness of the firefighting task.

As per Melzer and Moffitt (1997), the main components of a HMD are one or two imagers, i.e. the display, one or two optical systems that provide the user magnified virtual images of the imagers or a microprocessor based information processing unit, and a mechanical mounting assembly. Typically the imager is a micro display such as Liquid Crystal Display (LCD) or Light Emitting Diode (LED) or any other available technology. The electrical or technological component of the HMD will not be discussed here since it is not the focus of this research.

Based on the viewing ability from one or two eyes, Melzer and Moffitt (1997) have classified HMDs into two types. An HMD with just one imager and one optical system is classified as monocular HMD. In a monocular HMD, only one eye is able to view the image and no stereo vision is possible with such a system. In such monocular HMDs, the other eye has free sight into the environment, thereby, providing completely different information than the eye with the display. In monocular HMDs, the user gets to decide actively what he/she wants to see and is able to handle it efficiently after training. In the case of firefighters, there is a possibility of positioning this HMD at various positions relative to the eye: straight in front of the eye, or tilted up or down by an angle, enabling the user to have sight onto the environment with both eyes. This position, called the *bi-optics position,* is of major relevance in firefighting applications.

HMDs with two optics units are referred as binocular HMDs. They are of two types, the first type having just one imager or two imagers showing exactly identical information, the second type having two imagers showing slightly different information; e.g., stereo views onto a three-dimensional virtual scene. Compared to monocular HMDs, the binocular types are more relaxing to wear, but have higher obtrusiveness for viewing the environment.

In terms of optics, HMDs can be grouped into two categories: *Totally immersive look-around HMD*s and *see-through HMDs* (Melzer and Moffitt, 1997). Optical see-through HMDs have a semitransparent beam-combiner that combines light coming from the environment and light coming from the imager, yielding an overlay of the system-generated image onto the real scene. The total immersive HMD blocks user's sight onto the environment and therefore, they are not useful in the case of firefighting operations. Firefighting operations require an unobstructed view of the environment, therefore see-through HMDs are the best option.

Bretschneider et al. (2006) have formulated the main requirements for HMDs that can be employed in firefighting (see Table 1).

Table 1. Requirements of Head Mounted Displays for Firefighters

Category	**HMD requirements**
Handling	Handling has to be very simple, system has to be ready and adjustable within few seconds Stable in front of the eyes during the operation
Integration	Rugged, safe, resistant against heat, water, falling objects
Price	Reasonably priced
HMD Type	See through HMD or Binocular HMD
Compatibility	HMD has to be usable with and without breathing mask, with and without chemical suit, a helmet work during every operation
HMD Position	Movable from the working and in a safety position, see through HMD can be switched off Variable position in the visual field (directly in front of the eyes, in the upper part of visual field)

There have been multiple applications of HMDs in a fire brigade's operations. HMDs are being effectively used by showing images recorded by a thermal imaging camera, and by displaying maps and the status of the equipment and the environment to the firefighters while they are inside the structure. The advantage of a HMD is that it is "hands-free." HMDs can also be used in NBC operations, search and rescue after accidents, and also for detecting hot spots when the fire is extinguished. In the future, the amount of available electronic information from several sources (e.g., the firefighter himself, from sensors or external information from the command post) will highly increase the need for a "hands-free" device such as a HMD to display the relevant information (Bretschneider et al., 2006).

1.3.4 Situational Awareness and Safety

Situational Awareness (SA) is a concept that was first considered in aircraft fighter combat, and has thereafter attracted a great deal of interest, primarily from researchers active in the fields that study dynamic systems with man-machine integration. There have been many attempts by the researchers and practitioners in the human factors field to clear the ambiguities in the definition of situational awareness. At a very simple level, situational awareness is an appropriate awareness of a situation (Smith and Hancock, 1995). Three main definitions of situational awareness which dominate the field are listed here.

1. Endsley (1988) defines SA as the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and a projection of their status in the near future.

2. Bedny and Mesiter (1999) described SA as the conscious dynamic reflection on the situation by an individual. They further suggest that SA provides dynamic orientation to the situation, the opportunity to reflect not only the past, present and future, but the potential features of the situation. The dynamic reflection contains logical-conceptual, imaginative, conscious, and unconscious components which enables individuals to develop mental models of external events.

3. Smith and Hancock (1995) defined SA as the invariant in the agent-environment system that generates the momentary knowledge and behavior required to attain the goals specified by an arbiter of performance in the environment.

Even though the above three definitions may seem to be different than each other, they have been integrated into a single framework. The framework has been integrated by presenting five elements in a system: the person (comprising three main subsystems: *working memory, mental models* (drawing on knowledge, skills and experience) and *reflection together with* *projection*), and the world (comprising of *multiple subsystems*) (Stanton, Chambers, and Piggott, 2001).

The main differences in the above definitions are: the degree to which they distinguish between the importance of working memory, the global workspace, more long-term knowledge, or the nature of the interaction in determining SA. These differences can be characterized as either being mainly concerned with the *process of acquiring* SA or mainly being concerned with the *product* of SA (Stanton et al., 2001). The information processing paradigm dominates theoretical work on SA, but the more applied focus of naturalistic decision making has been associated with the rise in popularity of SA research (Zsambok, 1997). It seems as if there is a hierarchical relationship between the following concepts: SA is subsumed under naturalistic decision making which itself is subsumed under more general information processing. There is certainly an inheritance of underlying psychological theory and study between these concepts (Stanton et al., 2001).

One of the most commonly represented theoretical models of SA is the information processing model that has been suggested by Endsley (1995). The model represents an unfolding of SA as higher-order cognitive processing is performed. It is a three-level model of SA that was developed initially to understand tasks in the aviation field (e.g. piloting aircraft and air traffic control, where people are required to be up-to-date with a dynamically changing environment), but it can be argued that the model could be extended into other domains such as power generation, petrochemicals, etc. Endsley's (1995) model is arranged into three hierarchical levels of situational assessment, each stage being a necessary precursor to the next higher level. This model follows a chain of information processing, from perception, through interpretation, to prediction.

Level 1 SA: Perception of the elements in the environment. This is the lowest level of situational awareness. There is no interpretation of data performed at this stage. This stage is intended to represent the initial receipt of information in its raw form.

Level 2 SA: Comprehension of the current situation. Comprehension may follow on from the perception of the elements (not necessarily though) if the data can be integrated and synthesized to produce an understanding of the relevance to the situation. Comprehension is essential to understand the significance of the elements and to gain a picture of what is happening. Less skilled people will achieve a lower Level 2 SA despite achieving the same Level 1 SA, as compared to their skilled counterparts.

Level 3 SA: Prediction of future status. This is the highest level of situational awareness associated with the ability to project the future of the elements in the environment. Accuracy of the prediction is completely dependent on the accuracy and knowledge of the SA of levels 1 and 2. Based on the above argument, the three level model shows, SA is embedded within a cognitive model of human activity in a dynamic system. Endsley (1995) has shown how SA is influenced by task factors and individual factors. Therefore, it explains why two people faced with different task factors might arrive at different conclusions as might people with different abilities, experience, and training.

Situational Awareness and Firefighters

The fire environment or any other emergency situation calls for critical decision making under extreme stress, and the decisions often determine whether or not one survives the fire. SA is very important while considering human behavior in fires because SA is linked to human performance based on the knowledge of situation. Lack of SA may lead to errors in judgment and response during critical events. SA, along with good skills achieved in training, can bring expertise to the critical situation, which is required for decision making.

Lt. Stephen Walsh (1993) of the Quincy, MA fire department conducted a study with professional firefighters and emergency medical technicians for over a decade to learn what factors indicate a presence of SA in the critical fire environment. The results from this study identified seven SA factors: training, experience, commitment, confidence, physical awareness, fear and size-up. In order to achieve better operational performances, fire trainers should be mindful of these factors. Emergency responders as well as firefighters will continue to train and gain experience. SA is one of the building blocks in expert performance and decision making. (Walsh, 1993).

The Fire-Eye device is one of the devices that promises help in improving the firefighter's situational awareness while battling structural fires. The device indicates the status of the environment surrounding the firefighters and the firefighters certainly need training for appropriate decision-making at particular warning indicators, in order to become an expert in using such a device.

2.0 RESEARCH OBJECTIVES

2.1.1 Product Evaluation from Human Factors Perspective

As stated earlier, the design process has been split into five successive groups of coherent activities that form the different phases in the elaboration of a design. These phases are analysis, synthesis, detailing, optimization, and engineering for production. The designers and manufacturers are always interested in understanding a product's prospective users, their needs and preferences, and the future context of product's use. Sometimes the information regarding the users is available at the beginning of the design process and this helps the design team to design the product effectively. Various subjective and objective measures of evaluation are used by human factors engineers to evaluate a product. Electronics are being increasingly used in the manufacture of PPE which leads to dividing the PPE into two major components: hardware (electronics) and software to program or operate the hardware. Vermeeren and Bekker (1993) have suggested that the hardware aspects of any product should be primarily evaluated using small-scale qualitative user studies, whereas for evaluating software aspects, unstructured walkthrough methods are the best.

Traditionally, human factors engineers evaluate either a complete product or the early design stages of a product using various methods such as interviewing users, observations of use, expert walkthroughs, and formal laboratory testing. Based on the suitability and the feasibility of the listed methods, the type of evaluation method is decided by the manufacturer or the designers. Each of these methods has their own limitations and uncertainties and they can be used either early (concept stage) or during the design process based on the decision of the human factors professional. However, after the prototype of a product is completed and a first batch of product is manufactured, structured walkthroughs and quantitative user studies are conducted in order to evaluate the product (R. Den Buurman, 1997). The structured walkthrough method is based upon a scientific theory and requires an expertise that usually cannot be found in the design teams. In addition it is too tedious and time-consuming, both to conduct and in the analysis of results to extract design relevant changes. The same applies to the large-scale quantitative user tests, which involve large numbers of subjects and strictly controlled experimental set-ups.

In the case of a product made for firefighters and emergency responders, the probability of involving the actual users in experimental fire conditions is highly risky. The Fire-Eye device, which attaches to the visor of the firefighter helmet, cannot be used in any experimental set-up that does not involve fire or exposure to heat. Taking into account the unique situational requirements to evaluate such a product, a need to develop special testing methods which neither risk human life nor loses the fidelity of the actual fire situation, is important. Therefore, to conduct quantitative user studies for evaluation purposes of such a device, *laboratory tests (climatic chamber test)s* and *field tests* (e.g., using mannequins inserted with bullet cameras) are generally used by researchers and fire engineers. However, human factors engineers have not generally used such methods for the evaluation of products, especially PPE. Therefore, the methodology used in this research effort was certainly one of its kind in the area of Human Factors and Ergonomics Engineering. Such research method might help to set a trend in the area of human factors and ergonomics evaluation of PPE used in emergency situations in which humans cannot directly participate, as in the case of other devices which can be used in normal working conditions.

2.1.2 General Approach to Evaluate Devices for Firefighters

Evaluation plays different roles in the process of product development. The roles can be comparative, exploratory, verifying or diagnostic. The overall function of evaluation is to assess whether or not design goals have been fulfilled (Johnson and Baker, 1974). Assuming that the human factors issues discussed in the literature review related to the Fire-Eye device remain constant, the objective of the research was to specifically evaluate the performance of the warning indicators designed in the device. The broader research goal is also to test whether the warning indicators and the microprocessor-based hardware satisfies the design goals satisfactorily. Therefore, for the evaluation of the Fire-Eye device, two different approaches were followed: laboratory tests i.e. climatic chamber tests and actual field trials involving live fire tests.

In laboratory tests, the purpose was to standardize the physical environment in order to control the independent variables and to measure a dependent variable in quantitative terms. As per Johnson and Baker (1974), the characteristic of a field test is that of a natural, physical environment in which independent variables cannot be controlled and the dependent variables are difficult to measure and often can only be measured in quantitative terms. Therefore, in field tests, the purpose was to conduct the evaluation of the device in an actual firefighting scenario to which firefighters are usually exposed.

Karlsson and Rosenblad (1998) compared the qualitative and quantitative methods in product development for firefighters by evaluating the functional clothing of firefighters in climatic chamber tests versus field tests. They evaluated the thermal properties of the functional clothing for the firefighters. The researchers concluded that, although laboratory test procedures can be developed and improved in relation to design issues, field evaluations must be regarded as an integral part of an iterative development process. An iterative process rather than a step-by-step methodology, and a triangulation approach in terms of location (i.e., laboratory and field trials), as well as method (quantitative and qualitative data) will provide the developer with multiple viewpoints, allowing for results with greater accuracy in the product development process. The current research effort also intended to follow the similar research format followed by Karlsson and Rosenblad (1998) in order to test the product for firefighters (except for subjective evaluation of the device in actual fire scenario).

This research effort had two distinct objectives: to evaluate the performance of the warnings built in the Fire-Eye device in three different laboratory-scale (climatic chamber tests) tests and Full-scale (field) fire tests, and to compare the performance of the Fire-Eye device across laboratory-test and Full-scale test method quantitatively.

3.0 EXPERIMENTAL APPARATUS

All testing was conducted at the Building and Fire Research Laboratory at the National Institute of Standards and Technology, located in Gaithersburg, Maryland, between December 2005 and January 2006. The description of the experimental setup, instruments and devices that were used for the performance validation of the Fire-Eye device are described in detail below. This section is provided to help the reader understand the experimental procedures that were used to conduct the laboratory-scale testing and validation of the Fire-Eye device.

3.1 Instrumentation of Headform for Test Purposes

The head forms used in the laboratory experiments and large-scale fire tests were made from white Styrofoam. Each headform had a flat base that allowed it to be mounted securely on a flat surface. Due to the severe temperatures to which they were exposed (up to 200^o Centigrade [^{o}C]), a large portion of the headform surface was covered with 3M heat-resistant tape as shown in the left side of Figure 2. As per the manufacturer's product specifications, the heat-resistant tape can withstand temperatures in the range of 204^{o}C to 530^{o}C (400^{o}F to 1000^{o}F). In order to insert a bullet camera along with its power cord, the headform was drilled at an angle of 40° facing up from rear side using a sharp-edged steel pipe. Upon insertion of the bullet camera inside the headform, the monitor screen of the video recording unit was verified to display the warning indicator lights of the mounted Fire-Eye device to ensure that digital recordings to be captured subsequently were useful. The headform was then covered completely with a Nomex cloth head cover to protect the headform from extreme heat. Once the headform was covered with the Nomex cover and a facepiece (as part of a self-contained breathing apparatus [SCBA] of the type typically worn by firefighters), only the face of the headform (again, covered with heat resistant tape) was visible, as shown in the right side of Figure 2.

3.2 Characteristics and Instrumentation of Thermocouples

One objective of the laboratory-scale experiments and the Full-scale fire tests was to measure and record room temperatures at different locations in space. To measure the temperatures at these locations, thermocouples which were connected to the data acquisition system were used (Figure 3). A thermocouple is a junction formed from two dissimilar metals; it is a pair of junctions, one at a reference temperature such as 0^o C, and the other, called the 'sensing junction,' located at the surface or at a space whose temperature is to be measured.

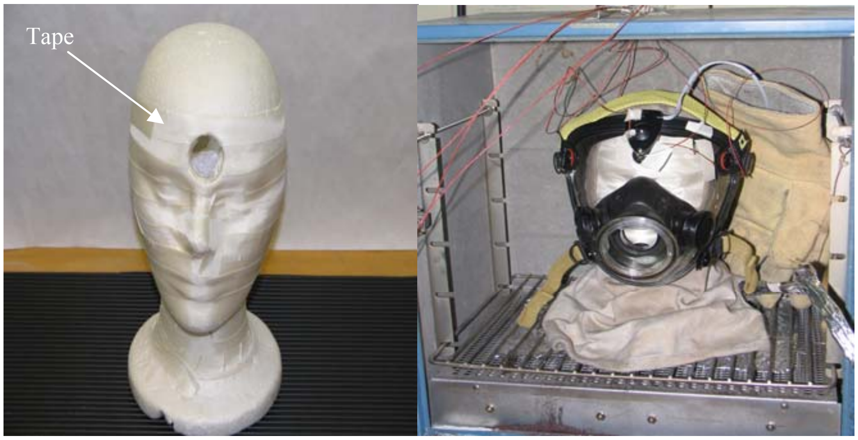


Figure 2. The left photograph shows the headform covered with heat- resistant tape and drilled for bullet camera insertion. The right photograph shows the Nomex cloth-covered headform equipped with an SCBA facepiece and a Fire-Eye device.

The temperature difference between the two junctions causes a voltage to be developed which is temperature-dependent. Therefore, a thermocouple actually measures voltage, and the data acquisition system converts that voltage into a temperature measure. Thermocouples are widely used for temperature measurement because they are inexpensive, rugged, and are reliable, and because they can be used over a wide range of temperatures.

The thermocouples used for the laboratory-scale experiments as well as for the Full-scale fire tests were type K nickel-chromel/nickel alumel (Ni-Cr/Ni-Al). The operating temperature range of a Type K thermocouple is from -269 ^{o}C to 1260 ^{o}C. Type K thermocouples have high thermopower, a low melting point, and good resistance to oxidation. The sensing junction bulb size is less than 1 mm. The length of each thermocouple used for the laboratory-scale experiments was maintained at an average of 20 feet.

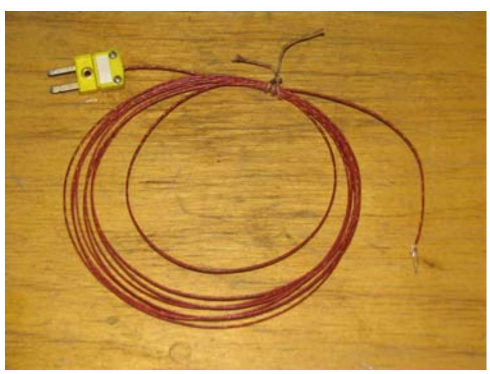


Figure 3. A thermocouple as used in experiments.

Thermocouples were prepared for the laboratory-scale as well as the Full-scale fire tests at the same time. Thermocouple wires that form the bead or junction were stripped of insulation for at least 10 mm (0.39 in) of length and were not more than 20 mm (0.78 in) from the bead. These thermocouples were attached directly to the surface of the SCBA facepiece and to the Fire-Eye device using heat-resistant tape and flame-resistant thread having a maximum diameter of 0.254 mm (0.010 in). In order to record exact surface temperatures, care was taken to keep the thermocouple beads in direct contact with the surface of the SCBA facepiece and of the Fire-Eye device. Thermocouple performance may be altered if the heat resistant tape is placed directly on stripped wires near or over the thermocouple junction. Basic thermocouple locations are described in the Table 2. It should be noted that all thermocouple wires were located and run across the SCBA facepiece as well as the Fire-Eye device so that they would not interfere with the other thermocouples or any device components. Overall, six thermocouples were used to record temperatures in each test for the test methods utilized in the laboratory-scale tests. The description of the location of each thermocouple is outlined in Table 2. The first five thermocouples were associated with the Fire-Eye device or the SCBA facepiece, whereas the sixth thermocouple was attached and placed at a one-inch distance from the Fire-Eye device attached to the facepiece. This sixth thermocouple was intended for recording the gas (ambient) temperature close to the device. Figure 4 shows a schematic diagram of the location of thermocouples on the Fire-Eye device and SCBA facepiece.

3.3 Fire-Eye Device Selection and its Nomenclature

A batch of 10 Fire-Eye devices was submitted by the manufacturer for test purposes. Six Fire-Eye devices were selected for the laboratory-scale experiments. In order to be consistent in the research effort, the six devices used in the laboratory-scale experiments were also used for Full-scale fire tests. Each Fire-Eye device was shallowly engraved with its assigned number ranging from 1 through 6 on the top panel in the front of each device using a thin steel stylus. Five Fire-Eye devices (Numbers 1, 2, 3, 5, and 6) were instrumented with two thermocouples, one touching the front surface and other touching the rear surface of each Fire-Eye device in order to track and record the exact temperature at those surfaces. Device 6 was essentially treated as a 'back-up device' in the event that any of the other devices were damaged in the test or if they malfunctioned.

Table 2. Nomenclature for the thermocouples used in the laboratory-scale experiments and the Full-scale fire tests. **(Specifically for FE 4)**

Thermocouple Label	**Description of Thermocouple Location**	**Channel Name in Data Acquisition System**
TC1	Thermocouple registering the temperature on the front surface of Fire-Eye device	FE FT TC1
TC2	Thermocouple registering the temperature on the rear surface of the Fire-Eye device	FE RR TC2
TC3	Thermocouple registering the surface temperature on the inside of the facepiece	FP TI TC3
TC4	Thermocouple registering the surface temperature on the outside of the facepiece	FP TO TC4
TC5	Thermocouple close to the platinum sensor inside the Fire-Eye device	FE IE TC5
TC6	Thermocouple registering the ambient temperature at a distance of 1 inch from Fire-Eye attached to the facepiece	TC6

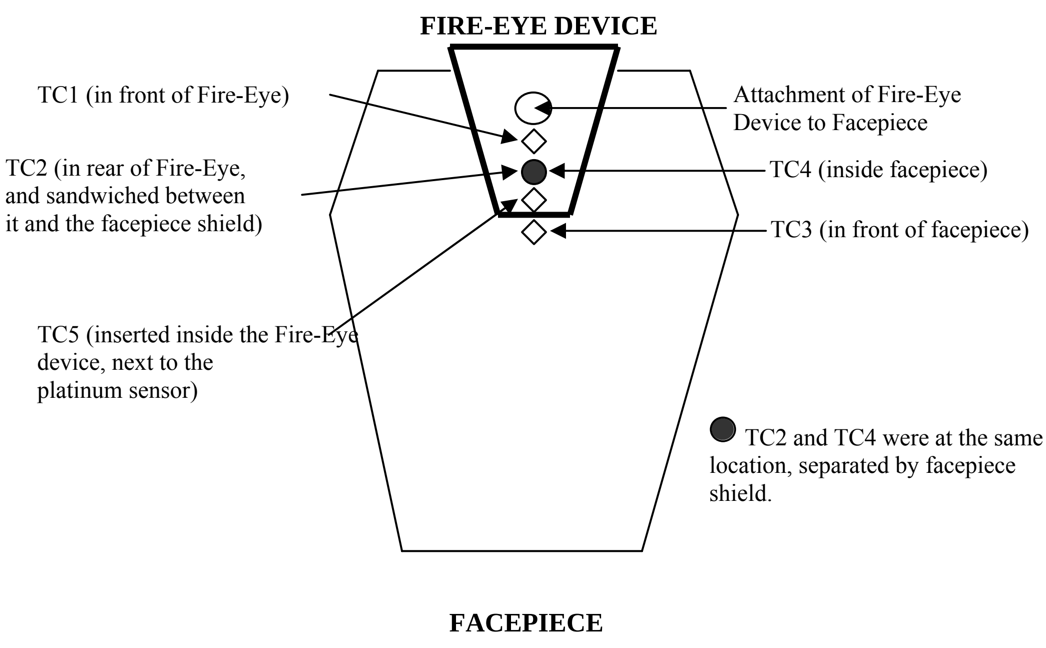


Figure 4. Location of thermocouples on the facepiece and Fire-Eye device.

Fire-Eye device #4 was instrumented with three thermocouples: one in front, one in the rear, and one inserted inside the Fire-Eye device and next to the platinum thermal sensor to track the temperature in its vicinity. Fire-Eye device #4 was opened (from the center with the screws provided) on the corners of the rear side of the device. Inserting the thermocouple inside Fire-Eye device #4 compromised its integrity, however. For all the selected Fire-Eye devices, except for Fire-Eye # 4, TC1 through TC 4 were identical, while TC5 served as an ambient temperature TC. The Fire-Eye device numbers, along with the manufacturer's serial number and thermocouple placement, are shown in Table 3.

Table 3. Nomenclature for the Fire-Eye devices.

Assigned Device Number	Manufacturer's Serial Number	Thermocouple Specification
1	10001629	TC1 and TC2
2	10001708	TC1 and TC2
3	10001638	TC1 and TC2
4	10001623	TC1, TC2 and TC 5
5	10001618	TC1 and TC2
6	10001530	TC1 and TC2

3.4 Facepiece Selection and Nomenclature

The Fire-Eye device is manufactured with the intent of interfacing it with a Scott Face Mask 2000 model facepiece (D. Appelt, personal communication, October 2005). Three such facepieces were procured with the intent of using them for the laboratory-scale experiments and Full-scale fire testing scenarios. The manufacturer's serial numbers along with the designated face piece numbers for testing purpose are listed in Table 4.

Table 4. Facepiece (FP) serial numbers and the thermocouples associated with them.

Assigned Facepiece Number	Manufacturers Serial Number	Thermocouple Specification
FP 1	804191-08	TC3 and TC4
FP 2	804177-01	TC3 and TC4
FP 3	802240-01	TC3 and TC4

Each facepiece was instrumented with two thermocouples, TC3 and TC4. TC3 was attached to the inside surface of the facepiece, whereas TC4 was attached to the front surface of the facepiece. The thermocouple bead attached on the inside of the facepiece overlapped with the thermocouple bead attached on the outside of the facepiece. TC3 and TC4 were positioned on top of each other and separated by the facepiece glass.

3.5 Digital Video Recording Unit

A bullet camera made by Sony Electronics Inc. and powered by a 30V battery was used to record the status changes indicated by the warning lights of the Fire-Eye device. The setup of the digital video recording unit is shown in Figure 5, and the bullet camera used for recording the indicator status is shown in Figure 6. The video data viewed through the bullet camera was recorded onto mini-DV tapes manufactured by Panasonic, Inc. The mini-DV tapes have a recording capacity of one hour of digital video. In order to withstand the temperature extremes generated in the testing scenarios, the wire connecting the bullet camera to the battery, which passed through the headform and facepiece, was covered with the heat-resistant tape.

Figure 5. The mini-DV digital video recording unit.

Figure 6. The Sony bullet camera used to record Fire-Eye device indicators.

3.6 Data Acquisition System: CR23X Micrologger R

The CR23X system, manufactured by Campbell Scientific Inc., and shown in Figure 7, is a self-contained compact data logger that measures most sensor types (such as temperature) directly, communicates via modems, reduces data, controls external devices, and stores both data and programs in either non-volatile flash memory or battery-backed static random-access memory (SRAM). The CR23X has an integral, 2-line alphanumeric display and power supply. A battery-backed, real-time clock and nonvolatile data storage is included in the system.

Figure 7. The data logger system CR23X.

There are 12 differential, individually configured analog inputs that were programmed to be used as 12 thermocouple channels for the laboratory-scale experiments (Campbell Scientific Inc., 1989). These 12 channels recorded the surface temperatures where the thermocouple bead would touch. There were 3 dedicated voltage channels available to record the voltage or heat flux in the CR23X system, but only one of these three voltage channels was used. The switch connected to a battery was used to create a ‘spike’ in real time electronic data indicating a change in status of warning lights of the Fire-Eye device (Figure 8). This channel was referred to as the ‘marker channel.’

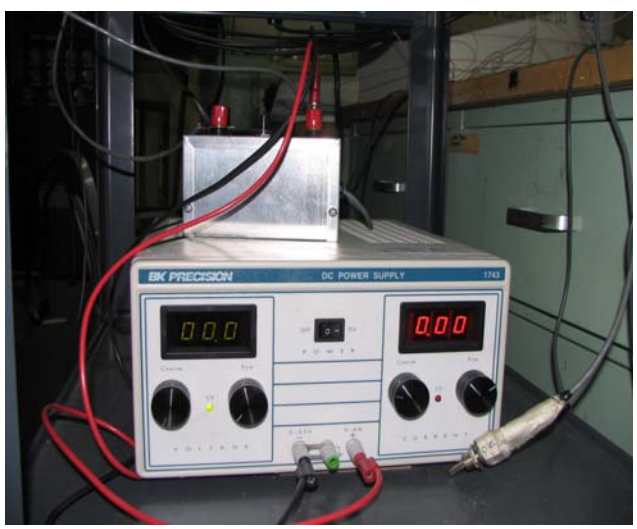


Figure 8. The marker channel and its switch.

The marker channel was also used to mark certain important test parameters, such as the beginning of a test, the end of a test, and to note the change of warning status (e.g., from blinking green to solid green). The marker channel created a spike of 20V in the data when it was actuated, leading to a change in status from 0V to 20V in the real-time data. A laptop computer, which was connected to the data logger system, is shown in Figure 9. The software that connected the data acquisition system to the laptop computer had an interface that was configured to display the temperatures of targeted thermocouples numerically as well as graphically.

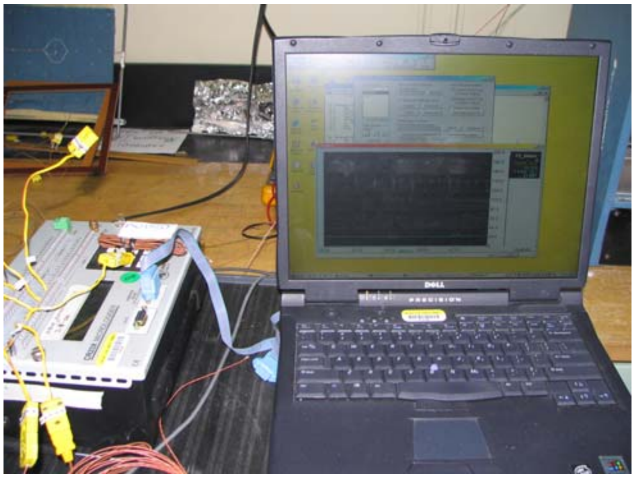


Figure 9. The laptop computer connected to the data acquisition system.

In order to record the temperature at each thermocouple location, the channels were programmed to specify the maximum temperature limit of 400^{o} F and the minimum temperature of 10^{o} F. The data acquisition system was programmed to collect data at an interval of every two seconds. Therefore, for a 30-minute test, the data system would generate approximately 900 data points. The data logger collected data continuously in real-time once it was powered. At the end of each test, the data for that test was labeled and stored as a separate file indicating the date, time, and the name of the test. All of the laboratory-scale experiments data files were labeled and stored in the format of ‘FE0512162pmSO.dat.’ The first annotation FE stood for the Fire-Eye, then the year 05, followed by the month, day, the time at the beginning of the test, and type of the test such as static oven (SO), flow loop (FL) or radiant panel (RP), for example. Each data file was stored on removable media at completion of a test.

3.7 Static Oven Description

A static oven utilizing conduction-type heat transfer was used to conduct the first set of laboratory-scale experiments of the Fire-Eye devices. The Static Oven (Figure 10) was manufactured by Blue M Electric Company, and was a 'Single Wall Transite Oven' (model SW-11TA). The internal chamber dimensions were 11 x 12 x 9 inches. The external dimensions of the oven were 12 x 13 x 17 inches . The internal capacity of the oven was approximately 1.5 cubic feet. The circular thermostat knob allowed control of the temperature between the range of 40^{o} C (104^{o} F) to 200^{o} C (392^{o} F). The wattage of the oven was 120 V, 7.5 A, and the internal walls were finished with a powder-coated Transite material. The small opening in the roof of the oven was used to insert the thermocouple wires attached to the facepiece and the Fire-Eye device. This opening was also used to insert a thermometer, which confirmed the temperature in the oven. An ambient temperature-recording thermocouple was also inserted from the same opening, positioned in front of the facepiece.

Figure 10. The static oven sealed with a temporary gypsum board wall.

The static oven door was replaced by a temporary one made with a thermo-proof concrete material containing a small viewing glass window whose dimensions were 4.5 x 11.5 in. The glass window was fixed in place by four screws around the glass and by additional thermo-proof material. The glass window allowed the experimenter to monitor the test as well as record the status change of the warning indicators in the Fire-Eye device. Figure 10 also displays the static oven fitted with the temporary wall and the wires inserted from the rooftop opening.

3.8 Fire Equipment Evaluator Description

A Fire Equipment Evaluator (FEE), which simulated convective-type heat flow, was used to conduct the second set of laboratory-scale experiments of the Fire-Eye devices. The FEE laboratory was located on the 3^{rd} Floor of BFRL at NIST's Gaithersburg, MD facility. The FEE was designed and constructed to simulate the particular fire conditions encountered by firefighters. The FEE is able to reach a temperature of 300^{o} C with a total thermal flux of 20 kW/m^2, which is considered to be the radiation flux at the time of flashover fire. A functional-block diagram of the FEE is shown in Figure 11, and a photograph of the FEE used for experimentation is shown in Figure 12.

Figure 11. Specifications and dimensions of a FEE tunnel (from Donnelly, Davis, Lawson, and Selepak, 2006, page 26).

The FEE consists of a stainless steel closed circuit and a fan driver. The flow loop's dimensions are 220 x 174 x 38 cm. The test chamber of the FEE is 36 inches long by 15 inches square, and can be expanded to fit larger equipment if needed. In case of this set of laboratory tests, the existing chamber dimensions were appropriate to hold the head form along with facepiece and Fire-Eye device. The operating conditions in the chamber included flow rates from 0.5 m/s to 2.0 m/s.

Figure 12. The Fire Equipment Evaluator (FEE) and air tunnel.

The operating temperature inside the chamber can be maintained up to 300^{o} C. The convective heat flux up can be programmed up to 16 kW/m^2 and the radiant flux can be programmed up to 4 kW/m^2. The chamber is also equipped to measure gas concentration if gas is injected inside it (Donnelly et. al 2006). The instrumentation for the FEE included thermocouples for temperature measurement, a bi-directional probe for velocity measurement, and flux gauges oriented to measure both convective and radiant flux. The photograph to the left in Figure 13 shows the test section of the FEE tunnel, and the photograph to the right shows the heat flow controls and graphical display of temperatures in the tunnel.

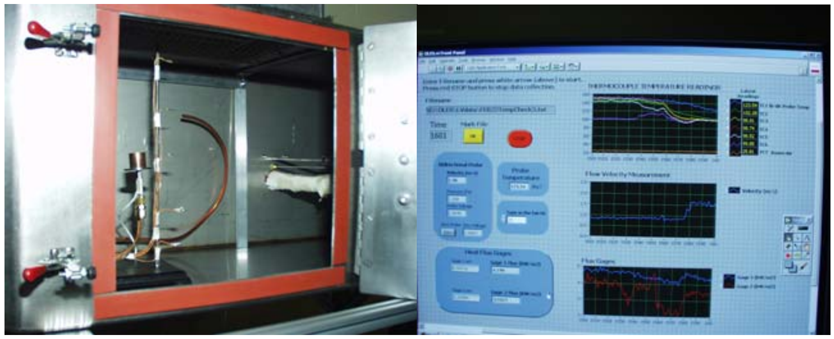


Figure 13. The FEE test section and a display of the temperature and heat controls in the FEE tunnel.

Temperature and velocity were two parameters that were controlled during the experimental procedures using the FEE tunnel. Temperature measurements were made in the test section using a 'type-K' thermocouple. The flow rate was maintained at an average speed of 1 m/s, which is the most common heat flow speed experienced by fire fighters in structural fires. (N. Bryner, personal communication, December 2005).

3.9 Radiant Panel Description

Many firefighters' burn injuries occur from exposures to the radiant heat energy produced by fire. In other cases, firefighters are burned by a combination of radiant energy and localized flame contact exposures. A Radiant Heat Energy source was used as part of the laboratory-scale experiments to validate the performance of the Fire-Eye device under controlled and reproducible radiant heat conditions (see Figure 14).

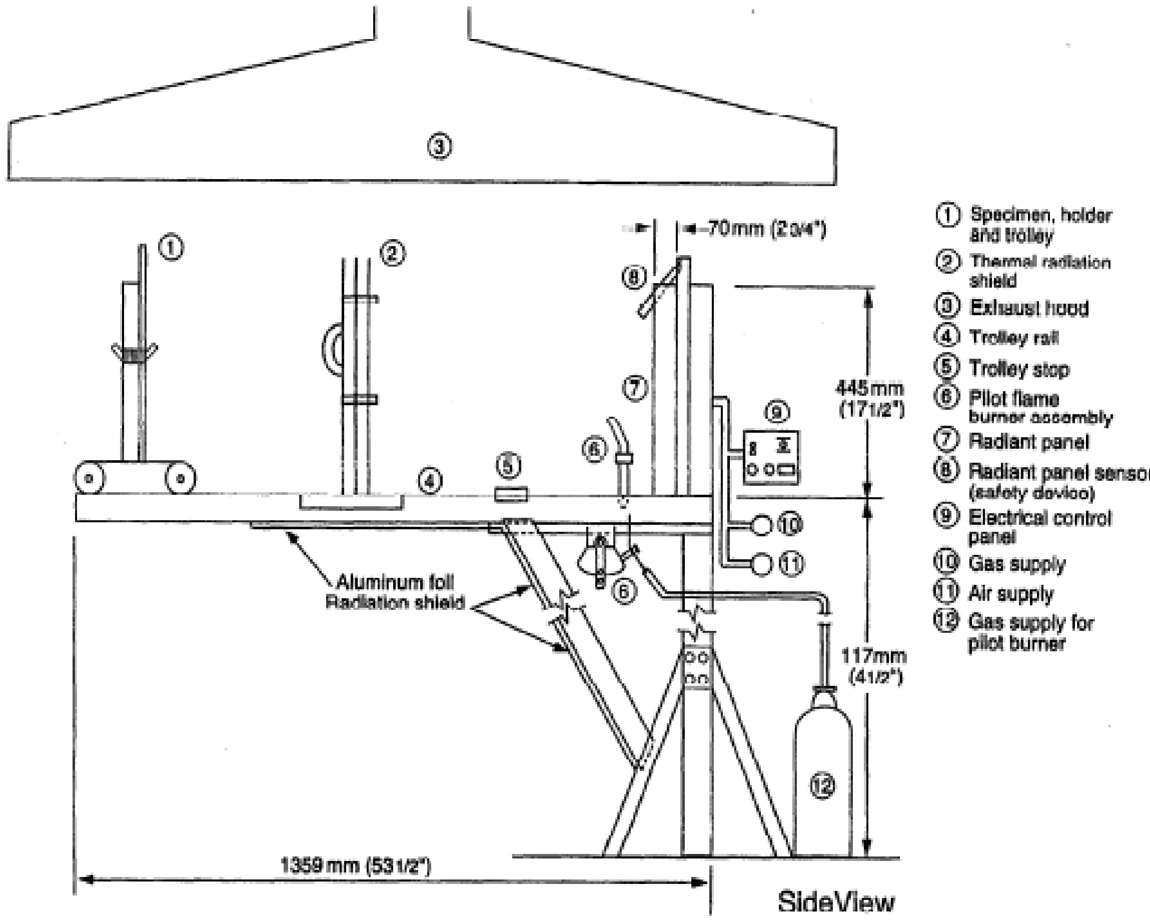


Figure 14. Side view sketch of the radiant panel test apparatus (from Lawson and Twilley, 1999, page 21).

An American Standards for Testing Materials (ASTM) standard under fixed Designation E 162–98, and which has been approved for use by agencies of the Department of Defense, specified the radiant heat source panel testing used for the laboratory-scale experiments. The relevant ASTM standard outlines the procedures for measuring and comparing the surface flammability of materials when exposed to a prescribed level of radiant heat energy, and is intended for measurements on materials whose surfaces may be exposed to fire. The rate at which the flames will travel along a surface depends upon the physical and the thermal properties of the material, its method of mounting and orientation, the type and level of fire or heat exposure, the availability of air, and the thermal properties of the surrounding enclosure (ASTM, 1997).

The test apparatus and its components are shown in Figure 15. The radiant panel consists of a porous refractory material vertically mounted in a cast-iron frame. A premixed air/natural gas fueled radiant panel produces the radiant heat energy with a radiating surface measuring 305 x 457 mm (12 x 18 inches). The panel is equipped with a ‘venture-type aspirator’ for mixing gas and air at approximately atmospheric pressure, a centrifugal blower to provide 100 ft^3/min (50 L/s) air at a pressure of 2.8 inches of water (700 Pa), an air filter to prevent dust from obstructing the panel pores, and a pressure regulator with a control/shut-off valve for the gas supply. This radiant panel is normally operated at an average surface blackbody temperature of 670 ^{o}C ± 4^{o}C (1238 ^{o}F ± 7^{o}F). A propane gas pilot line burner allowed the researcher to apply a flame directly across the test specimen’s width.

The flame height of the radiant panel may be adjusted to a low level for determining if fabrics or surface finishes will ignite, or the height may be increased to sweep across a specimen’s front surface. The pilot burner may be fixed in place, or it may be moved along the trolley rail to any location required for a specified test scenario.

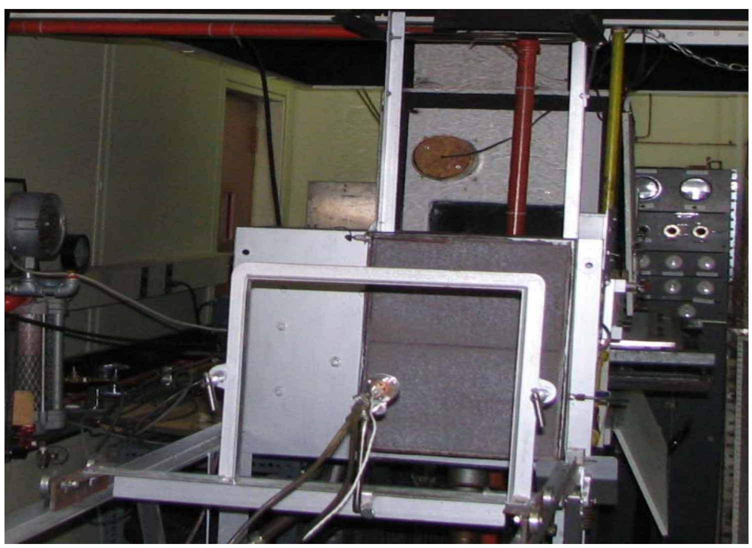


Figure 15. The radiant panel assembly.

The Fire-Eye test device was mounted on the movable trolley assembly (made with heat-resistant chromium steel) and was attached to the radiant panel test frame as shown in Figure 16. Positioning of the trolley allowed for adjustment of radiant flux exposures and provided the ability to expose test specimens to radiant energy environments that could be increased or decreased during the test (ASTM, 1997).

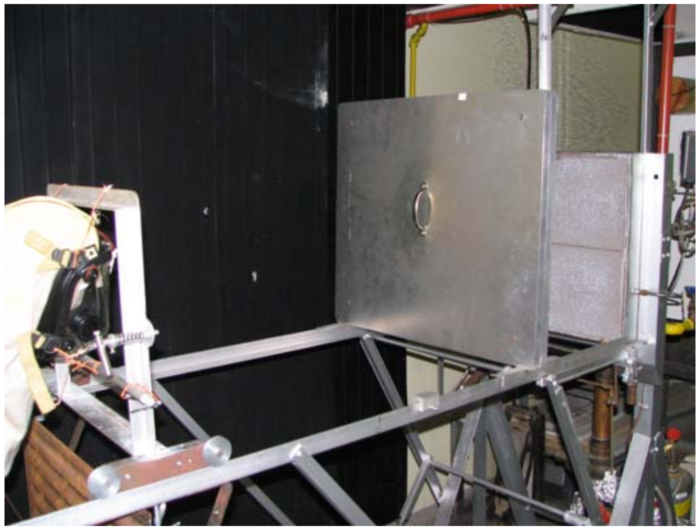


Figure 16. Side view of the radiant panel with a heat-shielding aluminum partition and the specimen holder mounted with a headform and facepiece.

A calibrated Schmidt-Boelter total heat flux transducer of the type specified in ASTM E1321, Standard Test Method for Determining Material Ignition and Flame Spread Properties, was used for measuring heat flux levels (ASTM, 1997). This water-cooled, thermopile type heat flux transducer had a nominal range of 0 to 50 kW/m^2 with a sensitivity of approximately 10 mV at 50 kW/m^2. The time constant for this heat flux gauge was not more than 290 ms, with a corresponding time to reach 95% of the final output of not more than 1 s. The heat flux gauge measured 25 mm (1 inch) in diameter and had a metal flange located 25 mm (1 inch) down its body, and away from the sensing surface (ASTM, 1997).

3.10 Batteries

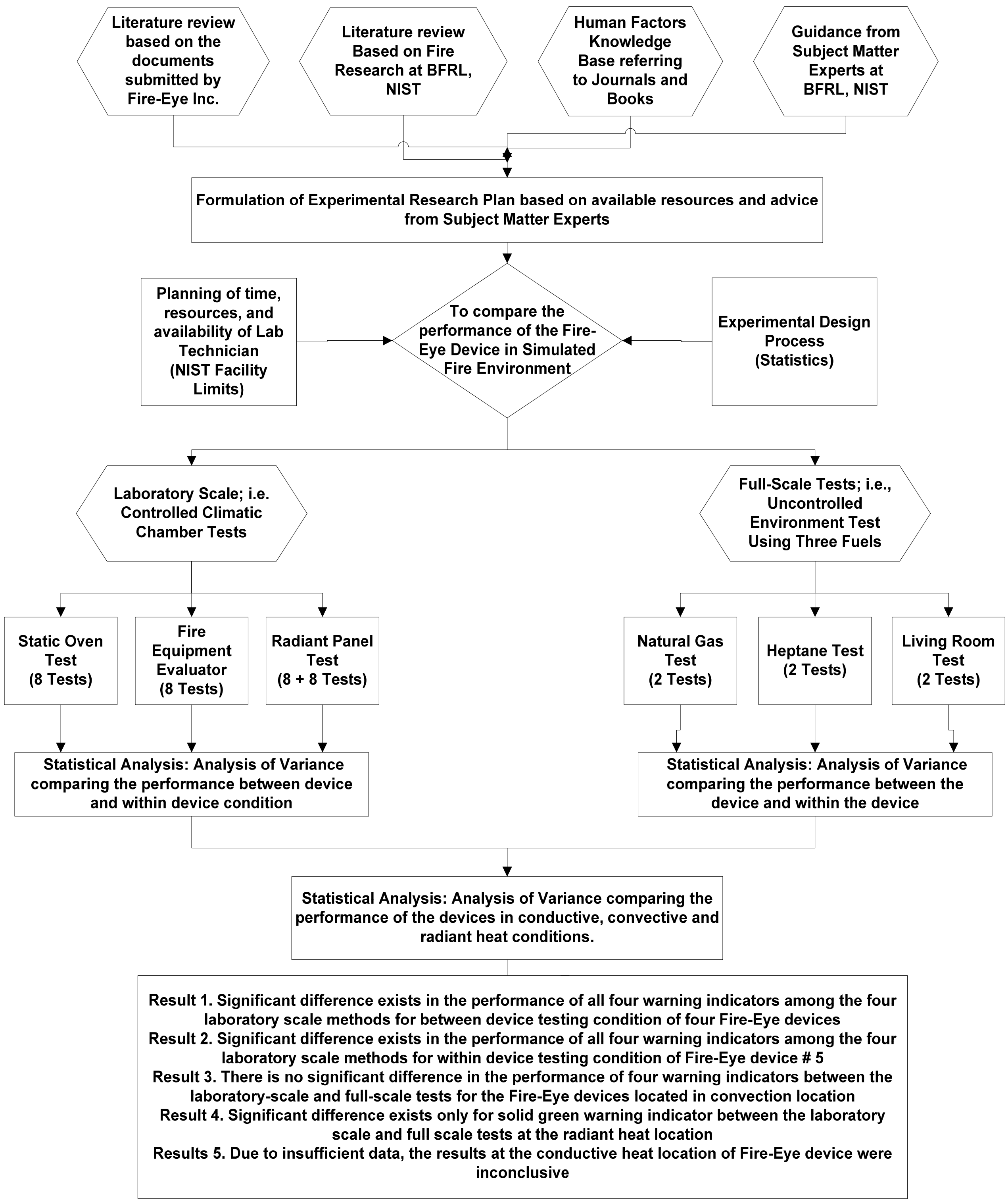
Fire-Eye devices operate using two AAA batteries (1.5 V, 1100 mAh). The batch of ten Fire-Eye devices were fitted with new AAA alkaline batteries manufactured by Duracell. To ensure that the variability in power due to used batteries was kept at a minimum, and to avoid any confounding effect of heat on the batteries inside the devices, it was decided to replace the two AAA batteries upon completion of each test. Through this procedure, the potential of low battery power influencing the research results were mitigated. As such, and after cooling the Fire-Eye device after each experiment, the AAA battery set in a particular device was replaced before that device was used for additional experimentation.

4.0 RESEARCH METHODOLOGY AND DESGIN OF EXPERIMENTS

Presented below are descriptions of the experimental scenarios and the devices evaluated within each.

The adjoining figure shows the step-by-step method followed as a part of this research effort. It also indicates the inputs as well as the information flow pattern adopted. The descriptive and inferential statistics are described later in the report.

RESEARCH FRAMEWORK - DISSERTATION PART II



4.1 Research Plan and Test Statistics

As mentioned earlier, six Fire-Eye devices were selected for the conduct of the laboratory-scale experiments. After reviewing literature specific to how various firefighter devices and equipment are tested and evaluated, it was decided to conduct three types of laboratory-scale experiments to simulate the following conditions:

1) Static Oven test representing the conductive heat effects of real fire scenarios,
2) Fire Equipment Evaluator test to recreate the convective heat flow of a real fire scenario, and
3) Radiant Panel test representing the kinds of heat effects in real fire scenario due to radiation.

Repeatability and reproducibility were the two main criteria used to design the test regimen for the three laboratory tests. To a lesser extent, the time for which the test facilities and apparatus were available was a key parameter that helped to determine the number of repetitions (rep) as well as the number of tests conducted for each device.

In order to validate the performance of the Fire-Eye device through reproducibility, it was proposed to test a particular device three times within the same test conditions. Three repetitions were conducted also helped to spotlight any 'abnormal performance' that might have presented during one of the three tests, such as a sample malfunction. Fire-Eye device #5 was selected for testing under this protocol for not only the laboratory-scale experiments, but also for the Full-scale testing to be described later. This research plan to test for reproducibility is shown in Table 5.

Table 5. Research plan to test the reproducibility of the Fire-Eye device.

Description of Tests	**Static Oven Test**	**Fire Equipment Evaluator**	**Radiant Panel**	
			Flux 1	Flux 2
Device # 5 – Test 1	Repetition 1	Repetition 1	Rep 1	Rep 1
Device # 5 – Test 2	Repetition 2	Repetition 2	Rep 2	Rep 2
Device # 5 – Test 3	Repetition 3	Repetition 3	Rep 3	Rep 3

In order to validate the repeatability of a range of Fire-Eye devices in identical test conditions for the laboratory-scale experiments, five devices were selected. Four devices (Fire-

Eye #1, 2, 3, and 6) were instrumented identically, whereas Fire-Eye device #4 was instrumented 'specially' with a thermocouple close to the platinum sensor, and inside the Fire-Eye device. The research plan to test the repeatability of the device is shown in Table 6.

Table 6. Research plan to test the repeatability of the Fire-Eye device.

Description of Tests	**Static Oven Test**	**Fire Equipment Evaluator**	**Radiant Panel**	
			Flux 1	Flux 2
Test 1 – Device # 1	Test 1	Test 1	Test 1	Test 1
Test 2 – Device # 2	Test 2	Test 2	Test 2	Test 2
Test 3 – Device # 3	Test 3	Test 3	Test 3	Test 3
Test 4 – Device # 4	Test 4	Test 4	Test 4	Test 4
Test 5 – Device # 6	Test 5	Test 5	Test 5	Test 5

As mentioned earlier, the data set from Fire-Eye device # 6 has been treated as a 'replacement dataset' should any of the other devices fail. Overall, there were 7 Static Oven tests, 7 FEE tests, and 14 Radiant Panel tests at two different flux levels. Also as mentioned in the earlier discussion, radiation is the most intense heat source that may cause varying damage to the devices within a very short span of time. Therefore, the radiant panel tests involving two different heat flux levels were selected and executed at the end of the laboratory-scale experiments, after completion of the Static Oven and FEE tests.

4.2 Facepiece Selection for Different Tests

The facepiece labeled as number 1 (Serial number 804191-08) was used for all Static Oven tests and FEE tests. In order to expedite the test set-up time and cooling time between the two radiant panel tests, facepiece # 2 (Serial number 804177-01) was used simultaneously with facepiece #1. All 3 facepieces were used simultaneously for the Full-scale fire tests.

4.3 Common Checklist for Laboratory Tests

Each of the three methods proposed for the laboratory-scale experiments differed in focus, scope, and intent. Before beginning any of the laboratory-scale experiments, certain procedures needed to be followed in the form of a 'checklist' in an effort to reduce or eliminate variability that may have arisen due factors that are controllable, such as measuring baseline temperatures before testing. In order to properly complete the research regimen, the following checklist was printed and referred to before the conduct of all laboratory-scale experiments:

1) Label and load a new mini-DV tape.
2) Mount the facepiece and the Fire-Eye device at the same location in each test.
3) Plug the thermocouples into the data acquisition system and ensure that each thermocouple reads the ambient temperature.
4) Plug the ambient temperature thermocouple and attach it to the facepiece at a distance of one inch from the Fire-Eye device.
5) Confirm that the beads of each thermocouple are touching the appropriate targeted surface in order to avoid any open connection during the experiment.
6) Confirm that the graphical as well as the numerical display on the computer displays the current ambient temperature.
7) Adjust the view of the bullet camera in order to focus on the warning indicators of the mounted Fire-Eye device.

Once the 'pre-experiment checklist' was verified, another checklist was consulted during the experiment:

1) Start the test by pushing the 'record' button on the video recording unit.
2) In the lab notebook, record events in the following order:
    a) Test begin time and ambient temperature at that moment,
    b) Time and temperature of Fire-Eye blinking green light*****,
    c) Time and temperature of Fire-Eye blinking solid green light*****,
    d) Time and temperature of Fire-Eye blinking solid red light,
    e) Time once the temperature reaches 140^{o} C,

    *****It should be noted that the Fire-Eye device *may not always progress through all stages of green*; if the temperature increases faster than 1°/sec for 10 sec (rapid heating), the device will not display 'solid green' at all, and will instead progress immediately to 'solid red' (the 'blinking red' indicator will not be displayed until the temperature is decreasing and the environment is cooling).

    f) Time and temperature of Fire-Eye blinking red light when the test environment begins to cool.

Finally, once the ‘during experiment checklist’ was verified, a third checklist was consulted after the completion of a particular experimental trial:

1) Allow the bullet camera and the Fire-Eye device to cool for at least 15 minutes at the end of each test.
2) Label and save the test data file from the data acquisition system after completion of a test.
3) Replace the two AAA batteries in each Fire-Eye device for next test.
4) Conduct a self-test of each Fire-Eye device after replacing the batteries by pressing the small button on the clip-box unit, which confirms the functionality of indicator lights on device.
5) Replace the Fire-Eye device with the next Fire-Eye device. Confirm the wiring connections and functioning capacity of all six thermocouples so that they are reading appropriate ambient temperatures.
6) Confirm that an ambient temperature thermocouple is reattached to the facepiece precisely one inch from the Fire-Eye device.

5.0 LABORATORY-SCALE EXPERIMENTAL PROCEDURES

A detailed, step-by-step procedure for the three laboratory test methods is described in below. The test procedures are described in the order in which they were actually conducted during the laboratory-scale experimental trials.

5.1 Static Oven Test Procedure

1) (Initially) Researcher familiarized himself in the use of the static oven’s thermostat to learn how movement of its knob corresponded to a temperature increase.
2) The headform was mounted, along with a facepiece installed with the Fire-Eye device, in the center of the static oven using the wires as shown in Figure 17. Four pieces of wire were used to suspend the facepiece in the center of the oven by tying them to the steel rods that were attached to the oven’s interior sides. A rectangular heat-resistant tile was placed below the base of the head form in order to shield it from heat.

3) The thermometer was inserted through the small opening in the roof of the oven to track temperatures during the test.
4) The makeshift oven door was closed. The power was set to ON for the oven and the thermostat was set at 50^{o} C.
5) Upon achieving an oven temperature of 50^{o} C, the test start time was recorded in the laboratory notebook, and the marker channel was actuated (hit) to create a spike in the data.
6) The temperature was increased at an interval of 10^{o} C every 3 minutes by turning the thermostat knob in a clockwise direction.
7) While the temperature in the oven was increasing, the change in status of the indicator lights was recorded by actuating the marker channel. These items were also recorded in the laboratory notebook.
8) The temperature in the oven was increased until it reached 140^{o} C. A record was made when the Fire-Eye device displayed blinking red lights, indicating that the environment was 'still heating.'
9) The static oven was turned off once the temperature reached 140^{o} C. The Fire-Eye device and the bullet camera were allowed to cool for 15 minutes before opening the makeshift door attached to the static oven. The oven door was opened and a high- speed cooling fan was focused on the facepiece for rapid cooling.
10) The static oven test was repeated using different Fire-Eye devices to complete the research plan. Eight tests were completed over a period of two days in this manner.

Note: In the first pilot test, the bullet camera overheated, leading to melting of an exposed portion of the bullet camera at the maximum temperature of 140^{o} C. As a result, all future testing in the static oven was halted at 140^{o} C.

Figure 17. The instrumented setup for the static oven experiment.

5.2 Fire Equipment Evaluator Test Procedure

1) Initially the FEE system was powered up and the NIST laboratory technician activated the devices associated with the system.
2) The FEE system was preheated for about 30 minutes so that a steady flow of heated air was available. The TC inside the test section area of the FEE was confirmed to indicate the appropriate ambient temperature. This TC temperature was used as the reference temperature for the experimental trial.
3) The headform covered with the instrumented facepiece and the Fire-Eye device was mounted in the center of the FEE's test area. The head form was suspended in the center of the test area using four small wires which were tied to steel rods attached to the walls of the test section (similar to that of the static oven experiments, see Figure 18).
4) The thermocouple connections were tested to ensure that the data acquisition system was reading the ambient temperature appropriately from all TC's.
5) The door of the test area of the FEE was closed and the temperature was increased to 50^{o} C.
6) The test was started once the temperature of 50^{o} C was achieved. The test start time was recorded in the laboratory notebook and the marker channel was actuated.
7) The temperature of the FEE test area was increased at an interval of 10^{o} C every 3

minutes from the test start time (to simulate a gradual heating environment as in a real fire scenario). The temperature was increased by the laboratory technician with the help of the controls attached to a separate computer interfaced with the FEE.

8) Changes in the status of the indicator lights were recorded by actuating the marker channel as well as by recording the temperature and time in the laboratory notebook.
9) In order to be consistent with the static oven test maximum temperature limit, the temperature in FEE was also increased until it reached 140^{o} C. The Fire-Eye device would display a 'solid red' light at this temperature. The 'blinking red' light would indicate a condition wherein the environment is hot, but is cooling. The 'solid red' light would indicate a condition wherein the environment is hot, and is getting hotter. However, and as noted previously for 'green' status, it should be understood that the Fire-Eye device *may not always progress through all stages of red*. If the temperature increases faster than 1°/sec for 10 sec (for example), the device will instead progress immediately to 'solid red' and the 'blinking red' indicator will not be displayed until the environmental temperature is decreasing. Thus, all temporal measures specific to the actuation of 'red' will hereafter refer to display of *either* 'blinking red' or 'solid red.' 'Blinking red' will always indicate the environment is cooling and the temperature is decreasing.
10) The FEE controls were turned off once the test area's temperature reached 140^{o} C. The Fire-Eye device as well as the bullet camera was allowed to cool for fifteen minutes. The door of the test area was opened and the headform, facepiece, and Fire-Eye device were removed.
11) The FEE test was repeated using different Fire-Eye devices to complete the research procedure. Eight FEE tests were conducted over a period of two days, and the timeline for each test is listed in the results section.

Figure 18. The instrumented setup for the Fire Equipment Evaluator experiment.

5.3 Radiant Panel Test Procedure

Before conduct of the Radiant Panel tests, a radiant heat source calibration was necessary. First, the thermal environment (heat flux of 1.6 kW/m^2) was selected for the first set of tests. The gas-fired radiant panel was ignited and was allowed to preheat for 45 minutes. The preheat time allowed stabilization of the radiant panel temperature before calibration was attempted. Using the calibration coefficient for the Schmidt-Boelter heat flux gauge, the millivolt output value was calculated for the selected incident heat flux. An inorganic calcium silicate calibration board with a hole located at its geometric center was attached to the trolley's specimen holder frame. The heat flux gauge hole was cut slightly larger than the heat flux gauge diameter so that the gauge could easily be inserted into the board and held in place. The calibrated heat flux gauge, as described earlier in section 2.9, was attached to a calibrated digital millivolt meter and was placed into the calibration board hole. The thermal radiation screen was kept in place until the radiant panel was ready to calibrate. Heat flux gauge cooling water was turned on, and the flow rate was adjusted to 0.57 L/min +/- 0.2 L/min (0.15 gal/min +/- 0.05 gal/min). The thermal radiation screen was removed and the gauge was allowed to heat until the signal output became relatively stable—this usually took only a few seconds. The specimen trolley was either moved towards or away from the radiant panel to determine the location that produced the desired heat flux of 1.6 kW/m^2. The test section location was marked and recorded with the millivolt output and heat flux value. Rail locks were put into place to keep the test specimen trolley from moving. When two or more heat flux exposure conditions were needed for an experiment, the trolley was moved to positions that produced the desired heat flux, and the above marking procedure was repeated. A trolley rail lock was placed on the rail at the closest and the most distant marked locations from the radiant panel (Lawson and Twilley, 1999). The step-by-step radiant panel experimental procedure follows:

1) In order to achieve a uniform and steady heat flux, the laboratory technician conducted calibration of the radiant panel earlier in the day when the tests were to be conducted.
2) For the first set of tests using radiant panel, a flux of 1.6 kW/m^2 was chosen as the target flux (i.e., the heat flux that firefighters face while fighting a fire and can survive in for 30 minutes or less without developing skin burns). To achieve a flux of 1.6 kW/m^2, the specimen was calibrated to be spaced at a distance of 33 in from a reference point of the radiant panel. This procedure was outlined above.
3) An aluminum separator was used to shield the Fire-Eye device from the radiant heat while the headform, along with the instrumented facepiece, was mounted on the specimen-carrying movable frame.
4) The headform and facepiece was mounted in the center of the movable frame such that the heat from the radiant panel was incident on the Fire-Eye device. The headform was tilted and tightened at an angle as shown in Figure 19, resulting in the Fire-Eye device positioned parallel to the radiant panel. In order to secure the headform in the desired location and inclination, two small wires attached to the facepiece were tied to steel frames.

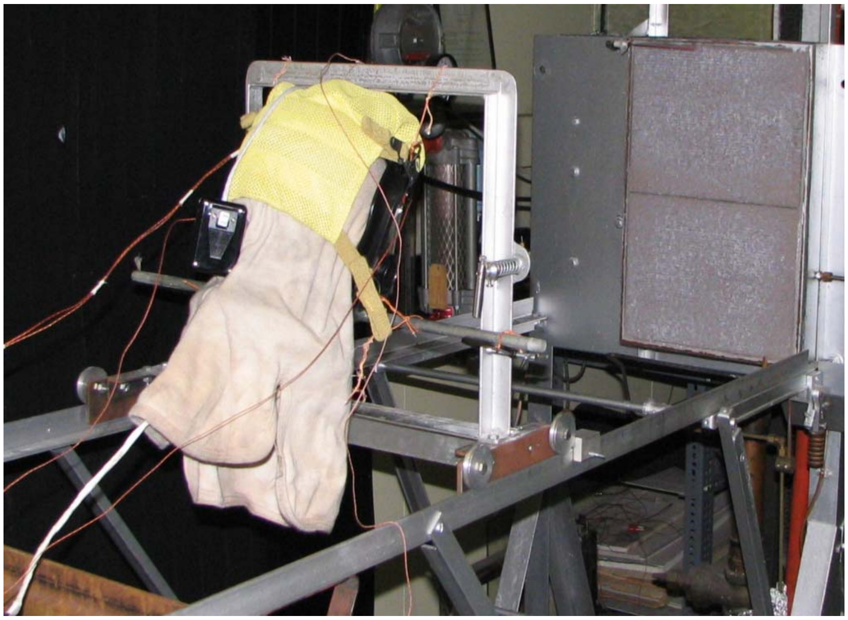


Figure 19. The instrumented setup for the Radiant Panel experiments.

5) The thermal shield was removed and exposed the instrumented headform to the heat from the radiant panel.
6) The experiment was started and the test start time was recorded in the laboratory notebook as well as by actuating the marker channel.
7) Changes in status of indicator lights were recorded in the laboratory notebook as well as by actuating the marker channel.
8) The thermal shield was inserted between the radiant panel and the facepiece when the Fire-Eye device produced a continuous blinking red indicator indicating the cooling of the environment. The movable specimen holder was moved away from the radiant panel to allow it to cool for fifteen minutes. The Fire-Eye device and facepiece were replaced for the next test.
9) Eight tests were repeated in the same fashion as above at a flux intensity of 1.6 kW/m2.
10) A set of tests was repeated at a flux intensity of 4 kW/m^2. In order to achieve the target flux level of 4 kW/m^2, the mask mounted with the Fire-Eye device, positioned on the movable trolley, was hooked at a distance of 16 in from the radiant panel. The timeline for each test is listed in the results section below.

6.0 RESULTS

The results of the aforementioned laboratory-scale experiments are presented below.

6.1 Thermal Environment for Static Oven and FEE Experiments

Figure 20 displays the thermal environment inside the static oven in which the Fire-Eye devices were tested across several TC locations. TC5 recorded the ambient temperature during each test. The graph in Figure 20 shows the rate of increase of temperature per second for each static oven test. It indicates the maximum temperatures that the various Fire-Eye devices were exposed to in the enclosed static oven environment.

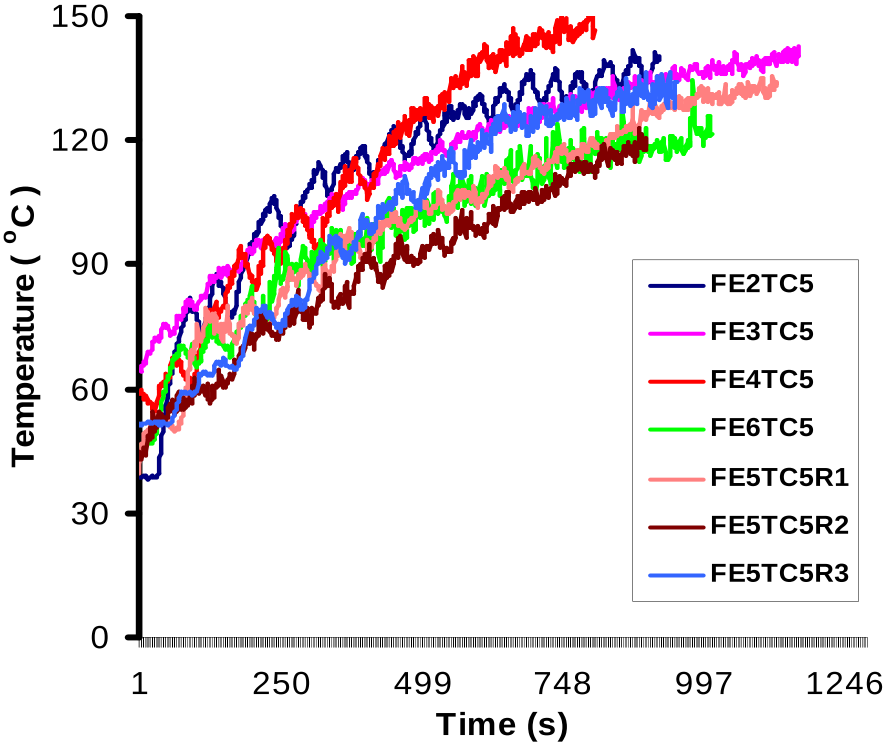


Figure 20. Thermal Environment in Static Oven tests.

Figure 21 displays the thermal environment inside the FEE test area for various Fire-Eye devices. The rate of increase of temperatures in the FEE tests was more uniform as shown in the graph. The temperature of the hot air circulating inside the FEE section was precisely controlled by the laboratory technician in each test. Therefore, the TC5 temperature profile for each test is identical or similar for each FEE test as shown in Figure 21.

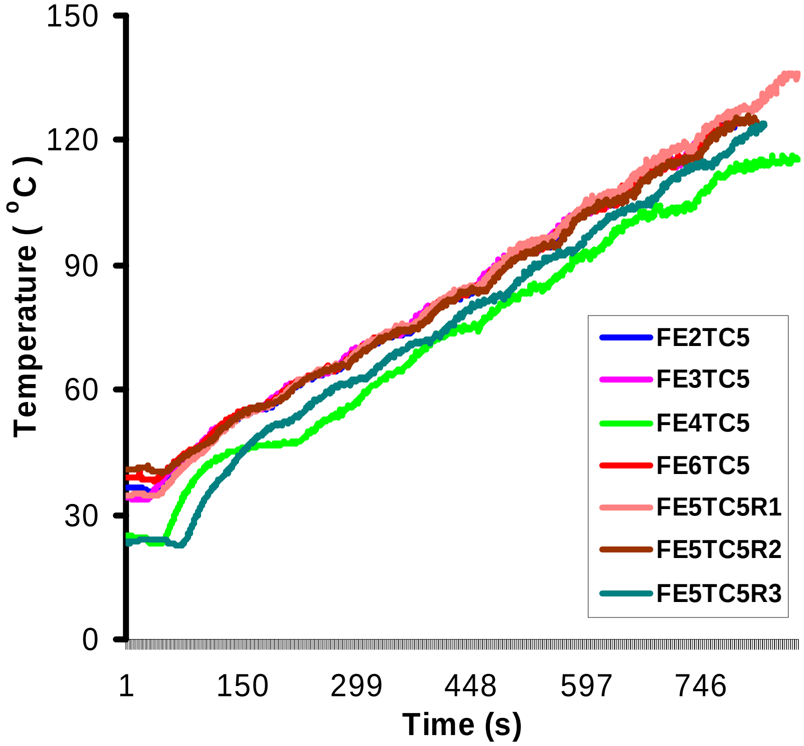


Figure 21. Thermal Environment in FEE tests.

In case of the Radiant Panel tests, the tests were conducted in a laboratory without any enclosed environment as in Static Oven or FEE. Therefore, the ambient room temperature at each test was the reference temperature for the two set of Radiant Panel tests.

6.2 Static Oven Test Results

Table 7 presents the timeline, test numbers, test dates, and data file names for each device tested in the Static Oven. Table 8 outlines the performance of various Fire-Eye devices within the Static Oven, and Table 9 presents the same information for Fire-Eye device #5. Figure 22 displays the graphical representation of the warning indicators of various Fire-Eye devices in the Static Oven test, whereas Figure 23 shows the graphical representation of the warning indicators of Fire-Eye device # 5 in three Static Oven tests.

Even though the 'blinking red' is not an actual stage of warning hierarchy of the Fire-Eye device, it has been represented in the plots to indicate the maximum temperature that was reached in the test before the environment started cooling. The ‘blinking red’ reference indicator in the graph also helps to indicate the length of time the device indicated solid red light when the environmental temperature was increasing.

Table 7. Timeline and details for the Static Oven experiments.

Test Number	Fire-Eye Label	Date	Test begin time	Test end time	Data file name
Test 1	FE0501	12/19/2005	14:49:20	15:19:58	FE1222A.DAT
Test 2	FE0502	12/19/2005	16:28:02	16:58:36	FE1220A.DAT
Test 3	FE0503	12/20/2005	10:10:14	10:55:56	FE1220B.DAT
Test 4	FE0504	12/20/2005	15:51:04	16:17:50	FE1220F.DAT
Test 5	FE0506	01/18/2006	15:13:32	15:47:12	FE0118G.DAT
Test 6	FE050501	12/20/2005	12:22:58	13:00:28	FE1220C.DAT
Test 7	FE050502	12/20/2005	14:25:28	14:55:16	FE1220E.DAT
Test 8	FE050503	01/18/2006	14:15:46	14:47:24	FE0118F.DAT

Table 8. Performance of different Fire-Eye devices in the Static Oven experiments.

Fire-Eye Device #	Blinking Green (^{o} C)	Solid Green (^{o} C)	Solid Red (^{o} C)	Blinking Red (^{o} C)
FE 01	63.76	No Status	99.23	112.61
FE 02	83.04	No Status	123.41	134.93
FE 03	74.90	89.77	90.38	108.56
FE 04	64.63	113.72	No Status	120.29
FE 06	55.89	90.71	90.26	102.01

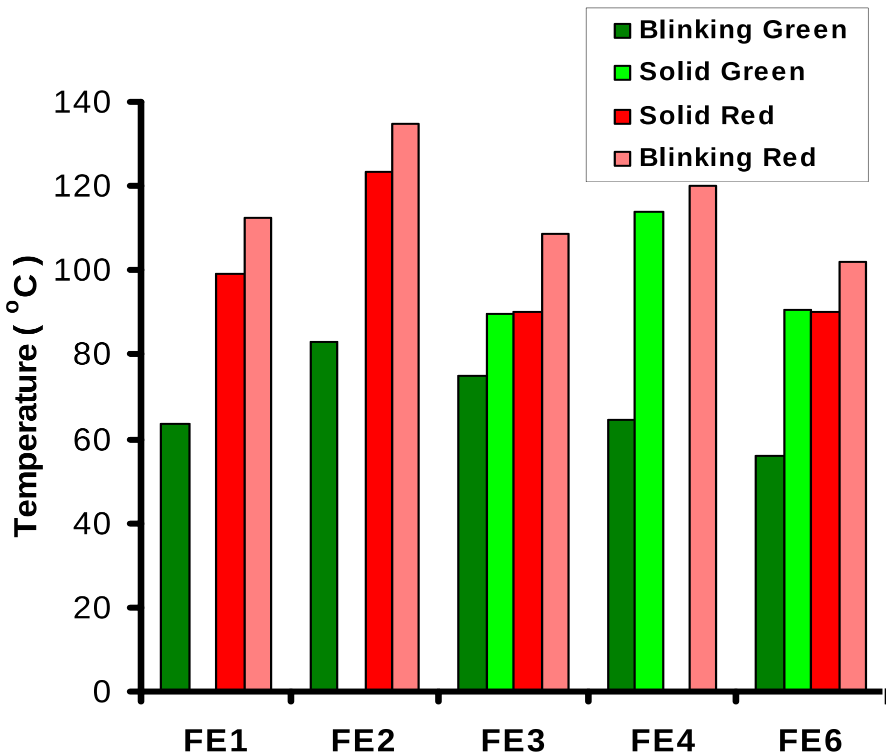


Figure 22. Repeatability of different Fire-Eye devices in Static Oven Tests

Table 9. Performance of Fire-Eye device #5 in the Static Oven experiments.

Fire-Eye Device #	Blinking Green (° C)	Solid Green (° C)	Solid Red (° C)	Blinking Red (° C)
FE 05 – Rep 1	58.47	85.64	90.31	108.96
FE 05 – Rep 2	72.57	90.25	105.34	110.38
FE 05 – Rep 3	52.75	78.92	82.18	94.06

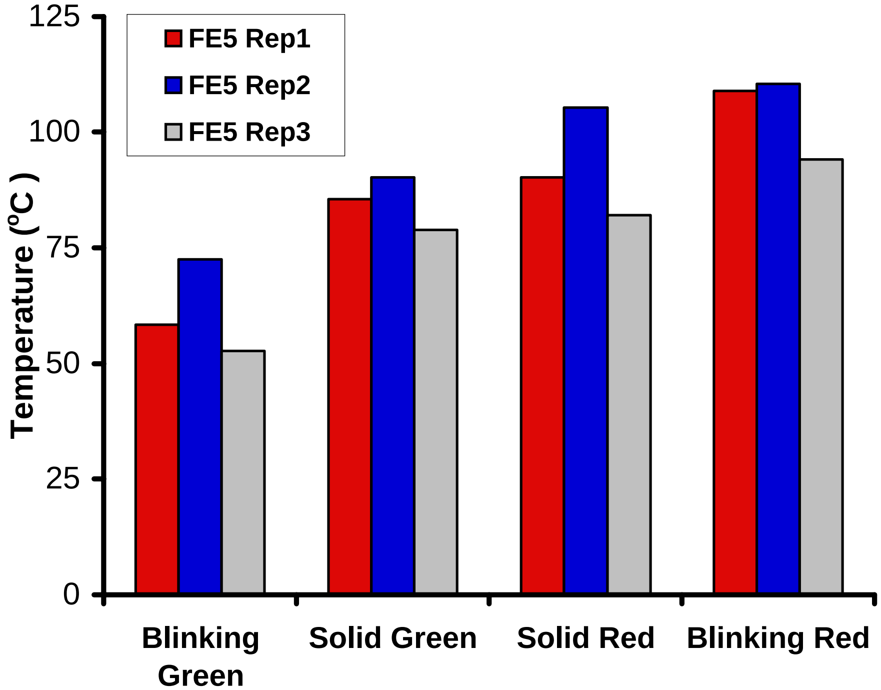


Figure 23. Reproducibility of Fire-Eye device # 5 in Static Oven Tests

Figure 24 shows temperature at the front surface (i.e., thermocouple 1) across various Fire-Eye devices in the static oven experiments. Figure 25 displays TC1 results for Fire-Eye device #5 across three repetitions. The rate of increase of temperature of TC1 was slightly different for each device in Figure 24. Figure 25 shows the rate of increase of temperature for the same device # 5 in three different tests also varied in each test. Figure 26 displays temperatures for four TC's for Fire-Eye device #4. TC2, the TC on the rear side of FE device, and TC 5, the TC inside the FE device registered almost same temperatures over the period of test. This identical temperature profile of TC2 and TC5 of FE # 4 indicates that both the surfaces experienced similar heat exposure.

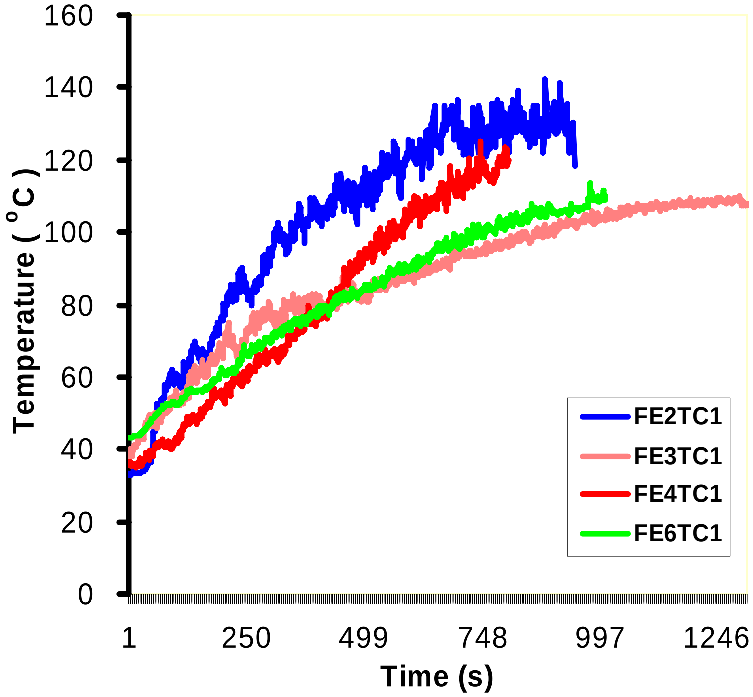


Figure 24. TC1 temperatures at the front surface (TC1) of different Fire-Eye devices in Static Oven tests.

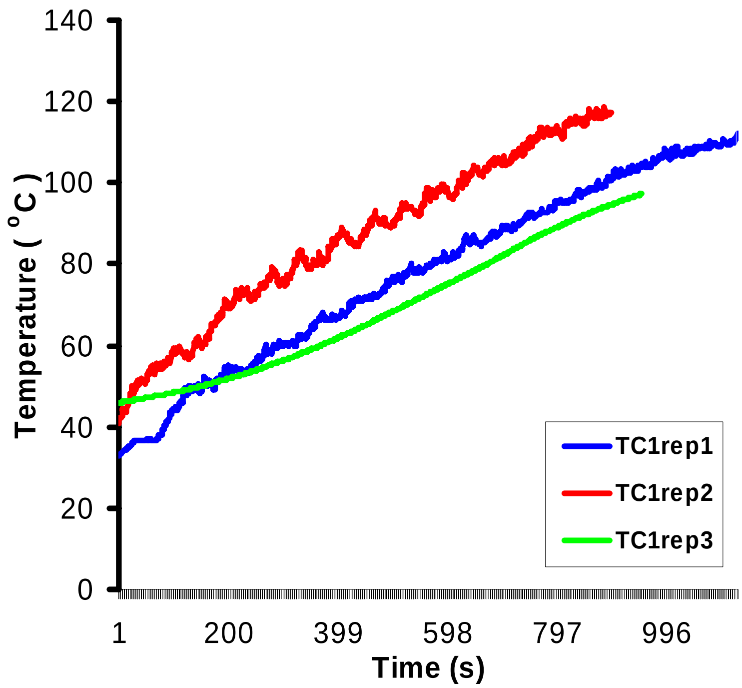


Figure 25. TC1 temperatures at the front surface of FE5 in three repetitions of the Static Oven test of reproducibility.

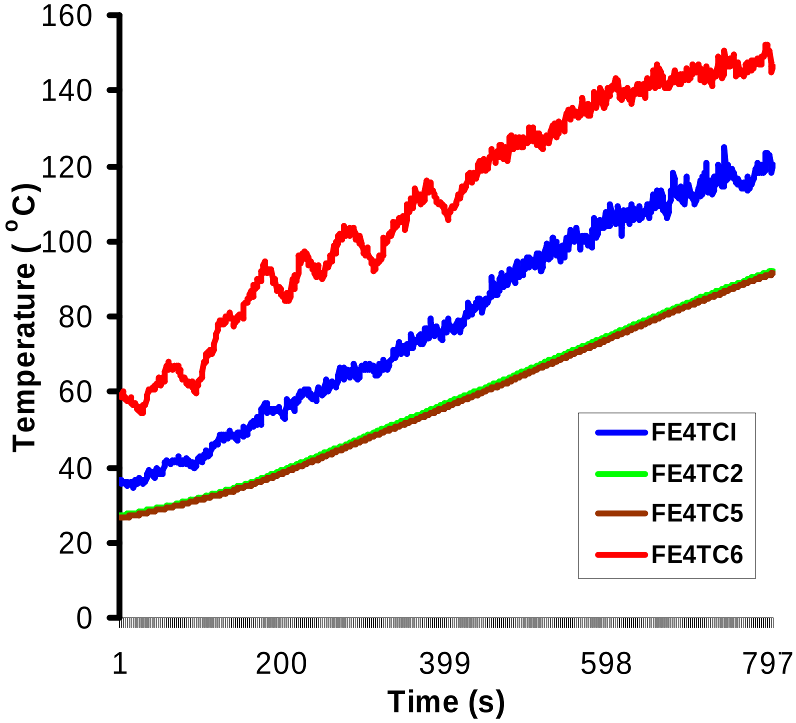


Figure 26. Temperatures at the four TC locations of FE #4 in a Static Oven test.

6.3 Fire Equipment Evaluator Test Results

Table 10 outlines the test identification numbers, Fire-Eye units, and timeline for the FEE experiments conducted. Table 11 presents the results for the Fire-Eye indicator light conditions as a function of temperature, and Table 12 presents the same data for Fire-Eye device #5. Figure 27 displays the graphical representation of the warning indicators of various Fire-Eye devices in the FEE test, whereas Figure 28 shows the graphical representation of the warning indicators of Fire-Eye device # 5 in three FEE tests.

Table 10. Timeline and details for the Fire Equipment Evaluator (FEE) experiments.

Test Number	Fire-Eye Label	Date	Test begin time	Test end time	Data file name
Test 1	FE0501	12/21/2005	13:50:46	14:10:30	FE1221D.DAT
Test 2	FE0502	12/21/2005	14:54:42	15:20:58	FE1221D.DAT
Test 3	FE0503	12/22/2005	10:04:06	10:26:30	FE1222B.DAT
Test 4	FE0504	12/21/2005	10:21:10	10:41:50	FE1221B.DAT
Test 5	FE0506	12/22/2005	11:01:52	11:28:20	FE1222C.DAT
Test 6	FE050501	12/21/2005	11:32:10	12:02:46	FE1221C.DAT
Test 7	FE050502	12/21/2005	15:56:30	16:23:44	FE1221D.DAT
Test 8	FE050503	12/22/2005	08:57:04	09:24:40	FE1222A.DAT

As shown in Table 11 and Figure 27, FE device # 1 ceased to function in the FEE test.

Table 11. Performance of different Fire-Eye devices in the FEE experiments.

Fire-Eye Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
FE 01	No Status	No Status	No Status	No Status
FE 02	49.87	84.14	88.60	92.19
FE 03	59.61	100.21	107.55	118.04
FE 04	65.37	104.57	106.67	107.17
FE 06	58.99	101.81	107.50	119.22

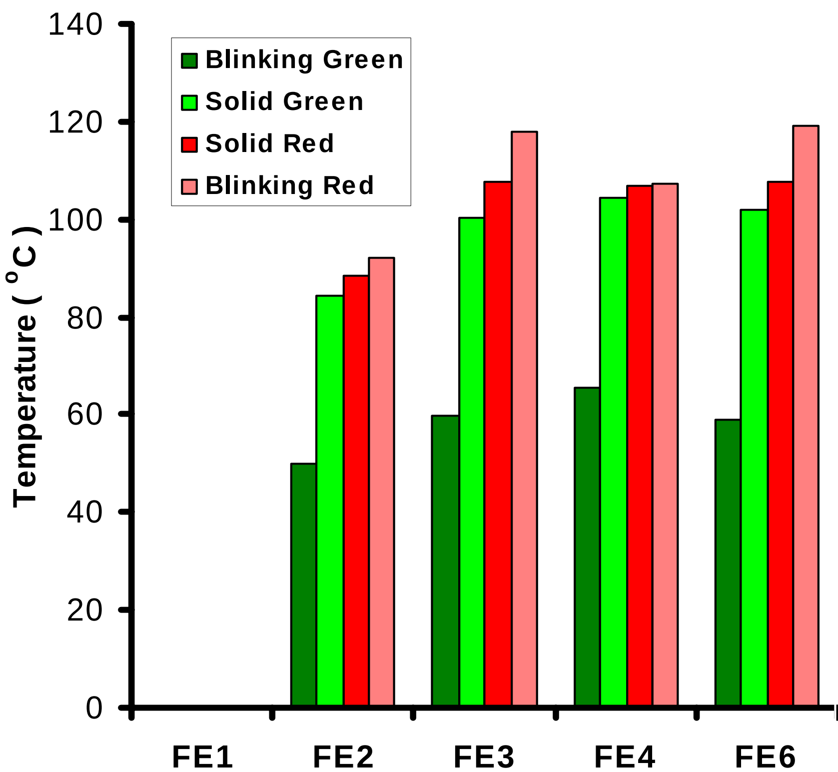


Figure 27. Performance of different Fire-Eye devices in FEE tests.

Table 12. Performance of Fire-Eye device # 5 in three repetitions of the FEE experiment.

Fire-Eye Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
FE 05 – Rep 1	61.67	104.43	110.85	130.76
FE 05 – Rep 2	61.47	106.27	110.16	121.15
FE 05 – Rep 3	66.57	107.22	113.71	120.30

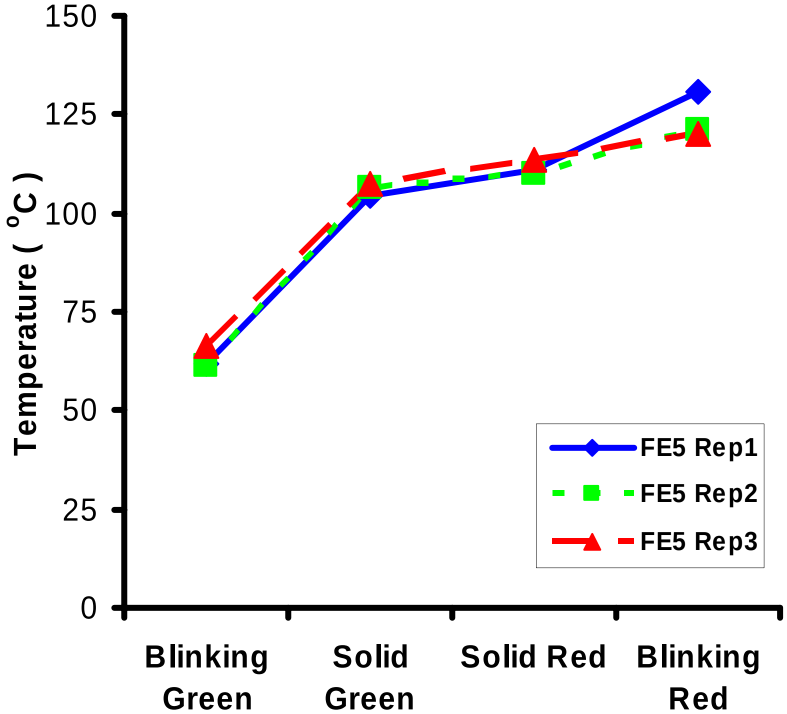


Figure 28. Reproducibility of Fire-Eye device # 5 in FEE Tests.

Figure 29 displays TC1 temperature results for different Fire-Eye devices as a function of time elapsed, and Figure 30 displays TC1 temperature results for Fire-Eye device #5 as a function of time across three repetitions. Figure 31 displays the temperature results of four TC's for Fire-Eye device #4.

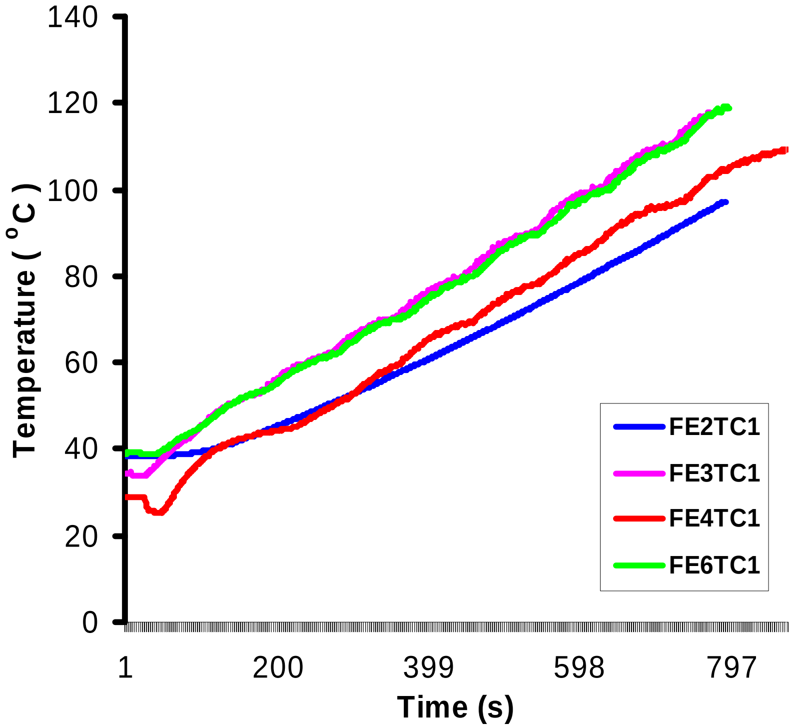


Figure 29. TC1 temperatures at the front surface of different Fire-Eye devices in the FEE tests.

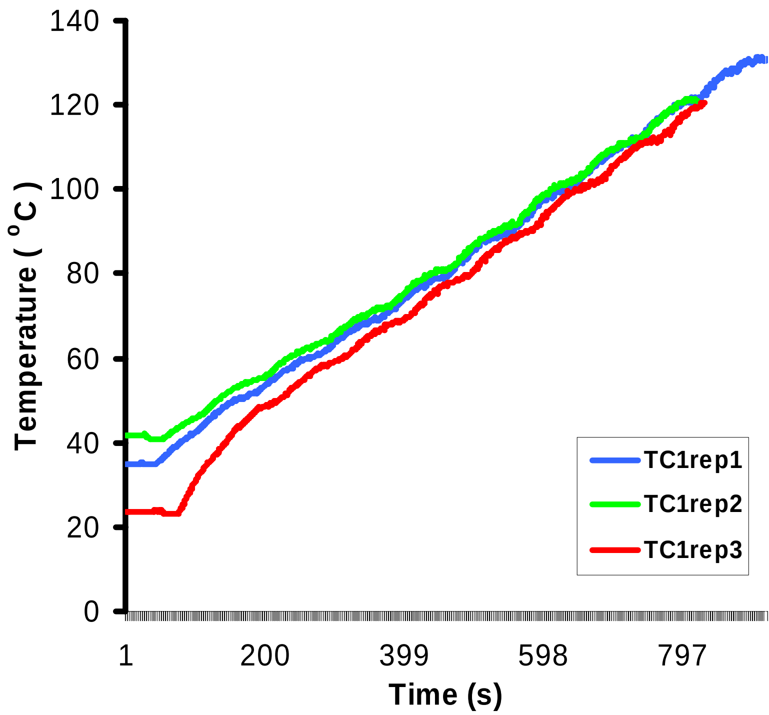


Figure 30. Temperatures at the front surface of FE5 in three repetitions of the FEE tests as before.

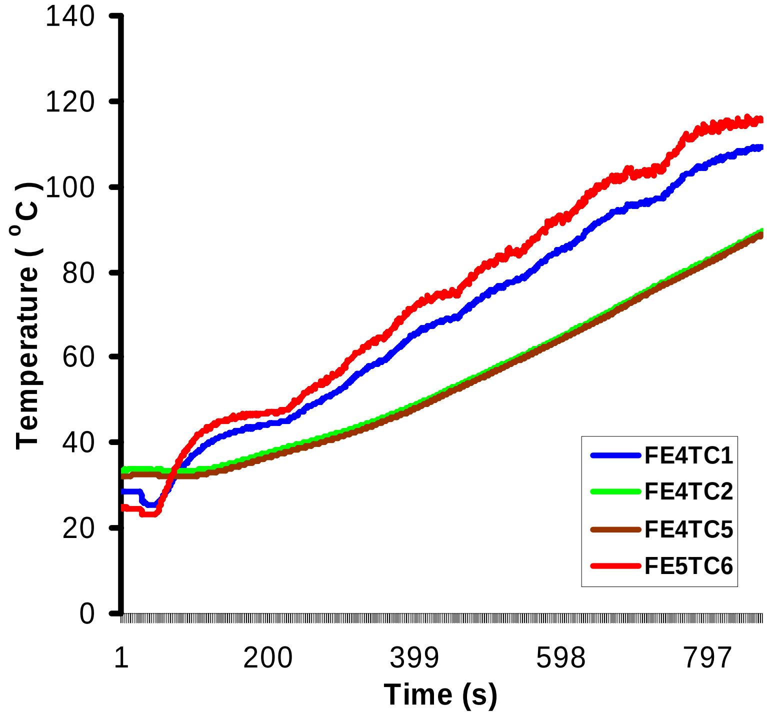


Figure 31. Temperatures at the four TC locations of FE4 in a FEE test.

6.4 Radiant Panel Test Results

Table 13 outlines the test numbers, Fire-Eye units, and timeline for the Radiant Panel experiments conducted at a heat flux level of 1.6 kW/m^2. Table 14 presents the results for the Fire-Eye indicator light conditions as a function of temperature, and Table 15 presents the same data for Fire-Eye device #5. Figure 32 displays the graphical representation of the warning indicators of various Fire-Eye devices in the Radiant Panel test at a heat flux level of 1.6 kW/m^2 , whereas Figure 33 shows the graphical representation of the warning indicators of Fire-Eye device # 5 in three Radiant Panel tests at a heat flux level of 1.6 kW/m^2.

Table 13. Timeline and details for the radiant panel tests at a heat flux 1.6 kW/m^2.

Test Number	Fire-Eye Label	Test Date	Test begin time	Test end time	Data file name
Test 1	FE0502	12/22/2005	15:05:34	15:28:08	FE1222F.DAT
Test 2	FE0503	12/22/2005	16:21:08	16:43:26	FE1222F.DAT
Test 3	FE0504	01/18/2006	13:18:02	13:44:44	FE0118E.DAT
Test 4	FE0506	12/22/2005	12:49:36	13:19:44	FE1222D.DAT
Test 5	FE050501	12/22/2005	14:07:26	14:35:04	FE1222E.DAT
Test 6	FE050502	12/22/2005	15:47:26	16:11:24	FE1222F.DAT
Test 7	FE050503	01/18/2006	11:26:12	11:53:54	FE0118C.DAT

Table 14. Performance of different Fire-Eye devices in radiant panel tests at a heat flux of 1.6 kW/m^2.

Fire-Eye Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
FE 02	44.45	87.26	88.14	95.57
FE 03	47.66	57.41	61.89	58.17
FE 04	61.44	84.60	86.28	89.18
FE 06	39.32	40.41	37.60	40.41

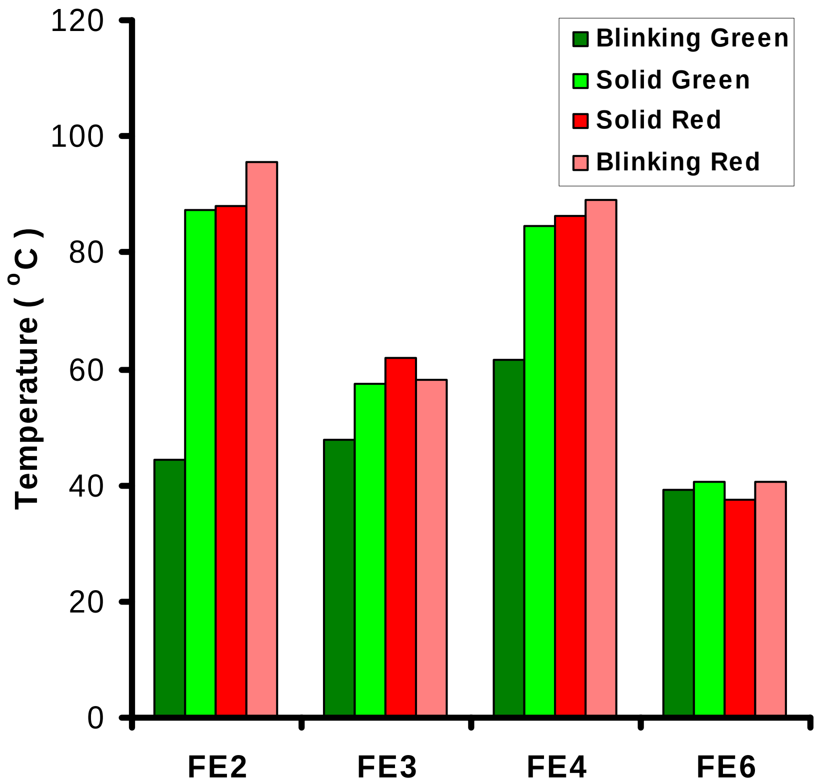


Figure 32. Repeatability of different Fire-Eye devices in Radiant Panel Tests at a heat flux level of 1.6 kW/m^2.

Table 15. Performance of Fire-Eye device # 5 in radiant panel tests at a heat flux of 1.6 kW/m^2.

Fire-Eye Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
FE 05 – Rep 1	54.52	71.87	72.98	77.39
FE 05 – Rep 2	59.47	84.83	86.64	94.48
FE 05 – Rep 3	61.61	87.29	87.10	88.93

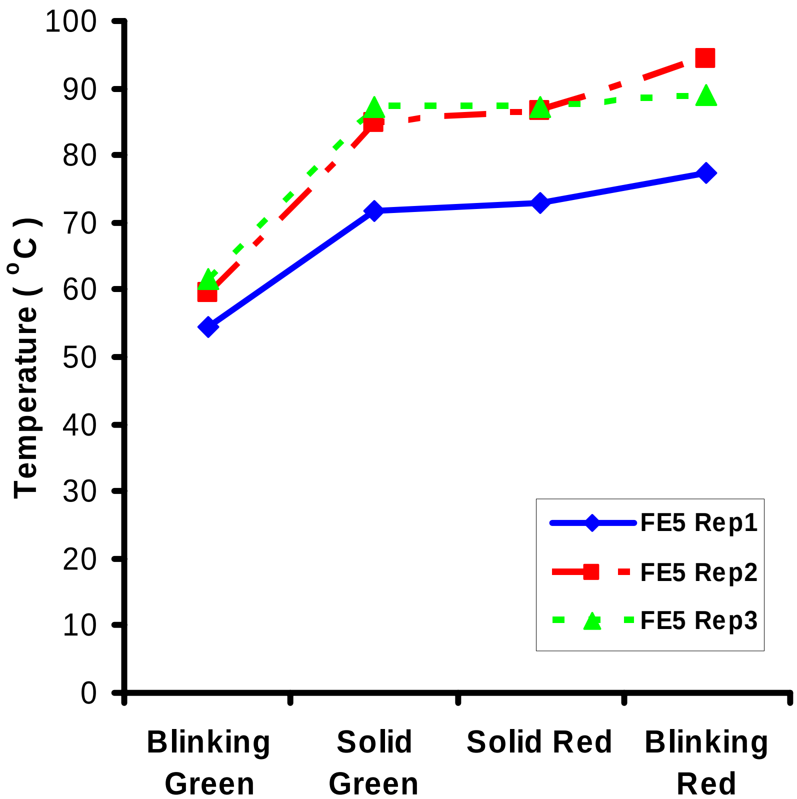


Figure 33. Reproducibility of Fire-Eye device # 5 in Radiant Panel tests at a heat flux of 1.6 kW/m^2.

Figure 34 displays TC1 temperature results for different Fire-Eye devices as a function of time elapsed, and Figure 35 displays TC1 temperature results for Fire-Eye device #5 as a function of time across three repetitions. Figure 36 displays the temperature results of four TC's for Fire-Eye device #4.

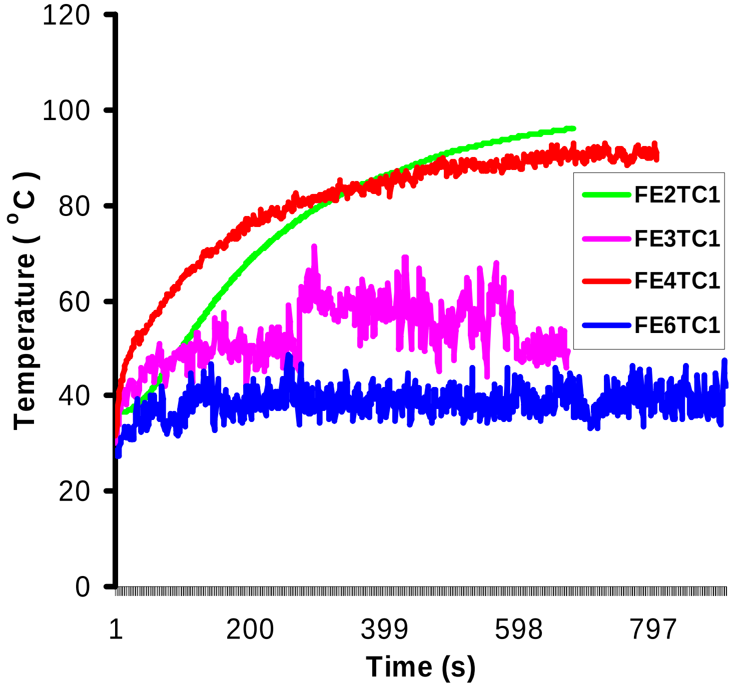


Figure 34. TC1 temperatures at the front surface of the Fire-Eye devices in the Radiant Panel tests at a heat flux of 1.6 kW/m^2.

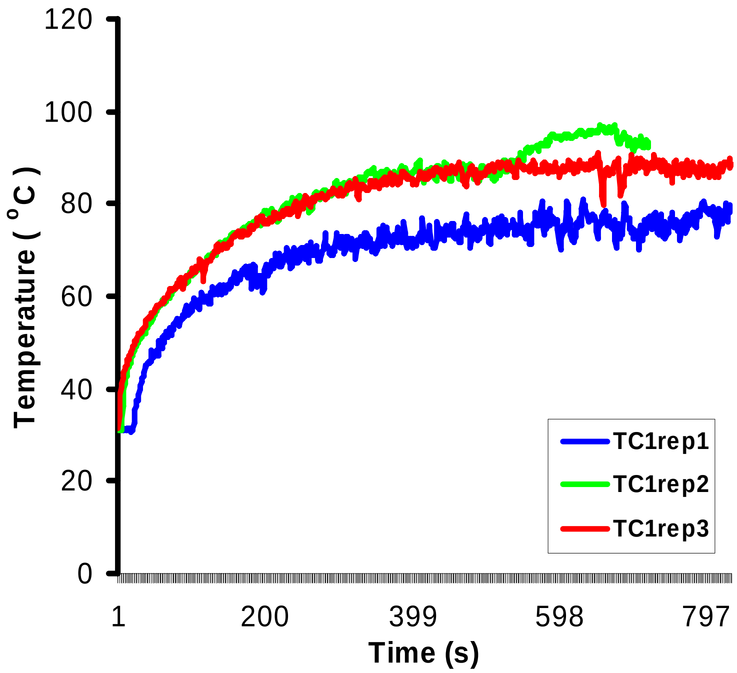


Figure 35. Temperatures at the front surface of FE5 during three repetitions of the Radiant Panel experiment at a heat flux of 1.6 kW/m2 as before.

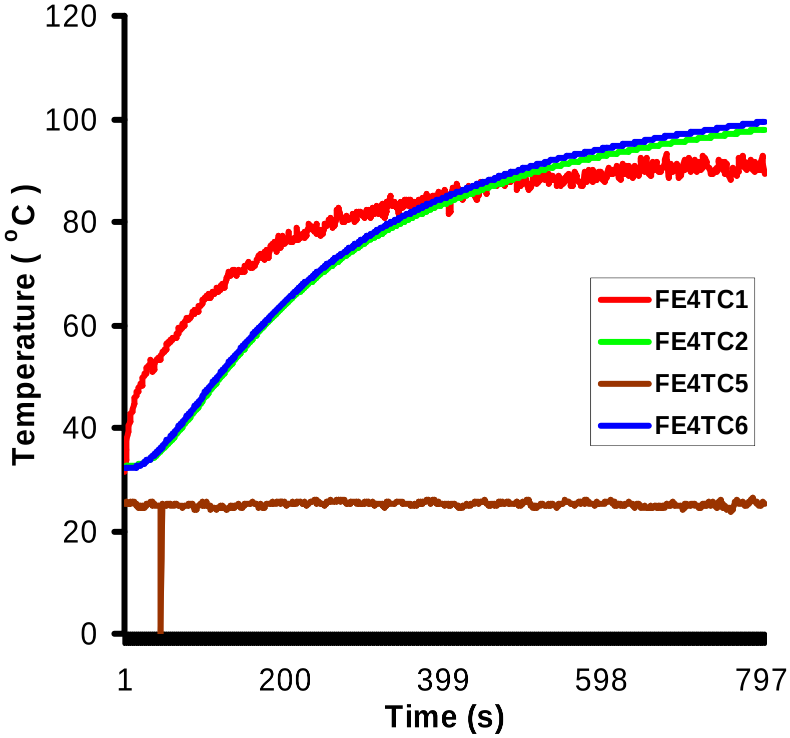


Figure 36. Temperatures at the four locations of FE4 in the Radiant Panel tests at a heat flux of 1.6 kW/m^2.

Table 16 outlines the test identification numbers, Fire-Eye units, and timeline for the Radiant Panel experiments conducted at a heat flux level of 4.0 kW/m^2. Table 17 presents the results for the Fire-Eye indicator light conditions as a function of temperature, and Table 18 presents the same data for Fire-Eye device #5. Figure 37 displays the graphical representation of the warning indicators of various Fire-Eye devices in the Radiant Panel test at a heat flux level of 4.0 kW/m^2 , whereas Figure 38 shows the graphical representation of the warning indicators of Fire-Eye device # 5 in three Radiant Panel tests at a heat flux level of 4.0 kW/m^2.

Table 16. Timeline and details for the radiant panel experiments at a heat flux level of 4.0 kW/m^2.

Test Number	Fire-Eye Label	Test Date	Test begin time	Test end time	Data file name
Test 1	FE0502	01/19/2006	15:40:45	15:51:58	FE0119H.DAT
Test 2	FE0503	01/19/2006	16:02:58	16:14:08	FE0119I.DAT
Test 3	FE0504	01/19/2006	10:42:10	11:00:20	FE0119C.DAT
Test 4	FE0506	01/19/2006	11:39:54	11:52:08	FE0119D.DAT
Test 5	FE050501	01/19/2006	12:26:16	12:38:06	FE0119E.DAT
Test 6	FE050502	01/19/2006	13:57:48	14:09:06	FE0119F.DAT
Test 7	FE050503	01/19/2006	14:39:12	14:51:04	FE0119G.DAT

Table 17. Performance of different Fire-Eye devices in the radiant panel experiments at a heat flux of 4.0 kW/m^2.

Fire-Eye Device #	Blinking Green (^oC)	Solid Green (^oC)	Solid Red (^oC)	Blinking Red (^oC)
FE 02	44.18	69.40	81.15	99.22
FE 03	67.28	89.92	96.57	101.45
FE 04	73.85	101.32	107.24	126.36
FE 06	42.68	45.14	47.41	47.64

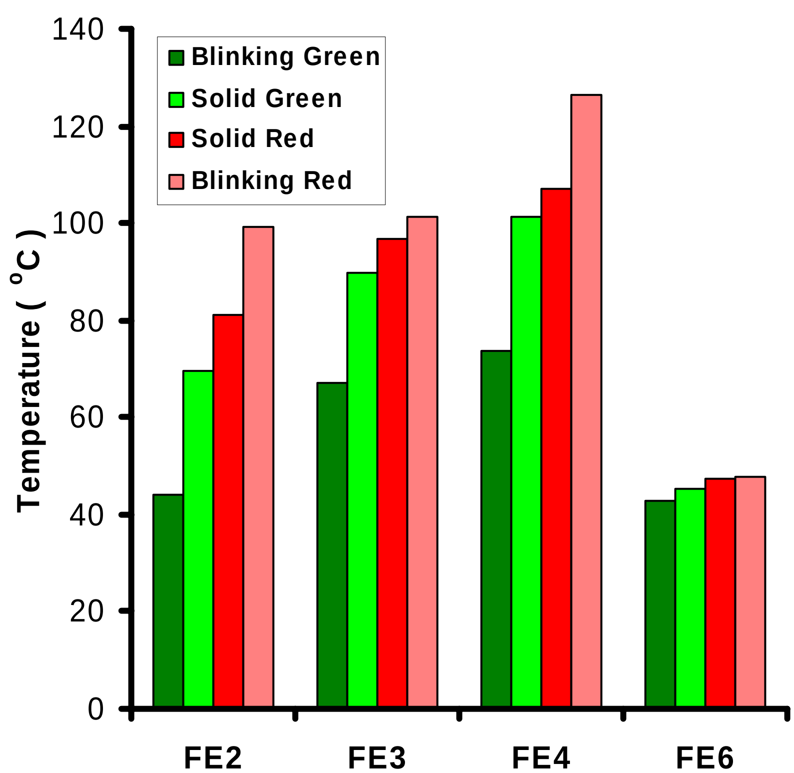


Figure 37. Repeatability of different Fire-Eye devices in Radiant Panel Tests at a heat flux level of 4.0 kW/m^2.

Table 18. Performance of Fire-Eye device # 5 in the radiant panel experiments at a heat flux of 4.0 kW/m^2.

Fire-Eye Device #	Blinking Green (^oC)	Solid Green (^oC)	Solid Red (^oC)	Blinking Red (^oC)
FE 05 – Rep 1	78.01	105.92	111.66	117.10
FE 05 – Rep 2	81.07	102.67	109.19	115.15
FE 05 – Rep 3	82.58	101.90	105.08	106.74

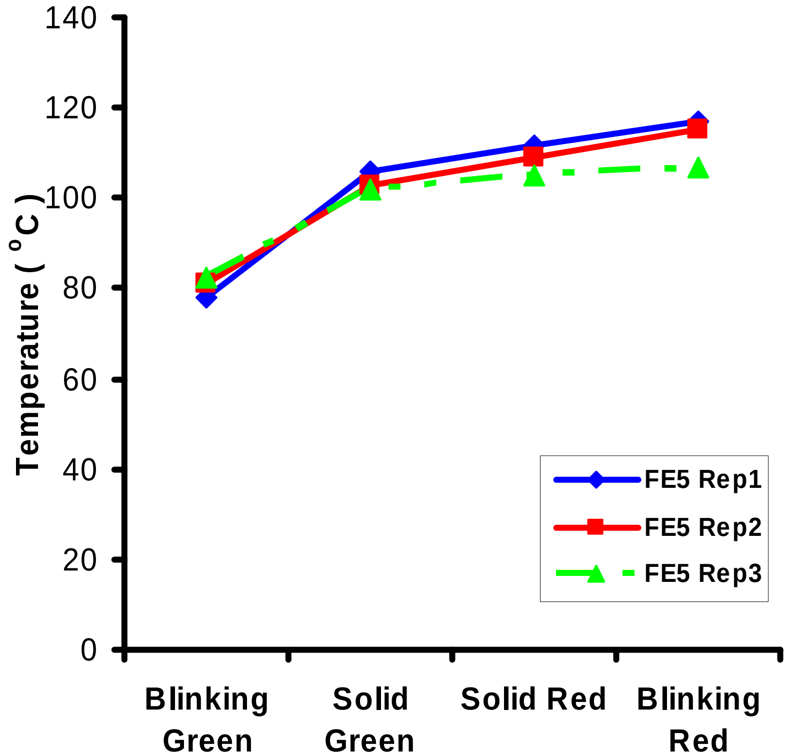


Figure 38. Reproducibility of FE Device # 5 in Radiant Panel Test at a heat flux level of 4.0 kW/m^2.

Figure 39 displays TC1 temperature results for different Fire-Eye devices as a function of time elapsed, and Figure 40 displays TC1 temperature results for Fire-Eye device #5 as a function of time across three repetitions. Figure 41 displays the temperature results of four TC's for Fire-Eye device #4.

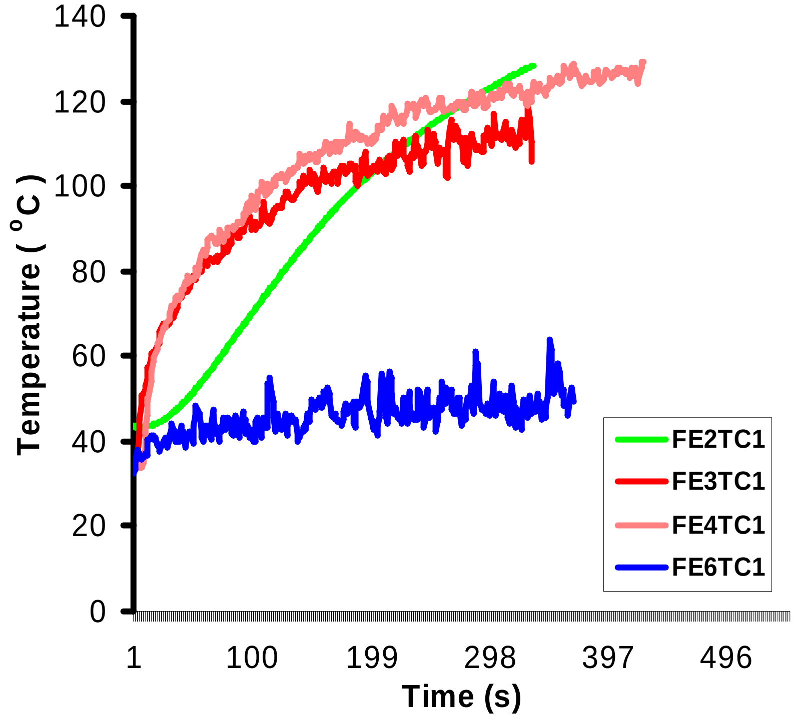


Figure 39. TC1 temperatures at the front surface of the Fire-Eye devices for the Radiant Panel tests at heat flux of 4.0 kW/m^2.

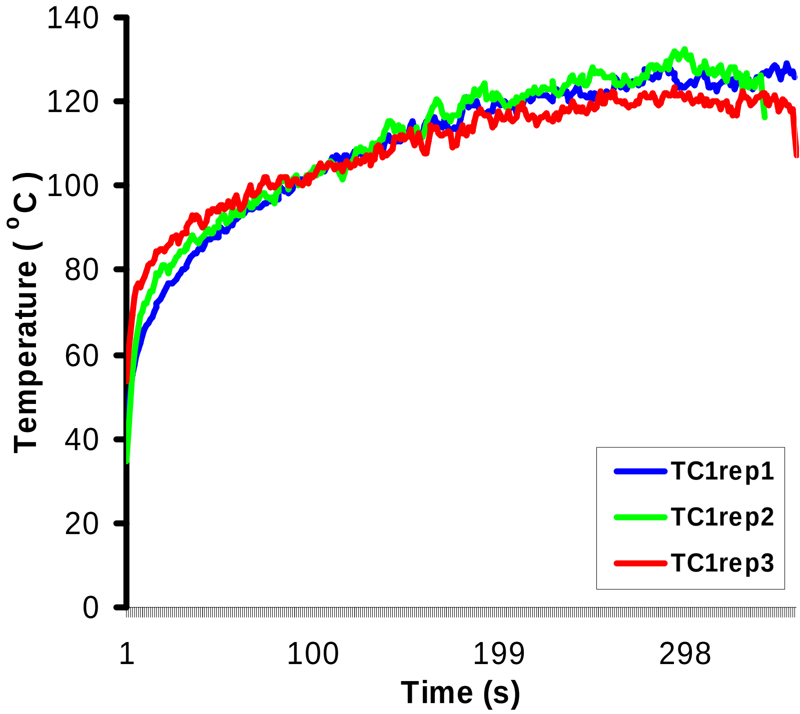


Figure 40. TC1 temperatures at the front surface of FE5 in three repetitions of the Radiant Panel test at a heat flux of 4.0 kW/m^2.

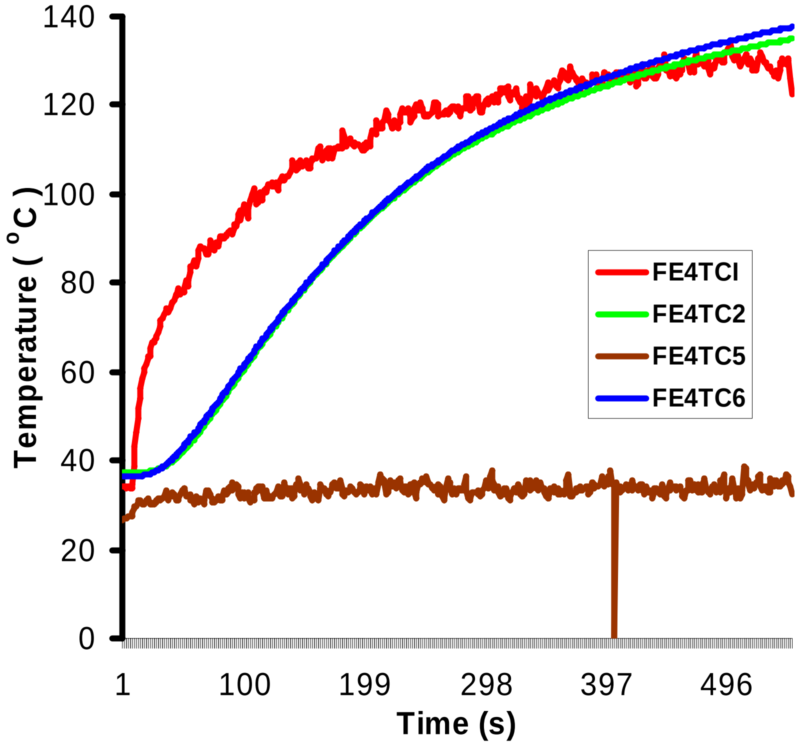


Figure 41. Temperatures at four locations of FE4 in the Radiant Panel test at a heat flux of 4.0 kW/m^2.

7.0 DISCUSSION

The testing and validation efforts for the Fire-Eye device in the controlled, laboratory-scale experiments provided a wealth of operational data. Systematic test methods involving conduction, convection, and radiation types of heat transfer were used to test the performance of the Fire-Eye device in one or a combination of the three heat transfer conditions.

7.1 Static Oven Tests

The first method of laboratory-scale experimentation was that of the Static Oven, which represented the conduction-type of heat transfer. The Static Oven environment was able to achieve a maximum temperature of 140 ^{o} C. However, and even though the thermostat knob was manipulated by the researcher in an effort to increment the oven's temperature by 10^{o} C every three minutes, the rate of temperature increase was not uniform, likely due to a non-standard gain for each thermostat detent. The Static Oven tests provided data indicating that the Fire-Eye device could withstand static, hot conditions at temperatures up to 140^{o} C.

The *repeatability* of the 'blinking green' indicator light across the six FE devices tested with respect to temperature was not uniform. The 'blinking green' indicator was noted to actuate throughout a large range of temperatures, from 56^{o} C—83^{o} C. Fire-Eye devices #1 and #2 did not display the 'solid green' indicators at all, whereas other devices displayed the 'solid green' warning indicator for a short period of time (again, across a wide range of temperatures from 90^{o} C—114^{o} C) before transitioning to 'solid red' indicators. The 'solid red' indicator was mixed with respect to the temperature at which it actuated between devices, ranging from 90^{o} C—123^{o} C, and FE #4 did not present a 'solid red' indicator at all. Finally, the 'blinking red' indicator activated across all FE devices while the environment was cooling, when tested for repeatability. They did so across a wide range of temperatures between 102^{o} C to 135^{o} C. These results suggest that repeatability between FE devices may be spread over too large a range of temperature.

The *reproducibility* for the 'blinking green' indicator was also not uniform, but to a lesser extent, from 53^{o} C—73^{o} C. FE device #5 was noted to produce 'solid green', 'solid red', and 'blinking red' indicators at temperature ranges of 79^{o} C—90^{o} C, 82^{o} C—105^{o} C, and 94^{o} C—110^{o} C, respectively. These data indicate that, for the same device tested multiple times, there are issues of reproducibility with respect to the actuation of the various FE indicators within the Static Oven.

7.2 Fire Equipment Evaluator Tests

The second method of laboratory-scale experimentation was that of the Fire Equipment Evaluator, which represented the convective-type of heat transfer. The FEE was able to create a temperature environment in the range of 130^{o} C—140^{o} C at a steady velocity of 1 m/s and a heat flux of 4 kW/m^{2}. It should be noted that Fire-Eye device #1 failed to display *any* warning indicators during the FEE experiment, suggesting issues of repeatability between devices. The 'blinking green' indicator of the other five Fire-Eye devices under identical test conditions (i.e., repeatability) was noted to actuate throughout a 15 ^{o} C range of temperatures, from 50^{o} C—65^{o} C. The 'solid green' indicator was observed to actuate across a wide range of temperatures between

84^{o} C—105^{o} C. The repeatability of the 'solid red' indicator was quite consistent (i.e., 107^{o} C—108^{o} C) with the exception of FE #2, with its actuation occurring at a temperature of 89^{o} C. Finally, the 'blinking red' indicator was noted to activate across a wide range of temperatures, between 92^{o} C—119^{o} C when the environment began to cool. Again, the variability of status indicators with respect to the temperatures at which they actuated across devices suggests further issues of repeatability.

With respect to reproducibility in the FEE experiments, the 'blinking green' indicator was noted to actuate between 62^{o} C—66^{o} C. The 'solid green' indicator was reasonably consistent, ranging from 104^{o} C—107^{o} C. The reproducibility of the 'solid red' indicator was reasonably consistent, ranging from 110^{o} C—114^{o} C across three trials, and finally, the 'blinking red' indicator was noted to activate between the temperatures of 120^{o} C—131^{o} C when the environment began to cool. These results suggest reasonable reproducibility of a particular FE device.

7.3 Radiant Panel Tests

The third method of laboratory-scale experimentation was that of the Radiant Panel, which represented the radiation-type of heat transfer. As explained earlier, radiation is the most intense and damaging mechanism of heat transfer to which a firefighter can be exposed. The Radiant Panel experiments were conducted at two radiant heat flux levels: 1.6 kW/m^2 and 4.0 kW/m^2. Any heat flux more than 1.4 kW/m^2 but less than 2.5 kW/m^2 has been described as a 'common thermal radiation exposure' while firefighting. This energy level may cause burn injuries with prolonged exposure, and an exposure of more than 2.5 kW/m^2 but less than 4.5 kW/m^2 can cause the skin to become blistered with a 30-second exposure, causing a second-degree burn injury (National Fire Protection Association (NFPA), 1971). Therefore, the two flux levels selected for the Radiant Panel experiments represented realistic fire exposures to which firefighters and their protective gear are routinely exposed.

Even though the Radiant Panel experiments were not able to reach the temperatures of more than 100^{o} C—110^{o} C at the flux level of 1.6 kW/m^2 (and as described previously), the Fire-Eye devices responded rapidly for radiant heat exposures at room temperature as the radiant panel was not an enclosed device. Within the heat flux level of 1.6 kW/m^2 and with respect to repeatability, the ‘blinking green’ indicator of the Fire-Eye devices varied between 39^{o} C—61^{o} C. The ‘solid green’ indicators were observed to actuate between 40^{o} C—87^{o} C, and the ‘solid red’ indicators actuated within the range of 37^{o} C—88^{o} C. The ‘blinking red’ indicator was noted to display in the range of 40^{o} C—96^{o} C when the environment began to cool. FE devices #2 and #4 appeared to perform similarly for many indicator conditions; however, FE devices #3 and especially #6 performed quite differently when compared to the others across all indicators, suggesting issues of repeatability.

With respect to reproducibility of the FE device in the Radiant Panel tests that were conducted in a heat flux level of 1.6 kW/m^2, the performance of FE #5 was largely consistent between 55^{o} C—61^{o} C for display of the ‘blinking green’ indicators. The ‘solid green’ indicator was noted to actuate between 72^{o} C—87^{o} C, and the ‘solid red’ indicator actuated between 73^{o} C—87^{o} C. Finally, the ‘blinking red’ indicator activated between the temperatures of 77^{o} C—95^{o} C when the environment began to cool. As one would expect the same device to present status indications at the same or similar temperatures, these results suggest issues of reproducibility within the heat flux level tested.

The Fire-Eye devices responded most rapidly to the heat flux level of 4.0 kW/m^2. Typically, the Fire-Eye devices started displaying the ‘blinking green’ indicator within 3 minutes of Radiant Panel exposure. The Radiant Panel experiments at this level of flux were noted to result in the shortest duration of time (12 minutes) for the devices to display all of the warning indicators (i.e., from ‘blinking green’ to ‘blinking red’) when compared to the earlier heat flux level of 1.6 kW/m^2. With respect to repeatability, the ‘blinking green’ indicator performance was noted to occur between the temperatures of 43^{o} C—74^{o} C. *The ‘solid green’ indicators were observed to actuate between 45^{o} C—101^{o} C, and the ‘solid red’ indicator actuated between the temperatures of 47^{o} C—107^{o} C. Finally, the ‘blinking red’ indicator was noted to actuate between the temperatures of 48^{o} C—126^{o} C.* The ranges of temperature at which all status indicators were actuated across devices appear to be quite large, suggesting issues of repeatability for this level of heat flux.

The reproducible performance of the device within the heat flux level of 4.0 kW/m^2 was largely consistent, with the ‘blinking green’ indicator actuating between 78^{o} C—83^{o} C. For the ‘solid green’, ‘solid red’, and ‘blinking red’ indicators, the temperatures at which they were noted to actuate were between 102^o C—106^o C, 105^o C—112^o C, and 107^o C—117^o C, respectively. The temperature ranges for actuation of the warning indicators appears to be small, at least when compared to the lower heat flux level tested, suggesting that the FE device maintained reasonable reproducibility.

SECTION II: Full-Scale Fire Tests

1.0 INTRODUCTION

Heat Release Rate (HRR) is defined as the enthalpy change per unit of time as a result of the conversion of the chemical energy of a fuel to heat in a combustion process. Usually, the fuel is carbon-based and the combustion process is of oxidation, utilizing the available oxygen from the air. Heat release rate is usually reported in kilowatts (kW) or megawatts (MW), and is an important value because it is a key predictor of the hazard of fire, directly controlling the rate at which heat and the toxic gases build up in an enclosed structure or is driven into more remote spaces. The heat release rate is also (effectively) the most pertinent measure of the *size* of a fire (Babrauskas, 2002).

Many different aspects of a fire can affect the performance of a heat-sensing warning device such as Fire-Eye. Any of the three kinds of heat transfer characteristics (i.e., conduction, convection, or radiation) can affect the status of the heat-sensing sensor of the device, depending upon the intensity and type of fuel burning in the fire. Therefore, it is important to validate the performance of the Fire-Eye device using different types of fuels, some generating soot, whereas others burning 'cleanly' (i.e., without soot).

Fires typically grow from a small incipient fire to a large one through ignition and flame spread across the various fuels that are available in the environment. While attempting to validate the performance of a thermal sensing device in a realistic fire scenario, the overall size of the fire in the testing space and the fire's spread over interior furnishings can significantly affect its output. One method of validating the performance of the thermal sensor is to conduct realistic 'room-corner' tests in standard settings (e.g., living room, bedroom). Unlike the laboratory-scale experiments, devices in the room-corner test are exposed to a Full-scale fire scenario. In the conduct of such testing, devices such as Fire-Eye should be mounted in an orientation that is representative of their use in real fire situations. The ignition source should ideally be kept consistent with a 'naturalistic' form of ignition (i.e., not artificial) in the room-corner tests.

Several room-corner test protocols are currently in use by testing laboratories and are specified by entities such as ASTM, NFPA, the Uniform Building Code (UBC), and the International Standards Organization (ISO). The test arrangements and procedures for the specified room-corner tests are all similar, but there are some differences that can significantly affect the performance of the specimens being tested (Dillon, 1998). These differences include the size, location and energy release rate of the ignition burner as well the height and distance of the specimen from the fire. In order to produce the most representative, realistic fire scenarios, three different kinds of fuels are often used, including liquid sooty, gaseous clean, and wood and fabric (such as a couch, an end table, and a lamp). These fuels were used in the large-scale fire tests of the Fire-Eye device to be outlined below. The height and the distance of the facepieces that were mounted with the Fire-Eye devices were representative of realistic fire conditions, such as the conduction-, convection-, and radiation-types of heat transfer that were described earlier. The primary measurements in the room-corner tests were *temperature*, the *total heat flux at various locations*, and the *video performance* of the Fire-Eye devices. In order to avoid any structural damage to the ISO room and any other infrastructure used for the large-scale fire tests, the scenarios were designed to avoid flashover temperatures (usually in the range of 800^{o} C—1000^{o} C). Another valuable objective of the room-corner tests was to compare the performance of Fire-Eye devices in the laboratory-scale experiments with that in the Full-scale fire tests.

2.0 EXPERIMENTAL APPARATUS

This section describes the various instruments, fuel characteristics, and the ISO room specifications. This section also describes the instrumentation used for measuring the temperatures, heat flux, and to collect the digital video recordings.

2.1 ISO Room Specifications

The facility used for testing the Fire-Eye device was the ISO 9705 Full-scale room fire chamber (see Figure 43) at the Building Fire Research Laboratory (BFRL) of National Institute of Standards and Technology (NIST), Gaithersburg, MD. The ISO 9705-2003 room corner scenario is an internationally recognized standard test environment, and the tests conducted within it can be repeated and reproduced relatively easily. The ISO 9705 room dimensions are 2.4 m wide x 3.6 m deep x 2.4 m high. The door (centered at the bottom of the front wall) in the front is 2.0 m high x 0.8 m wide. The exhaust hood for the ISO room (in front of the door receiving the gases exhausting from the front door) is 3.0 m wide x 3.0 m deep x 1.0 m high and the exhaust duct diameter is 0.4825 m.

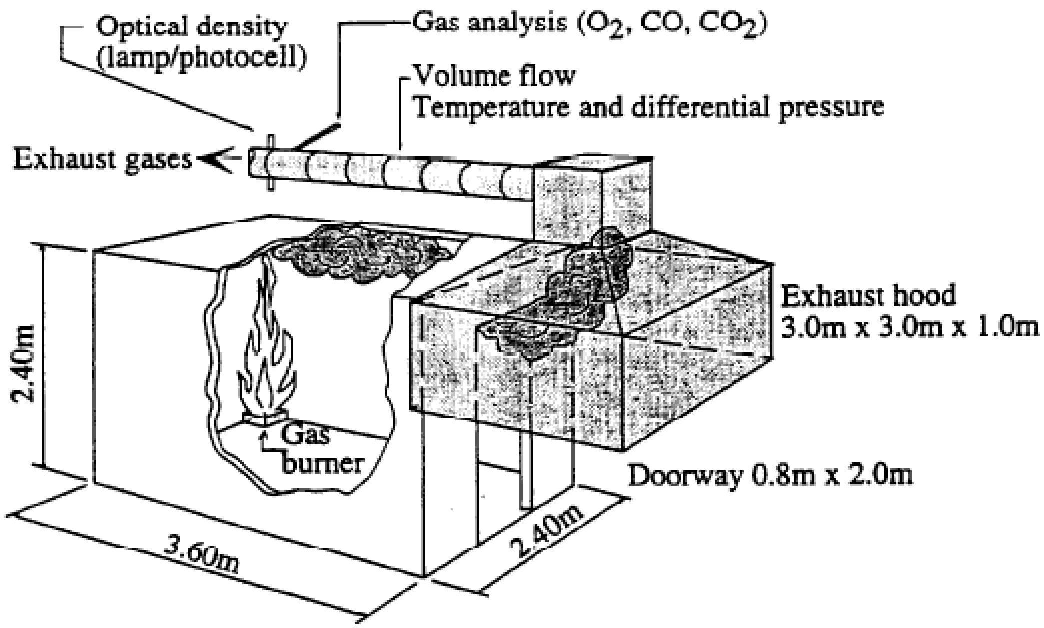


Figure 42. Schematic Drawing of the ISO 9705 Room-Corner Test (Dillon, 1998).

2.2 Modeling of the ISO Room

A photograph of the ISO room is shown in Figure 43. The door in the front wall of the ISO room is the only access to the room. The room consists of a sheet metal stud framework lined with three layers of 1.27 cm thick gypsum wallboard and a single layer of 1.27 cm thick calcium-silicate board. The gypsum wall board can withstand temperatures in the range of 800-1000^{o}C. The floor of the room is made up of cement board.

Figure 43. ISO room and its exhaust hood.

The gypsum board walls sometimes get crumbly when it is too hot inside the room; hence, cement flooring is used instead of gypsum board flooring. The large, instrumented exhaust hood allows for oxygen calorimetry and gas analysis to be performed on the exhaust gases originating from room fires. Calorimetry consists of collecting all of the gases produced by the fire, measuring the rate of flow of the gases, sampling a small and well-mixed portion of the gases, and measuring the volume fractions of specific gas species (especially the oxygen volume fraction) (Bryant, Ohlemiller, Johnsson, Hamins, Grove, Guthrie, Maranghides, and Mulholland, 2004).

The ISO room was instrumented with two thermocouple 'trees' whose locations and specifications are described in the thermocouple trees section (Section 2.4). Three water-cooled total heat flux gauges were used to record the heat flux at the target locations where the Fire-Eye devices were located. The burners for the first two types of fuels used in the tests were located in the rear left corner of the room. The fuel was supplied through sealed pipes that were originally instrumented in the room. The measurements for the physical locations of the fuel burners, Fire-Eye devices, thermocouple trees, and the total heat flux gauges in the ISO room were measured from the rear leftmost corner of the room. Electric matches, passed through hollow copper pipe, were used as an ignition source for all tests. The ignition spot for each large-scale test originated at the same place, located at the leftmost rear corner of the ISO room.

2.3 Fuels Used for Large-Scale Fire Testing

As stated earlier, three different types of fuels were selected to conduct the Fire-Eye device performance validation in Full-scale fire environment. The selection of fuel was based on the soot-producing ability of the fuel as well as its resemblance to realistic fire scenarios in a structural fire. The first two fuels were fired using burners, whereas an ignition by electronic matchstick was used for the living room burn test.

Figure 44 displays the control panel used for controlling and recording the fuel flow statistics during the tests. The heat release rate and the flow rate are controlled from the panel and the numerical display indicates the current flow rate. The panel also maintained controls that could instantly cut-off the fuel supply if the test conditions progressed into a dangerous scenario that could potentially harm the persons or property of the large-scale fire chamber.

Figure 44. Control panel for the gas and liquid fuel supply.

The first fuel selected for the first two tests was Natural Gas. The Natural Gas heat of combustion is 905.35 BTU/ft^3. The specific gravity of Natural Gas is 0.6 and the flow coefficient is 1.0. The heat of combustion per unit of oxygen (O_2) is 12.55 MJ/kg of O_2. Natural

Gas burns cleanly without creating any soot. It is stored in compressed cylinders or tanks. Natural Gas was supplied to the burner using a pipe connected to the cylinder inserted through the rear wall (see Figure 45). The size of the burner used for the test was 1 ft wide x 1 ft long x 1 ft high. The burner was of standard calibration type and was spaced 6 in away from the left wall and 6 in away from the rear wall of the ISO room. The hood setting of 3 m was used for the Natural Gas tests. The burner was ignited with electric matches through a hollow copper wire as shown in Figure 45.

Figure 45. The Natural Gas burner.

The second fuel selected for the purpose of Full-scale fire testing was Heptane. The heat of combustion for Heptane is 30593 kJ/L, its flow coefficient is 1.0, and the heat of combustion per unit of oxygen (O_2) is 12.68 MJ/kg of O_2. Heptane produces large amount of soot while burning, and is typically stored in a compressed cylinder or in tanks. The type of burner used for the Heptane test was a 'pan burner.' The diameter of the pan burner was 24 in, and it was raised at a height of 18 in from the floor of the ISO room using two vertically-erected concrete blocks as shown in Figure 46. The pan was placed at a distance of 3 in from the left wall and 3 in from the rear wall of ISO room. The hood setting of 3 m was used for the Heptane tests and, as for the Natural Gas fuel, the burner was ignited by electric matches through a hollow copper wire as shown in Figure 45. The Heptane was supplied through a nozzle inserted into a pipe that was drilled through the rear wall of the ISO room. The nozzle was located at the center of the circular pan and at an elevation of 18 in from the surface of pan. The pipe carrying Heptane inside the ISO room was covered with white foam insulation.

Figure 46. The pan burner used for the Heptane tests.

The third fuel selected for the Full-scale fire testing was representative of the wood and synthetic fabric usually used in the living room furniture. The fuel consisted of a couch, an end table, and a table lamp. Two identical sets of these items were procured from a local furniture store that sold used furniture. The couches were niagara blue in color and were manufactured by Klaussner® Furniture Industries located in Asheboro, NC (see Figure 47). The width of the couch from end to end was 86 in, whereas the height of the couch from the ground including the two upright cushions was 29 in. The depth of the couch from its front corner to its rear corner was 36 in, and the height of the couch (excluding the cushion height) was 25 in. There were two upright backrest cushions and two horizontal cushions placed on the couch—the cushion in the upright position against the backrest was 36 in wide and 17 in high. The weight of the couch without the upright cushion was 41.58 kg, and the two upright cushions weighed 5.53 kg. The total weight of the couch including the cushions was 47.10 kg. The cushions were filled with foam, and the external finish was made with a mixture of polyester-vinyl type of material.

Figure 47. One of two couches used as fuel for the living room fire tests.

The end table was 25 in wide x 25 in deep x 23 in high, and weighed 13.722 kg. The lamp and the shade were 17 in high. The lamp was 9 in wide at the center and 6 in wide at the base, and its shade was 18 in wide at bottom, 7 in wide at the top, and 11 in high. The lamp and the shade together weighed 2.54 kg (Figure 48).

Figure 48. End table and lamp used as fuel for the living room fire tests.

2.4 Thermocouple Trees

Two thermocouple trees were positioned to monitor the thermal environment inside the ISO room (see Figure 49). Eight thermocouples were attached to each tree one foot away from the ceiling to the floor. The highest thermocouple on each tree was an inch below the ceiling, whereas the second thermocouple on each tree was exactly one foot below the ceiling. All other thermocouples, from TC #3 through TC #8, were placed one foot apart, the last thermocouple being at the floor level. The thermocouples used in the tree were type K thermocouples made from Chromel and Alumel. These thermocouples can withstand temperatures up to 1260^{o} C. The size of the sensing junction bead on each thermocouple was approximately 1 mm. The bigger the size of the sensing junction bead, the slower the temperature sensing response of the thermocouple.

Figure 49. Two vertical thermocouple trees used in the ISO 9705 burn room.

During a typical room-corner test in the ISO 9705 room, a hot layer of gases develops at the top, and cold air moves at the bottom of the room. Therefore, the thermocouples in the top 2-3 feet (upper layer) of the room display higher temperatures than are the actual temperatures, whereas the thermocouples at a distance of 1-2 feet from the floor will show a higher temperature than is the actual ambient temperature due to the radiative heating effect. Therefore, it should be noted that the radiative heat correction was not applied to the temperatures recorded by the thermocouples in the room due to the limitation of the availability of facility for extended period of time. This disparity in displaying the temperature at different heights in the room occurs due to the fact that the walls are cool, whereas the environment is hot.

2.5 Instrumentation of Fire-Eye Devices and Facepieces

The nomenclature used for labeling the six Fire-Eye devices in Table 3 was also used in the Full-scale fire tests. The three Scott AV Face Masks were also as specified earlier (i.e., in Table 4), and were equipped with three Fire-Eye devices. Each facepiece was instrumented with two thermocouples, one attached to the inside surface and the other attached to the outside surface of the transparent glass shield of the facepiece. Each fire device was instrumented with two thermocouples, whereas the Fire-Eye #4 was instrumented with three thermocouples. Ambient temperature thermocouples were also attached to each facepiece at a distance of an inch from the Fire-Eye device, as in the laboratory-scale experiments. Each facepiece/Fire-Eye device unit had a minimum of five thermocouples attached, whereas the facepiece with Fire-Eye #4 had six thermocouples attached. While testing the three Fire-Eye devices simultaneously, seven thermocouple channels were allocated to each mask in the Data Acquisition System (DAQ, discussed in detail below). Each thermocouple maintained a dedicated channel for data collection. The length of the thermocouples attached to the Fire-Eye devices averaged 20 feet. This length was not sufficient, however, to plug the other end of thermocouples in the DAQ. Therefore, a *thermocouple junction* consisting of thermocouple extension wires was used to plug the channels into the DAQ. The bundle of junction wires along with the thermocouples plugged in those wires is shown in Figure 50.

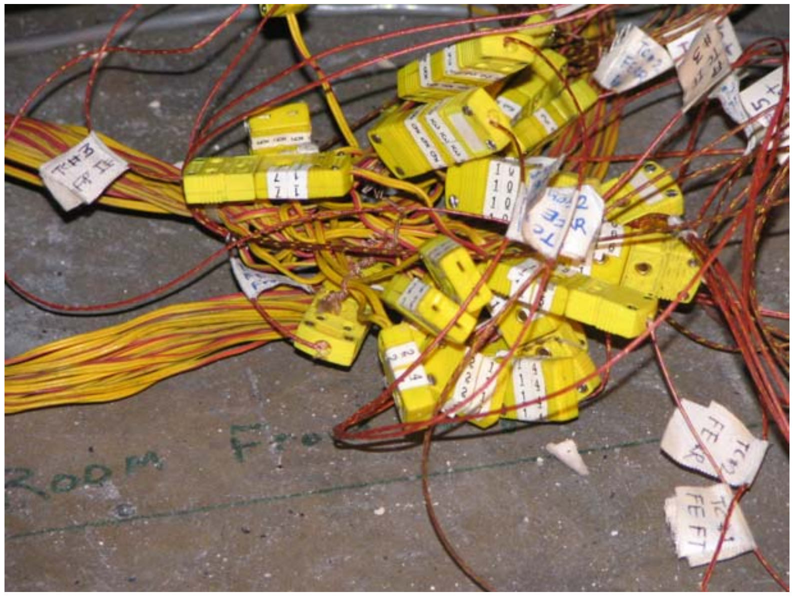


Figure 50. Thermocouple junction bundle for the facepiece/Fire-Eye units.

2.6 Heat Flux Transducers

Three calibrated Schmidt-Boelter total heat flux transducers were used to measure heat flux at three Fire-Eye device locations. The heat flux transducers are a water-cooled thermopile type, operating between 0 kW/m^2 to 50 kW/m^2. The transducers operate with a sensitivity of approximately 10 mV at 50 kW/m^2. Each heat flux gauge measured 25 mm (1 in.) in diameter and had a metal flange located 25 mm (1 in.) down its body, and away from the sensing surface. Figure 51 shows a part of the heat flux gauge attached to the left side of the mask. Table 19 shows the serial numbers and dedicated data channels for the total heat flux gauges used at three mask locations. Each serial number had a separate multiplicative factor to convert the mV into kW/m^2 of total heat flux, which was recorded by the DAQ. The calibration chart of each flux gauge can be seen in Appendix E. The three heat flux gauges were pointed towards the fire source so that they could record the heat flux at the location of each Fire-Eye device.

Figure 51. Heat flux gauge mounted to the left of the facepiece.

Table 19. Nomenclature for the heat flux gauges used at the three mask locations.

Flux Gauge #	Total Heat Flux Gauge Serial #	Data Acquisition Channel Number	Wattage
Gauge 1	126844	Channel 3	20 W
Gauge 2	126846	Channel 4	20 W
Gauge 3	126842	Channel 5	20 W

2.7 Data Acquisition System

The input signals from the various sensing devices such as thermocouples and heat flux gauges were collected using NIST's Large-Scale Fire Research Facility DAQ. The DAQ was configured to collect data from the instruments or sensors being utilized for the experiment (e.g., to perform calorimetry calculations). The data acquisition consists of sampling the electrical output of each calorimetry instrument as it responds to the physical conditions that it monitors, converting the electrical output to a digital signal, recording a time history of the digital signal, and converting the record to a value of scientific significance and displaying it in near real-time. The DAQ also provided a user interface for control of the calibration burner's output and to record the subsequent response of its instruments (Bryant et. al. 2004).

The DAQ hardware (manufactured by National Instruments) was stored in an instrument rack within the instrument control room of the Large Fire Research Facility. The transfer of data between the DAQ and computer was via a PCI (Peripheral Component Interconnect) bus computer interface. The primary DAQ board had 16 analog input channels at a 16-bit digital resolution and was capable of a sampling rate of 333 kHz. A total of 40 analog input signals were required for the calorimetry computation. Seven signal conditioning and multiplexing modules were employed and each module had a capacity for 32 input channels. The channels were scanned at a rate of 200 Hz and the signals were dumped to a single channel on the primary DAQ board. Each multiplexed channel was electronically averaged for 1 s and the digital value was stored to the computer. The signal-conditioning features of the module included an electronic filter (200 Hz low-pass) and gain (amplifying up to 100 times). The gain was typically applied to low-voltage signals, such as those produced by the thermocouples (Bryant et. al. 2004). Figure 52 shows a picture of the thermocouples and heat flux gauges plugged into the data collection system.

The user interface for the DAQ was written in a LabView program that computed the heat release rate and displayed user-specified data and computations. The program was run on a Windows workstation with dual 733 MHz processors and was located in the instrument control room of the Large Fire Research Facility. The output was displayed on the workstation monitor and was updated as the fire test proceeded. Figure 53 shows the two visual monitors utilized, each with three real time temperature channels and other test parameters displayed on the left of the screens.

During a fire test, all measurement channels were available for display. Calorimetry instrument readings, velocities, and heat release rate were displayed graphically with up to six min of history. In addition, plots of other important, but non-calorimetry-related measurements were displayed when specified. Two marker channels were available and were used to keep track of specific events during a particular fire test.

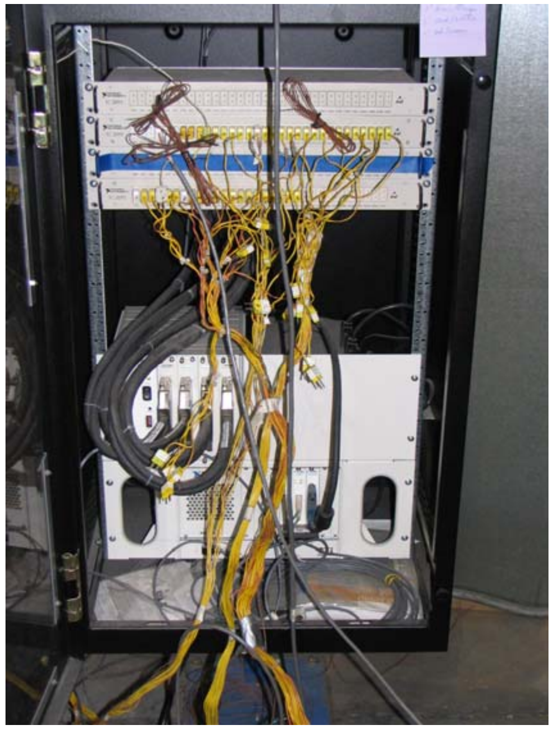


Figure 52. Data acquisition input unit for the thermocouples.

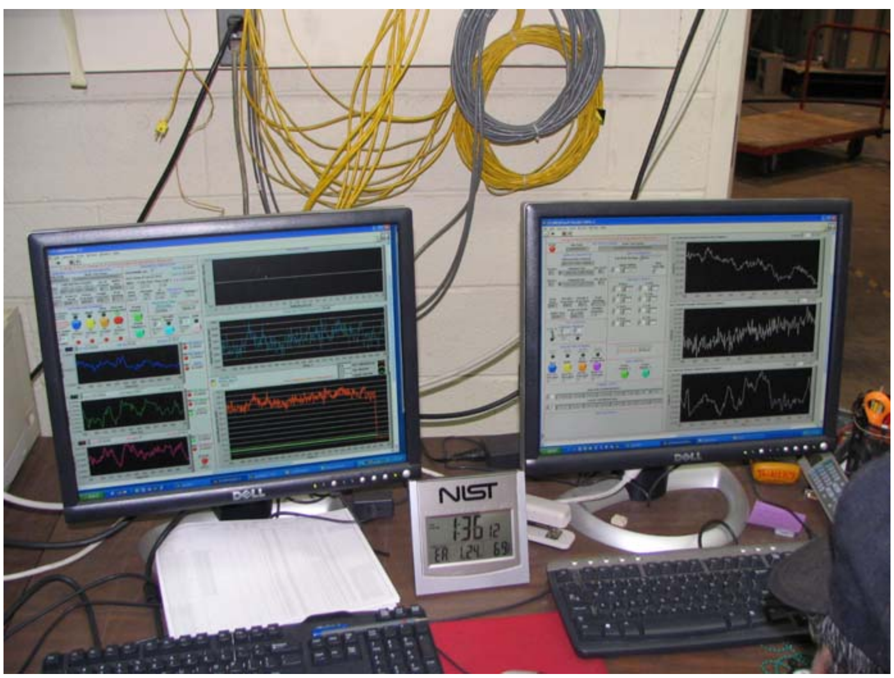


Figure 53. Visual displays showing the fuel flow rate as well as temperatures at different locations.

The markers are initiated with pushbuttons that were prominent on the display screen.

Event marking placed simulated voltage spikes from 0 to 5 V and 10 to 15 V for one second in the channels as markers. Plotting the data in these channels along with a basic measurement or calculated value enabled relation of the events to the response of the calorimetry system or a particular component of the system. Such events include the beginning of zeroing, spanning, background averaging periods, ignition, and extinguishment of the fire.

The DAQ was programmed to collect real-time data for 53 channels, including the temperature and heat flux during the Full-scale testing of the Fire-Eye devices. Forty-four of the 53 channels were *temperature* channels measured in ^{o}C, whereas 4 of the remaining 9 channels were programmed for *heat flux* measured in mV. The list of channels used for data collection in the Full-scale fire tests can be seen in Appendix D.

2.8 Digital Video Recording System

The performance of three Fire-Eye devices was recorded simultaneously using three bullet cameras fitted into the head-forms as described in the laboratory-scale experiments. For the Full-scale fire testing, the three bullet cameras were connected to three digital video recording units, each of which was powered by individual batteries. Figure 54 displays the arrangement of the digital video-recording units used to record the performance of the indicator lights of the three Fire-Eye devices during the Full-scale fire tests. Each test was recorded following the nomenclature for labeling the mini-DV tapes, similar to the procedure followed in the laboratory-scale experiments (see Table 7).

3.0 RESEARCH PLAN AND DESIGN OF EXPERIMENT

Presented below is information outlining the experimental design used for the large-scale fire tests, including devices, instrumentation, protocol, and setup.

3.1 Qualitative Description of Mask Location

As described earlier, three masks were located at three different locations and elevations to simulate the realistic heat transfer circumstances of conduction, convection, and radiation.

The heat flux density was typically highest at the mask closest to the fire, as it received the most radiation. The mask farthest from the heat source received the least radiative heat, but was subjected to conductive heat. The mask at the higher elevation in the enclosed space received the most convective heat since the burning process pushed the heated gases high up into the structure. Since the room height was just 8 feet, the mask at an elevation of 5 feet from the floor received substantial heat from the heated gases.

Figure 54. The digital video recording units for the three bullet cameras.

Table 20. Nomenclature of masks and the heat flux intensity associated with their location**.**

Mask Number	Type of Heat transfer	Heat Flux Intensity	Location
M 1	Radiation	High	Close to fire
M 2	Convection	Medium	High up from floor
M 3	Conduction	Low	Away from fire

3.2 ISO Room Test Layout and Location of Masks

The test layout for the ISO room specific to each fuel test is displayed in Figure 55. A separate room layout was utilized for the Natural Gas and Heptane fuel tests when compared to the living room furniture fuel tests. Figure 56 displays the location of mask 1 in the ISO room, which was located diagonally at a distance of 33 in from the front corner of the Natural Gas burner, and 37 in from the left wall. Mask 1 was elevated to a height of 1 foot from the floor (in order to raise it to the level of burner) so that the heat generated from the burner was normally incident on the fire-eye device. The position of mask 1 was maintained as the same for the Heptane and the living room tests for consistency.

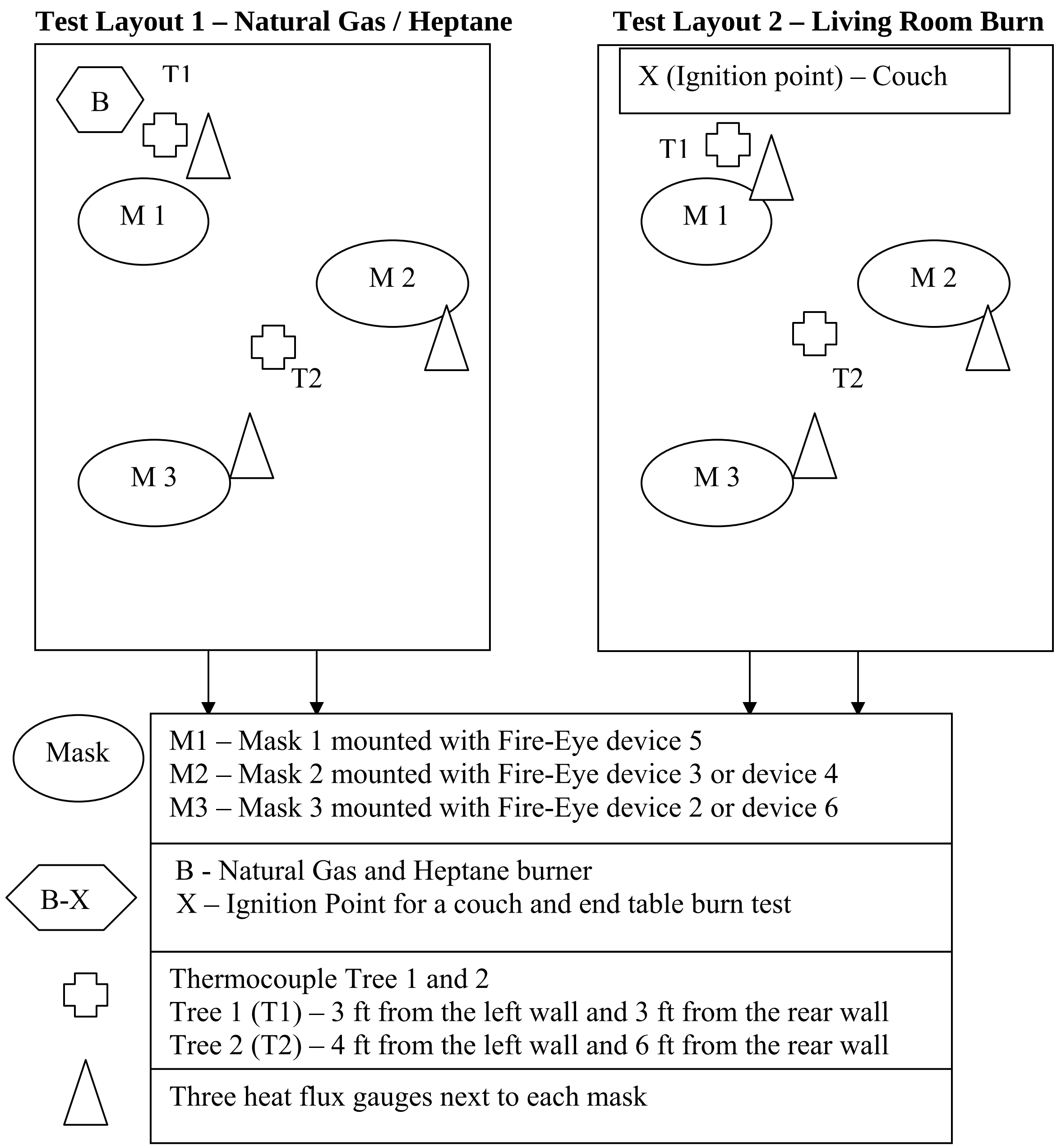


Figure 55. Layout and arrangement of the facepiece and Fire-Eye device in the ISO room (Viewpoint is from the top down).

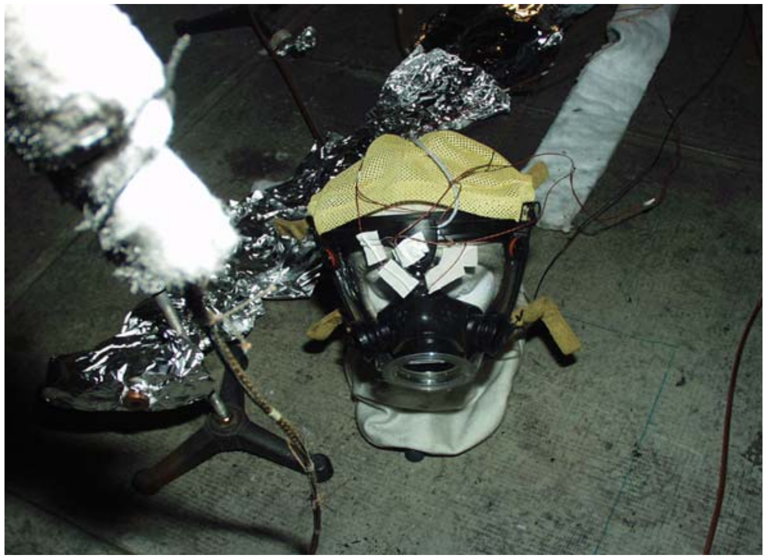


Figure 56. Mask 1 located at a height of 1 foot from the ISO room floor.

A diagonal distance of 33 in was maintained from the radiant heat source in an effort to mirror the distance of the radiant panel as in the laboratory-scale experiments in a flux of 1.6 kW/m^2. Heat flux gauge #1 was located on the same arc at a distance of 33 in from the Natural Gas burner, to the left side of and close to mask 1 (see Figure 56). The mask 1 location was representative of a firefighter operating very close to a fire source, and exposed to radiant heat generated from that source.

Figure 57 displays the location of mask 2 in the ISO room, which was at a distance of 6 feet from the left wall and 6 feet from the rear wall. Mask 2 was elevated 5 feet from the room floor using an iron rod mounted on a stand. Mask 2 simulated the convective heat transfer condition of a fire. Heat flux gauge 2 was mounted on the same stand below mask 2 as shown in figure 57. During a real fire incident, the burnt gases and soot rise to the highest points in the enclosed structure (the space closest to the roof) while the oxygen is burning at the fire's source. The elevation of mask 2, therefore, was representative of a firefighter moving inside a burning fire toward the fire source or toward hot smoke, and the heated air moving in the direction of firefighter.

Figure 57. Mask 2 located at a height of 5 feet from the ISO room floor.

Figure 58 shows the location of mask 3 in the ISO room. Mask 3 was located at a distance of 2 feet from the left wall and 10 feet from the rear wall, and was elevated to a height of 3 feet from the room floor. Mask 3 simulated the conductive heat-transfer condition in a realistic fire scenario. Heat flux gauge #3 was mounted on the same stand, and below the mask 3 as shown in figure 58. During a real fire incident, the location of mask 3 would be representative of a fire fighter crawling or moving by bending his/her back in order to avoid the hot gas layer formed at a height of 5 to 8 feet. At the height of 3 feet from floor, the conductive-type of heat transfer is more prominent than is radiation or convection.

Figure 58. Mask 3 located at a height of 3 feet from the ISO room floor.

3.3 Experimental Design for the Full-scale Fire Tests

Figure 59 shows the experimental matrix for testing Fire-Eye devices in the Full-scale fire facility. Test 1 and Test 2 were planned using Natural Gas fuel, whereas Test 3 and Test 4 were planned using liquid Heptane fuel. Test 5 and Test 6 were conducted using Living room furniture as a fuel. As per the test plan, two ISO room test burns were conducted using each type of fuel. In order to validate the performance of Fire-Eye device with different kinds of fuels, six tests were performed over a period of two days.

In order to test the reproducibility of the Fire-Eye device, it was decided to use device number 5 (the same as for the laboratory-scale testing). The Full-scale fire tests maintained a protocol of two repetitions for Fire-Eye #5 with each fuel, whereas the laboratory-scale tests had three repetitions for Fire-Eye #5. In the six tests, Fire-Eye device #5 was tested at the same location (i.e., with Mask 1) to help mitigate the variability that may have arisen due to a location change.

In order to test the repeatability of the Fire-Eye device, device numbers 2, 3, 4, and 6 were tested at different locations. In order to maintain consistency with the laboratory-scale experiments, these four devices were tested during two Full-scale burns using the same fuel. Two devices were tested in the first burn and the remaining two devices were tested in the next burn using the same fuel. For example, FE 2 and FE 3 were at locations M3 and M2 (respectively) during the first burn, and FE 4 and FE 6 were at location M2 and M3 for the second burn. In order to reduce the set-up time (e.g., re-instrumentation) between the two tests, and to mitigate any variability that may have presented with respect to a device location change, particular devices were maintained at the same position between fuel burns. Replacement of a device’s batteries and the fuel source were the only procedures undertaken between burns, which provided time for the Fire-Eye devices, bullet cameras, and the facepieces to cool before a subsequent test.

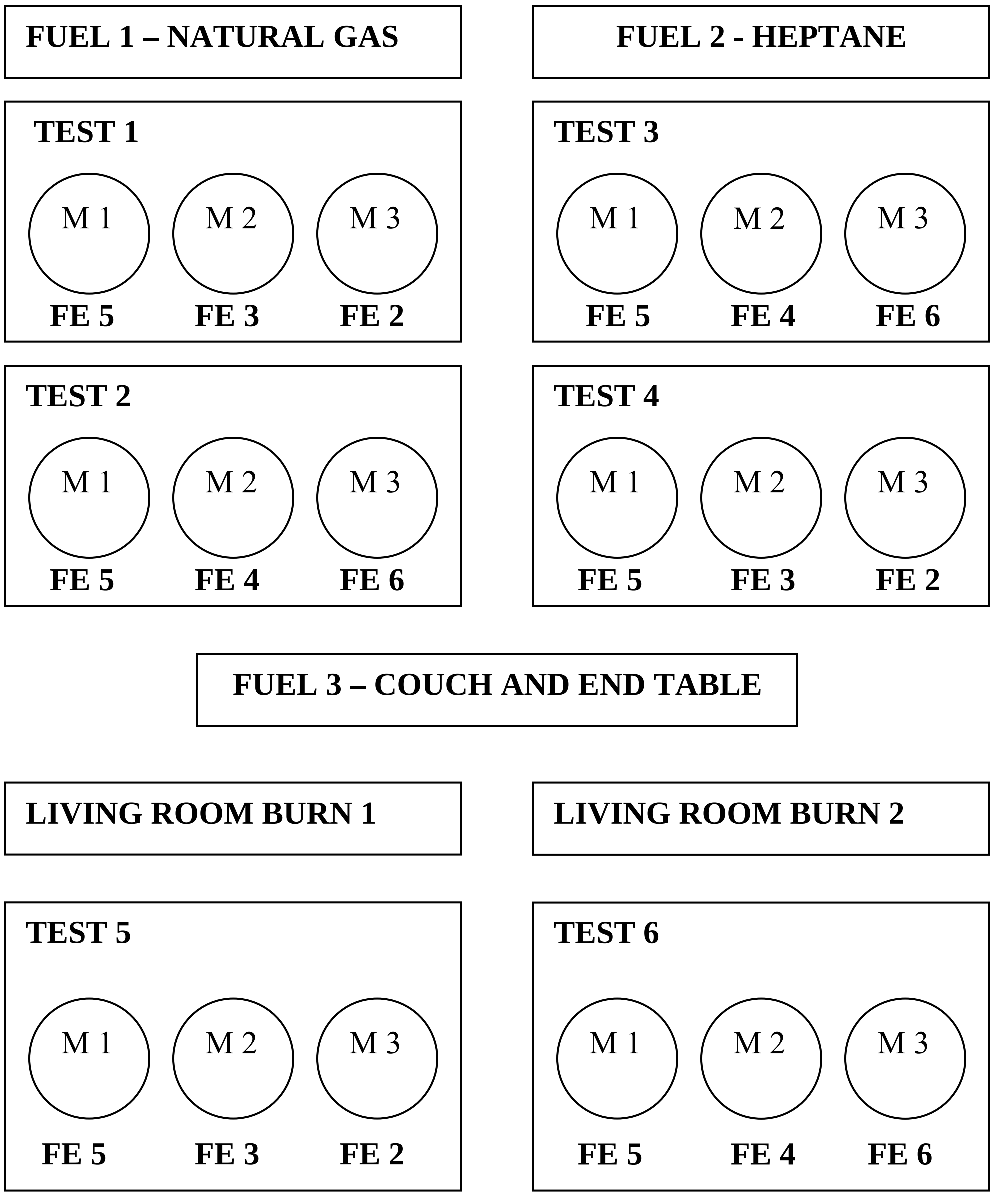


Figure 59. Test plan for the Fire-Eye devices in the Full-scale fire facility.

3.4 Checklist for a Full-scale Fire Test

A checklist was created several days in advance of the Full-scale testing (see Appendix C). The checklist covered important topics such as programming and confirming the channel list, troubleshooting the channels before beginning a test and testing to ensure that all of the thermocouples were reporting the correct temperatures. The checklist further covered pretest topics such as thermocouples, fuel system, heat fluxes, data acquisition system, video capturing devices, pictures, bullet cameras, and posttest activities. Some of the important steps that were followed before, during and after the Full-scale tests are presented below:

Pre-Test Preparation

1. The data acquisition system was programmed by specifying the channel's names, channel numbers, and module details.
2. Troubleshooting of a few channels was conducted so that all the channels were working and reading exact ambient temperatures before the test.
3. The batteries of the Fire-Eye devices were replaced.
4. The bullet cameras were verified to be in operation and their views adjusted in order to record the performance of the indicators of the Fire-Eye devices.
5. Heat Flux gauges were instrumented and the water-cooling system was operated in order to cool the gauges during and after the test.
6. Photographs were taken of the pretest settings.
7. Details of the fuels and their associated flow rates were tested and verified.
8. The dimensions of the thermocouple trees and the masks were measured and recorded in the laboratory notebook.
9. The thermocouples attached to the Fire-Eye devices were verified to be touching the device's surface and the data system was verified to be reading the correct temperatures.
10. The burners and the fuel supply were checked, and adjustments were made to the ignition source.

At the Beginning of the Test

1. The pilot flame was ignited and the ignition of the flame confirmed.
2. The test start time was recorded in the laboratory notebook.
3. The bullet cameras were inserted inside the headforms and recording of their video output was started.

4. The size of fire was recorded and photographed as the test progressed.
5. The flow rate was increased and recorded into the laboratory notebook.

Post-Test Checklist

1. Sensitive instrumentation was covered.
2. Water (used as a coolant for the heat flux gauges) was turned off.
3. The ISO room and the instrumentation of the Fire-Eye devices were inspected.
4. The timings/important markers during the test were recorded.
5. Post-test photographs were taken.
6. The Fire-Eye devices were allowed to cool and the batteries replaced for the next test.
7. Fire-Eye devices were removed from their facepieces and the next device and its instrumentation were mounted.

3.5 Safety Mechanisms used for the Full-scale Fire Tests

A fire experiment, whether controlled or uncontrolled, is inherently hazardous and as such, safety was a primary concern while planning and conducting the Full-scale fire tests. The Full-scale fire facility was equipped with various active and passive safety mechanisms. One of the most important safety mechanisms followed was allowing *only* trained and experienced personnel to operate and participate in fire tests. Safety steps were documented in a safety form that was completed a week before beginning the experiments, and which explained the components and tasks involved in a fire test. A safety team comprised of three personnel was in control of operations issues related to all testing. Each team member possessed a specific role and that individual updated the checklist prior to the beginning of a fire test. The NIST Safety Office conducted a meeting of the team members prior to the fire testing in which the duties of each team member (as well as spectators) were discussed. A general safety form that was required to be filled out and signed by the Laboratory Chief is included in Appendix B.

Other safety mechanisms included maintaining the fire test area clear for visual monitoring and ensuring that the properly sized water extinguishing system was ready. A trained and fully-equipped fire fighter, who was also a member of the safety team, was available to extinguish the living room fire. There were other safety systems such as manual shut-off valves and emergency shut-off buttons located near exits to manage unforeseen failures of components, such as the Natural Gas burner or the Heptane burner. Figure 44 shows some of the emergency shut-off buttons on the control panel for fuel supply.

4.0 TEST PROCEDURES

The test procedures followed for each of the Full-scale fire tests are presented below.

4.1 Natural Gas Test Procedure

The relative humidity of the fire test facility was 25.9% for the Natural Gas test. The barometric pressure was 751.15 mg of mercury (Hg), and the ambient temperature of the space inside and outside the ISO room was 23.2^{o} C. The test terminating criteria for the Natural Gas tests were to reach a temperature of at least 120^{o} C at TC1 for Mask 1 and Mask 2, which would mirror the laboratory-scale experimental temperature conditions. The test procedure was as follows:

1. Complete the instrumentation of the masks and the Fire-Eye devices as per the test plan for Natural Gas test #1. Confirm that the DAQ is reading appropriate values for all 53 channels.
2. Ready the three video recording units as well as adjust the bullet cameras to appropriately view the Fire-Eye devices. Insert new mini-DV tapes into each unit to record the performance of Fire-Eye devices.
3. Program the DAQ to store the details of each test by labeling the test as '012306NG3mISOroomTest1.' The test name included the month, date, year, type of fuel, hood size, test facility (ISO room), and test number.
4. Adjust the heat release rate (HRR) of the Natural Gas fuel to zero and record the time(s) with the help of the DAQ operator. (Computer monitor 1)
5. Start the MIDAS computer and record a reference time with the help of the DAQ operator. (Computer monitor 2)
6. Ignite the gas burner inside the ISO room using the electric matches through the hollow

copper wire (see Figure 45).

7. Record the ignition time and start the digital video recording system.
8. Raise the HRR to 26.6 kW after 3 minutes from the time of ignition.
9. Raise the HRR to 50 kW after 6 minutes from the time of ignition.
10. Raise the HRR to 100 kW after 9 minutes from the time of ignition.
11. Check the temperatures at M1TCI and M2TC1 and confirm whether they have reached at a level of 120^{o} C.
12. Reduce the HRR after 12 minutes to 0 kW and turn off the Natural Gas supply.
13. Stop the HRR computer and MIDAS computer.
14. Repeat the test for test plan #2 as per Figure 59.

Figure 60. Full-scale fire test in progress using Natural Gas as fuel.

4.2 Heptane Test Procedure

The relative humidity of the fire test facility was 29.7% for the Heptane test. The barometric pressure was 750.77 mm of mercury (Hg), and the ambient temperature of the space inside and outside the ISO room was 16.1^{o} C. The test terminating criteria for the Heptane tests was to reach a temperature of 120^{o} C at M1TC1 or M2TC1. The test procedure was as follows:

1. Complete the instrumentation of the masks and the Fire-Eye devices for Heptane test #1, per the test plan in Figure 59. Confirm that the DAQ is reading appropriate values for all

53 channels.

2. Ready the three video recording units as well as adjust the bullet cameras to appropriately view the Fire-Eye devices. Insert new mini-DV tapes in each unit to record the performance of Fire-Eye devices.
3. Program the DAQ to store the details of each test by labeling the test as '012306Heptane3mISOroomTest1.' The test name included the month, date, year, type of fuel, hood size, test facility (ISO room), and test number.
4. Adjust the frequency of Heptane flow to zero and record the time(s) with the help of the DAQ operator. (Computer monitor 1)
5. Start the MIDAS computer and record a reference time with the help of the DAQ operator. (Computer monitor 2)
6. Ignite the Heptane flow burner inside the ISO room (using the electric matches) through the hollow copper wire (see Figure 61).
7. Record the ignition time and start the digital video recording system.
8. After 3 minutes from ignition, raise the frequency of nozzle flow to 0.5 Hz to reach a HRR of 70 kW.
9. After 6 minutes from ignition, raise the frequency of nozzle flow to 0.76 Hz to reach a HRR of 100 kW. Record the appropriate test status in lab notebook.
10. After 9 minutes from ignition, raise the frequency of nozzle flow to 0.82 Hz to reach a HRR of 130 kW. Raise the frequency of nozzle flow to 0.76 Hz to reach a HRR of 100 kW after 6 minutes from the time of ignition.
11. Pull back mask #1 in order to protect it from high radiative heat at the location of mask 1, and confirming that M1TC1 has reached a temperature of 120^{o}C.
12. After 12 minutes from ignition, raise the frequency of nozzle flow to 1.0 Hz to reach a HRR of 160 kW. Stop the liquid fuel flow one minute after reaching a HRR of 160 kW.
13. Check the temperature at M2TC1 and confirm whether it has reached at a level of 120^{o} C.
14. Turn off the Heptane fuel supply.
15. Stop the HRR computer and MIDAS computer. Repeat the test for second test plan as per Figure 59.

Figure 61. Full-scale fire test in progress using Heptane as a liquid fuel.

4.3 Living Room Fire Test Procedure

The relative humidity of the fire test facility on the day of the living room fire test was 27.1 %. The barometric pressure was 749.18 mm/Hg, and the ambient temperature of the space inside and outside the ISO room was 21^{o} C. The general test terminating criteria for the living room tests was to avoid flashover temperatures more than 600^{o} C to 800^{o} C at the height of 7 to 8 feet from floor. The specific test terminating criteria was to not allow the temperatures at M1FE1 and M2FE1 to rise above 160^{o} C. Once the temperatures at either of these two TC reaches 160^{o} C, then the fire would be extinguished with water sprinkler by a trained firefighter present at the time of testing. The test procedure was as follows:

1. Arrange the couch, corner table, and table lamp as shown in the pre-test scenario in Figure 62. Maintain the location of the masks constant as in the earlier four tests.

Figure 62. Full-scale living room burn set-up before ignition.

2. Complete the instrumentation of the masks and the Fire-Eye devices for the living room test #1, per the test plan in Figure 59. Confirm that the DAQ is reading appropriate values in all 53 channels.
3. Ready the three video recording units as well as adjust the bullet cameras to appropriately view the Fire-Eye devices. Insert new mini-DV tapes into each unit to record the performance of Fire-Eye devices.
4. Program the DAQ to store the details of each test by labeling the test as '012306Livingroom3mISOroomTest1.' The test name included the month, date, year, type of fuel, hood size, test facility (ISO room), and test number.
5. Start the HRR computer and record the time (s) with the help of the DAQ operator. (Computer monitor 1)
6. Start the MIDAS computer and record a reference time with the help of the DAQ operator. (Computer monitor 2)
7. Ignite the leftmost rear corner of the couch using the electric matches (through the hollow copper wire). A photograph of the living room test several seconds after ignition is shown in Figure 63.

Figure 63. Living room fire test in progress after ignition.

8. Track the temperatures inside the room as well as outside the mask and Fire-Eye devices from the MIDAS computer monitor.
9. Record the Fire-Eye device performance in the lab notebook.
10. Turn off the fire by forcefully sprinkling water on the furniture as soon as the test terminating criteria is reached in terms of temperatures in the upper layer of room.
11. Start the high-speed cooling fan to cool the ISO room and its contents.
12. Record the damage (if any) done to the masks and the Fire-Eye devices by taking pictures of post-test scenarios. A post-fire scenario is shown in Figure 64.
13. Stop the digital video recording units after recording 15 minutes of post-test cooling activities of Fire-Eye devices.

Figure 64. After-test scenario for the living room fire test.

5.0 RESULTS

The results of the Full-scale fire testing scenarios are presented below.

5.1 Temperature Profiles in the ISO Room

The temperature profiles in the ISO room at the locations of Thermocouple Tree 1 and Thermocouple Tree 2 are displayed in Figures 65-76. The graphs show the range of the temperatures reached in the upper, middle, and the lower level of the ISO room during each test. The figures (# 65 through # 76) are arranged in the order that the tests were conducted, and show that the intensity of temperatures increased from Test 1 through Test 6. The Natural Gas test environment was the least intense temperature environment, whereas the living room fire test was the most intense temperature environment. The time span of a test was inversely proportional to the intensity of thermal environment of that test. Therefore, the Natural Gas tests were the longest but less thermally intense tests, whereas the living room fire tests were the shortest but most thermally intense tests. The temperatures were recorded every second during the test, and each plot displays the temperature profile per second for the test duration.

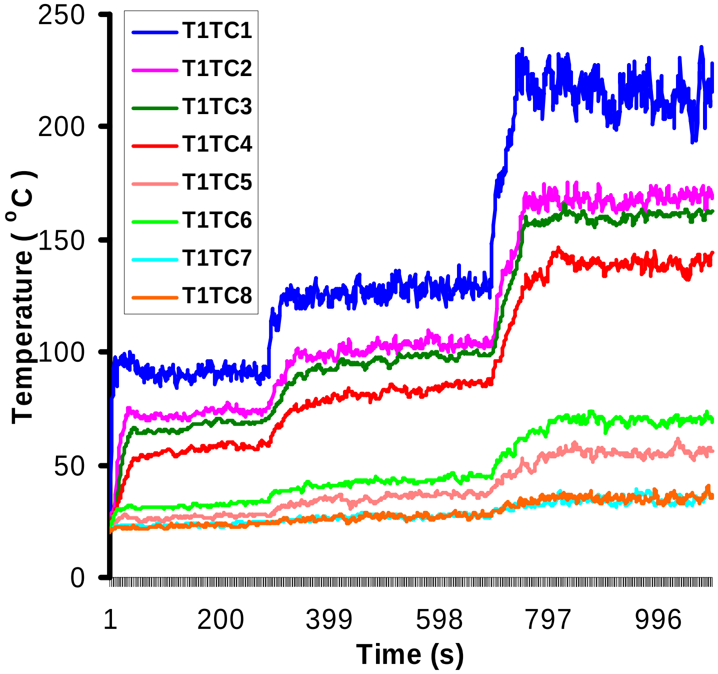


Figure 65. Temperatures at Thermocouple Tree 1 for Natural Gas Test #1.

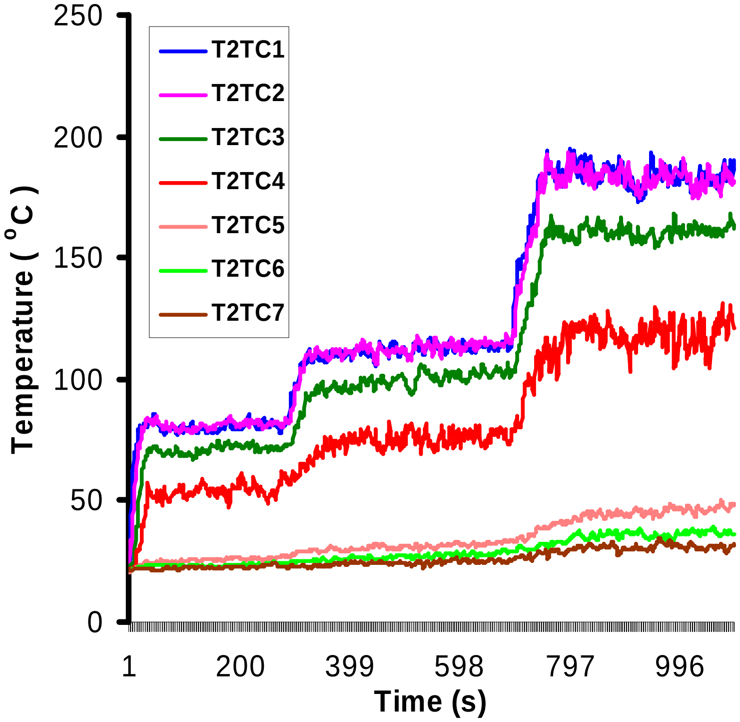


Figure 66. Temperatures at Thermocouple Tree 2 for Natural Gas Test # 1

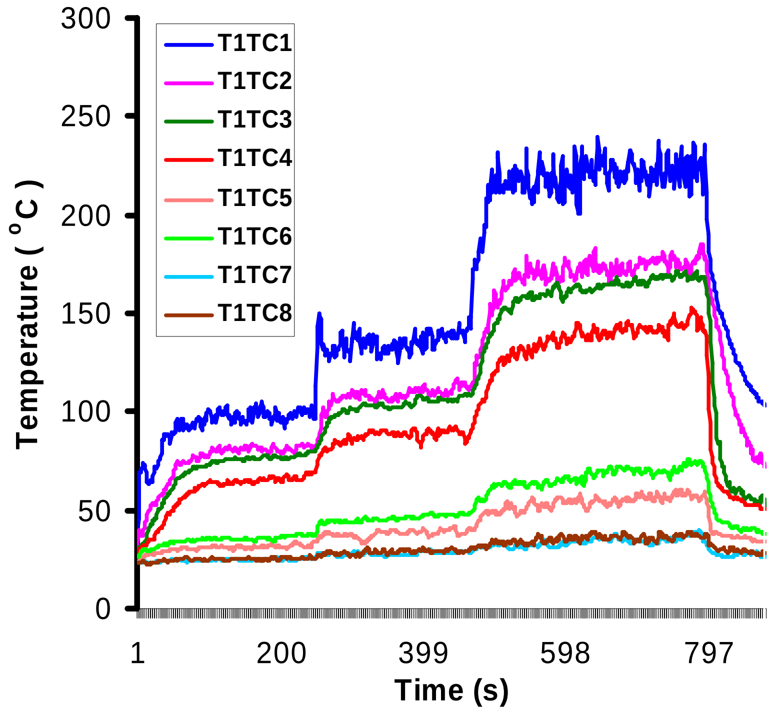


Figure 67. Temperatures at Thermocouple Tree 1 for Natural Gas Test #2.

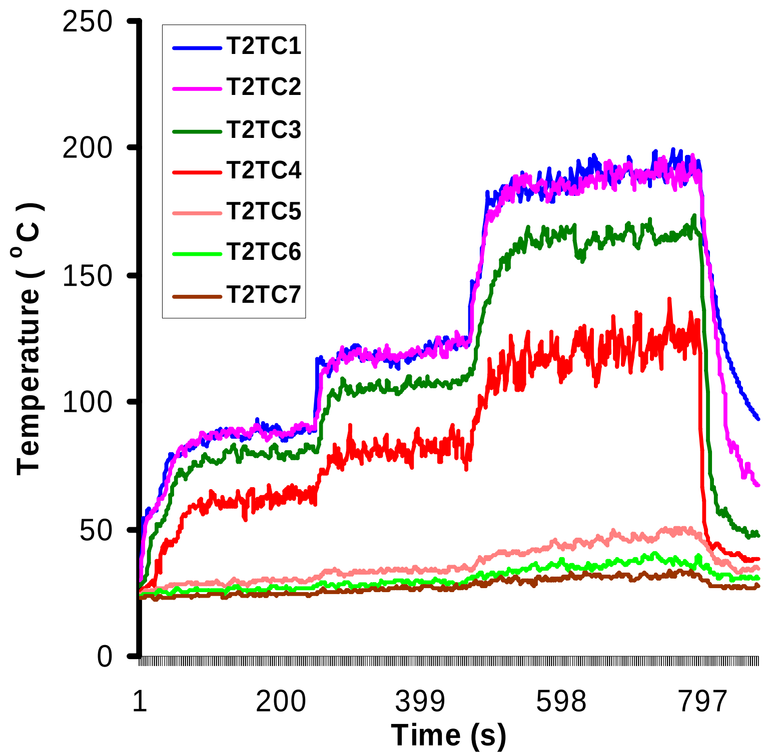


Figure 68. Temperatures at Thermocouple Tree 2 for Natural Gas Test #2.

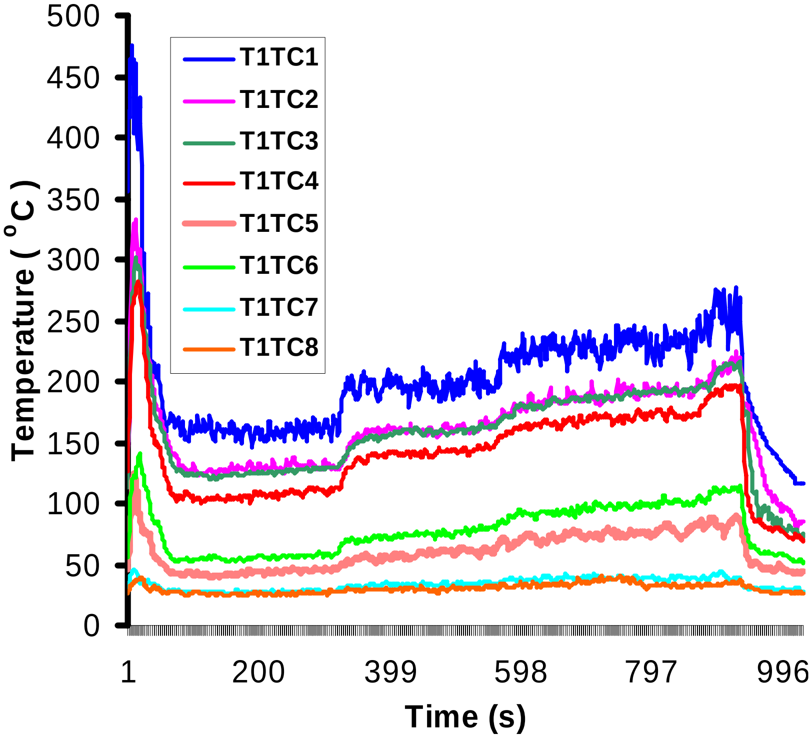


Figure 69. Temperatures at Thermocouple Tree 1 for Heptane Test #1

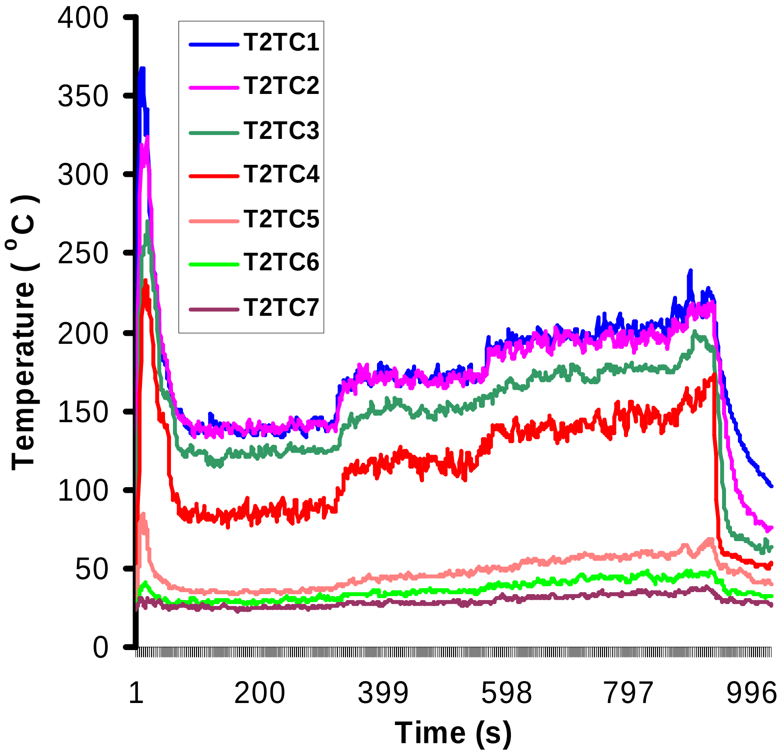


Figure 70. Temperatures at Thermocouple Tree 2 for Heptane Test #1.

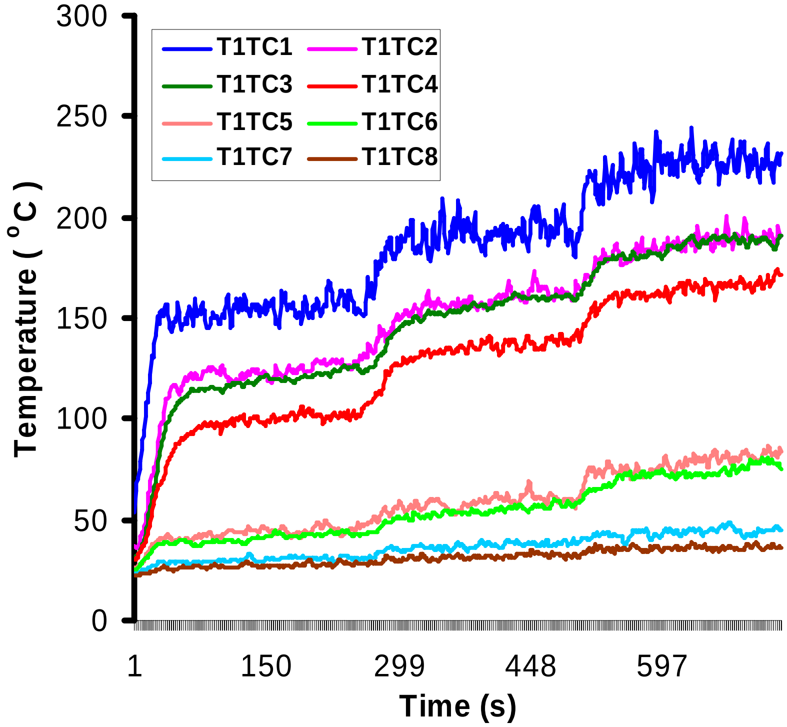


Figure 71. Temperatures at Thermocouple Tree 1 for Heptane Test #2.

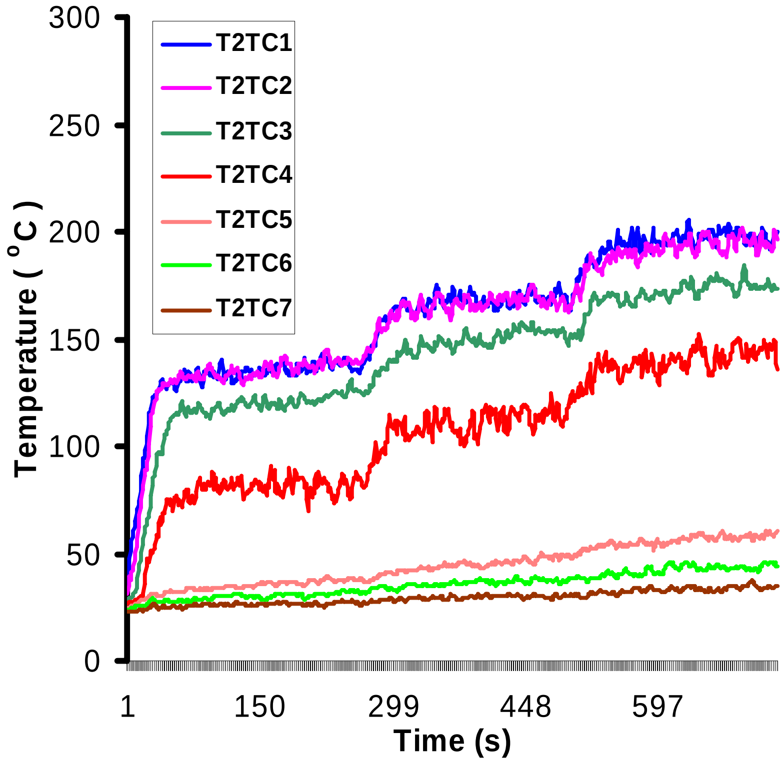


Figure 72. Temperatures at Thermocouple Tree 2 for Heptane Test #2.

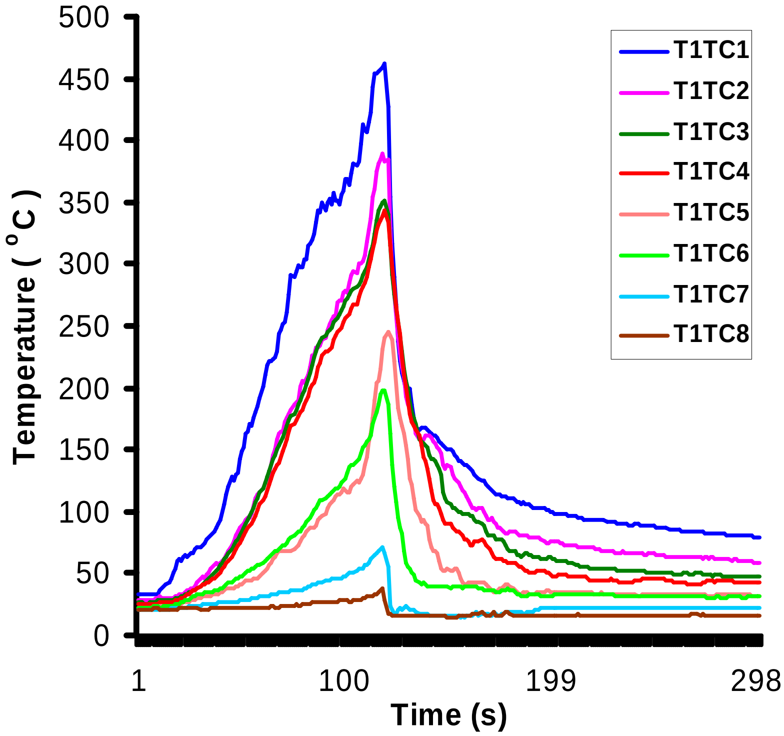


Figure 73. Temperatures at Thermocouple Tree 1 for Living Room Test #1.

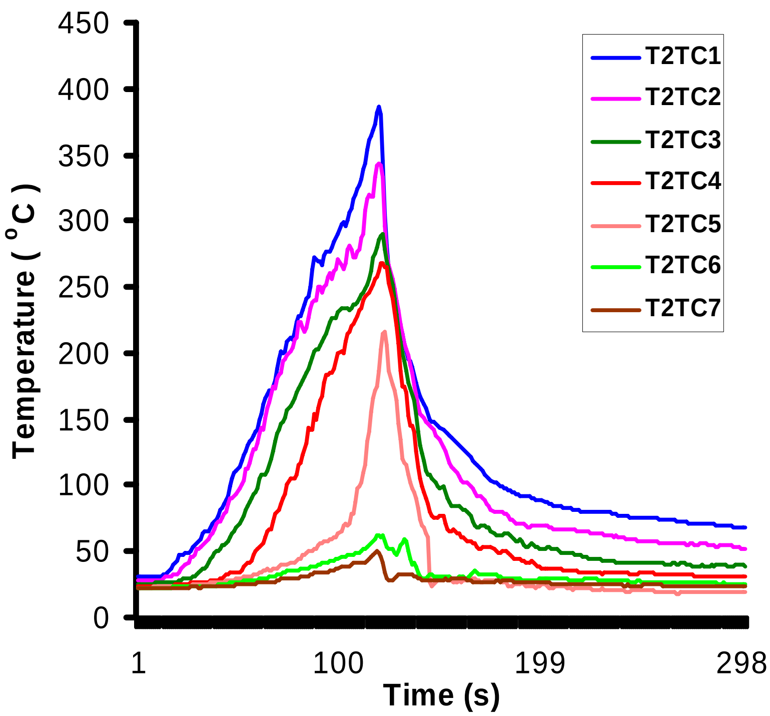


Figure 74. Temperatures at Thermocouple Tree 2 for Living Room Test #1.

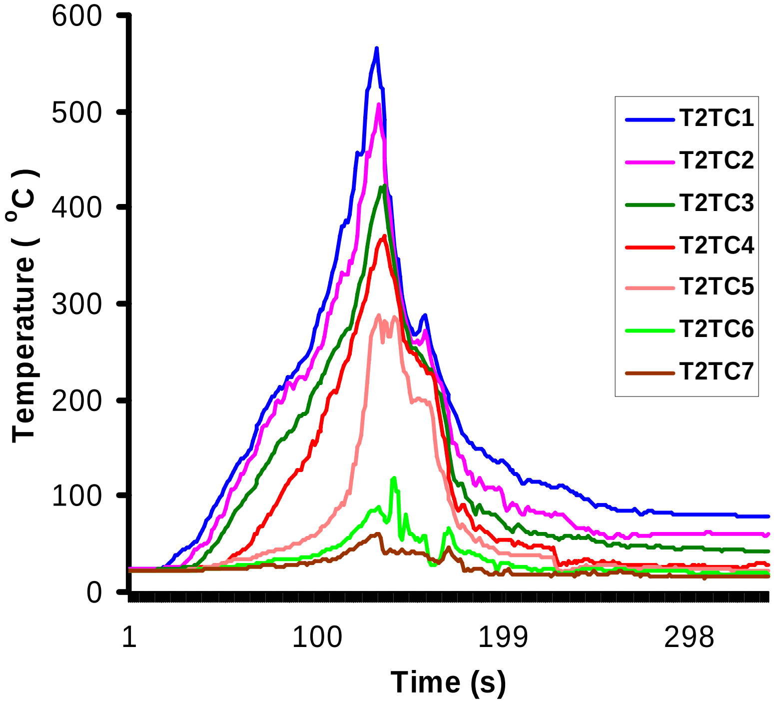


Figure 75. Temperatures at Thermocouple Tree 1 for living room Test #2.

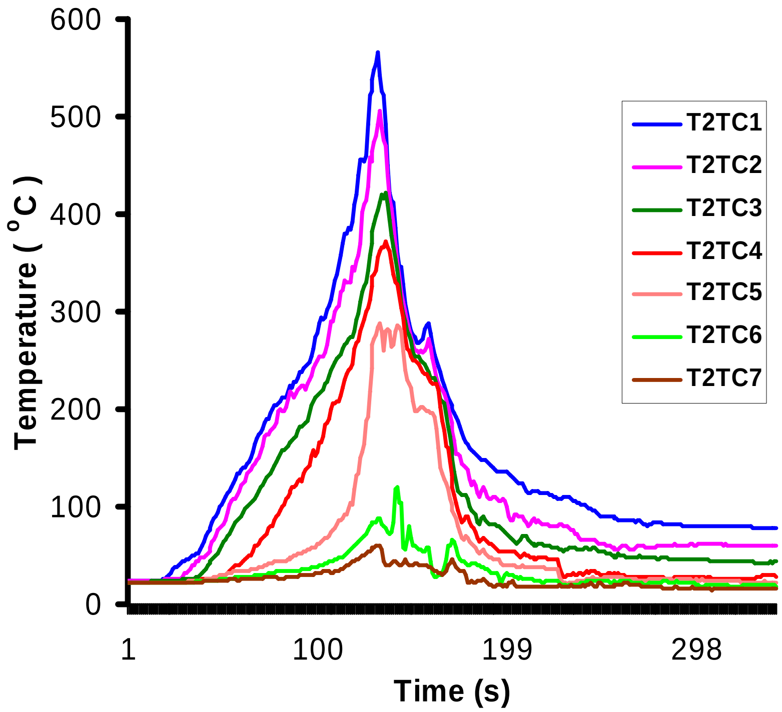


Figure 76. Temperatures at Thermocouple Tree 2 for living room Test #2.

5.2 Heat Flux Profile at Three Mask Locations

A unique equation that converted the recorded voltage (V) into heat flux (kW/m^2) was used for each heat flux gauge positioned at the three masks. The calibration graphs for each flux gauge can be seen in Appendix E. The heat flux gauges attached at each mask recorded the voltage in volts, and the voltage was converted into milli-Volts (mV) to match the conversion units suggested on the calibration graph. The milli-Volt quantity was converted into kW/m^2 using MS Excel. The heat flux value (kW/m^2) for each heat flux gauge was mapped on the graph for every second of the test duration. The heat flux values for the three masks in each test are displayed in the graphs that follow (Figures 77-82).

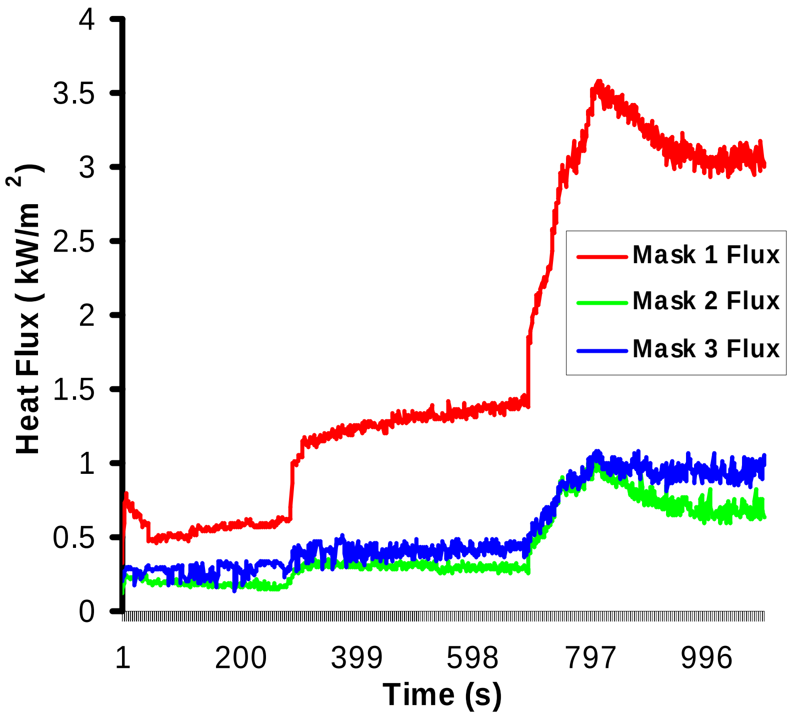


Figure 77. Heat Flux profile at three masks for Natural Gas Test #1.

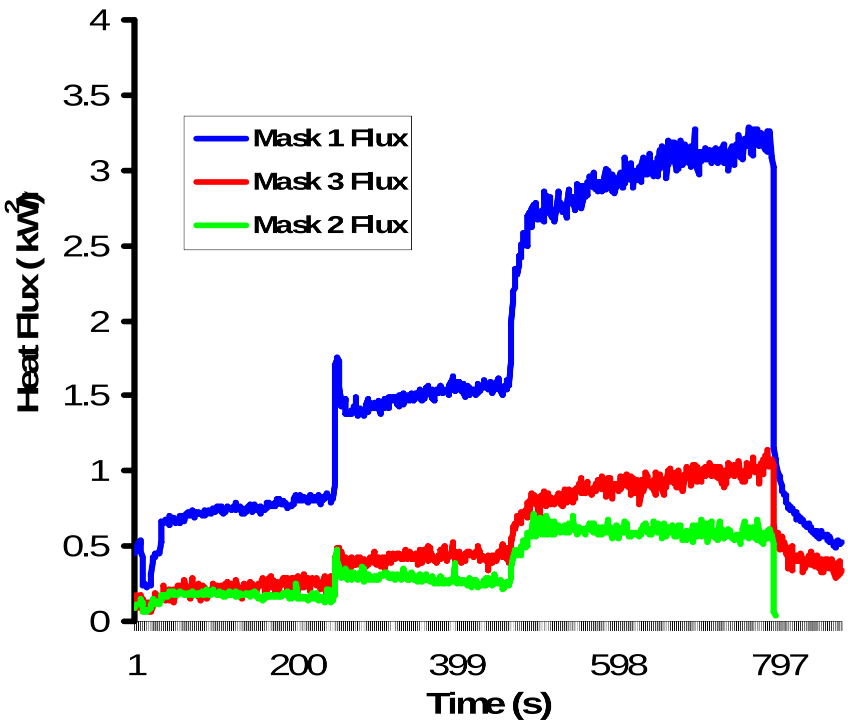


Figure 78. Heat Flux profile at three masks for Natural Gas Test #2.

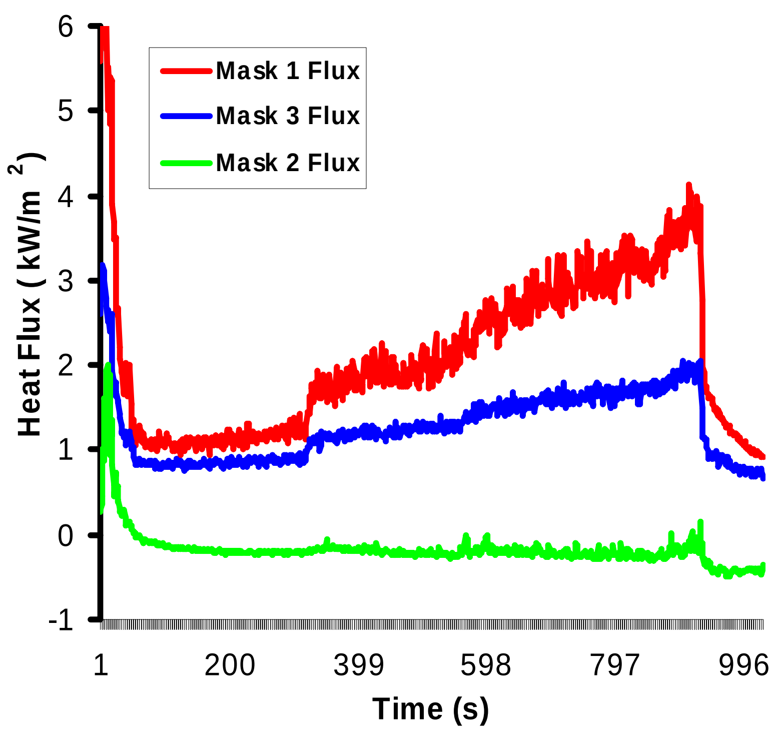


Figure 79. Heat Flux profile at three masks for Heptane Test #1.

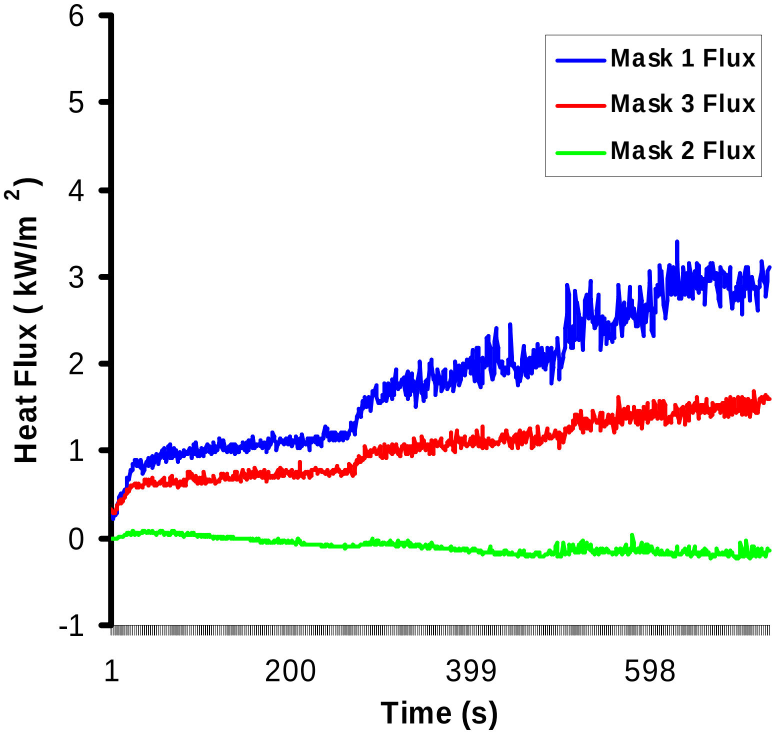


Figure 80. Heat Flux profile at three masks for Heptane Test #2.

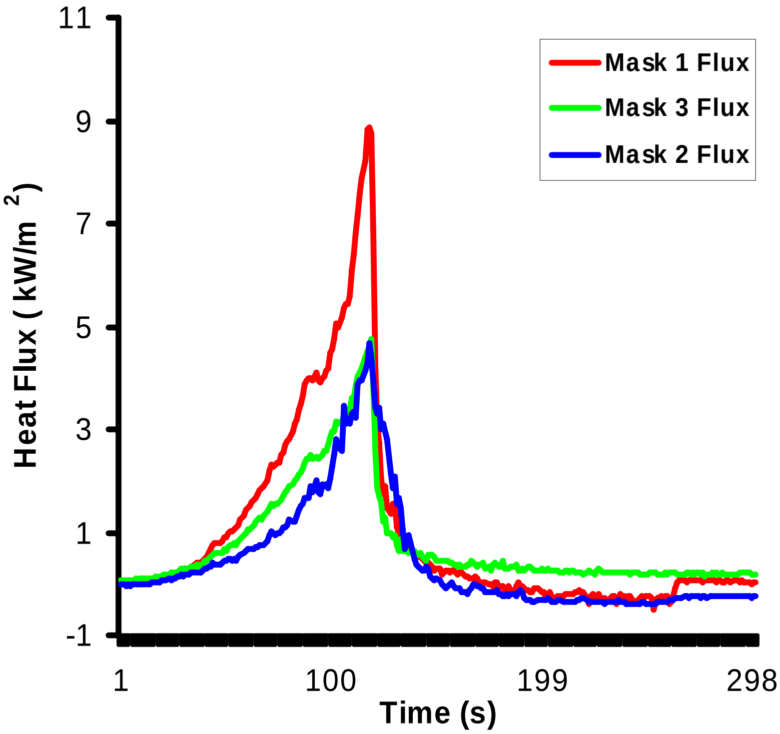


Figure 81. Heat Flux profile at three masks for living room Test #1.

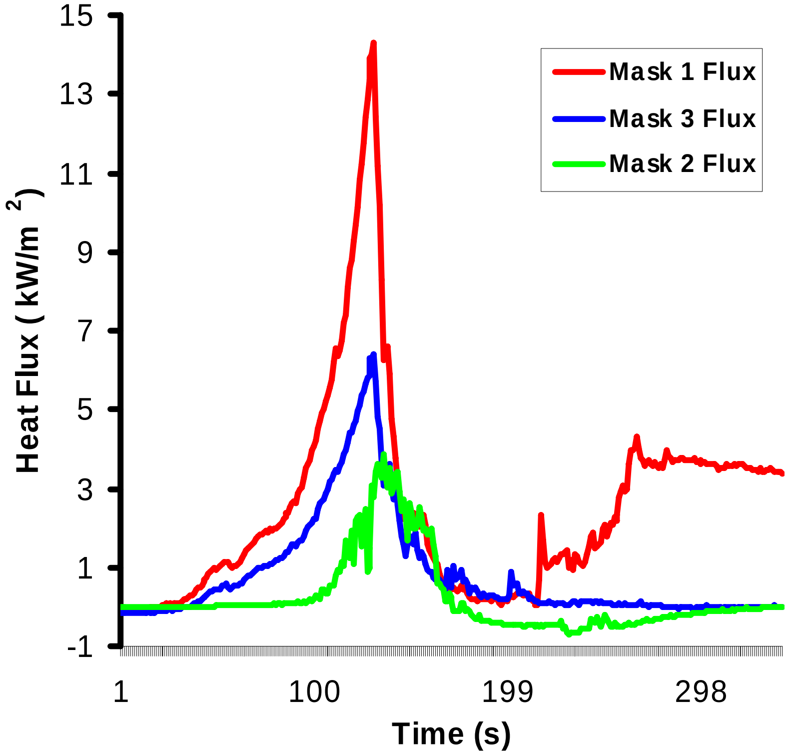


Figure 82. Heat Flux profile at three masks for living room Test #2.

5.3 Results of the Natural Gas Tests

The Natural Gas test flame height from the surface of the burner was between 3 and 4 feet in both tests (see Figure 60). The ignition time was begun just after the test begin time as the test was begun after initiating the bullet cameras as well as the MIDAS and HRR computers. There was also a brief lag time between the fuel flow rate and actual HRR recorded at the burner. Table 21 shows separate rows for the begin time and ignition time for the Natural Gas Test #1. Table 22 shows the specific temperatures at TC1 and TC3 for specific Fire-Eye devices, when the warning indicators changed their blinking status during the test.

Table 21. Timeline and details for Natural Gas Test #1.

Natural Gas Test 1	Mask 1	Mask 2	Mask 3
Test begin time	0:00	0:00	0:00
Time at ignition	0:10	0:10	0:10
Blinking Green	8:34	10:25	18:30
Solid Green	15:21	16:57	No change
Solid Red	16:48	18:45	No change
Blinking Red	17:33	19:42	No change
Test end time	23:12	23:12	23:12

Table 22. Performance of the three Fire-Eye devices in Natural Gas Test # 1

Natural Gas Test 1	**Mask 1 (Fire-Eye#5)**		**Mask 2 (Fire-Eye#3)**		**Mask 3 (Fire-Eye#2)**	
Temperature (^oC)	M1TC1	M1TC3	M2TC1	M2TC3	M3TC1	M2TC3
Blinking Green (^oC)	62.44	65.23	66.27	59.30	53.95	59.33
Solid Green (^oC)	108.31	115.65	110.47	100.83	No change	No change
Solid Red (^oC)	114.56	121.10	116.30	107.41	No change	No change
Blinking Red (^oC)	115.58	122.44	120.01	110.55	No change	No change

The graph in Figure 83 shows the temperatures for the three thermocouples at the location of Mask 1. TC1 and TC3 are attached to the front surface of the FE device and the facepiece, whereas TC5 is the ambient temperature sensing thermocouple. The graph in Figure 84 shows the temperatures for the three thermocouples at the location of Mask 2, whereas the graph in Figure 85 shows the temperatures for the three thermocouples at the location of Mask 3. The graphs signify the difference in the temperatures at the surface of the FE devices as well as the facepiece based on their location from the source of fire and their height from the floor.

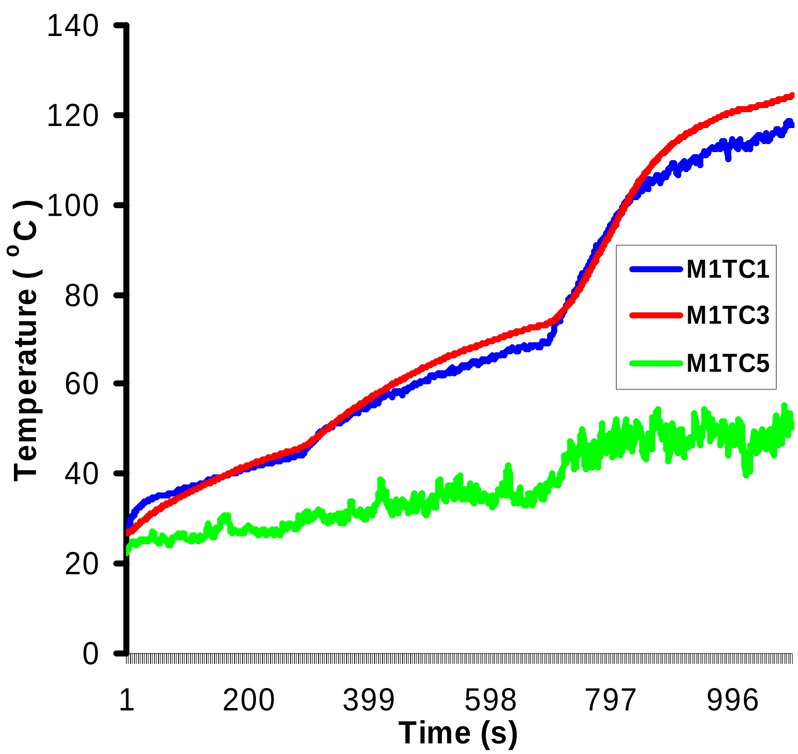


Figure 83. Temperatures at Mask 1 for Natural Gas Test #1.

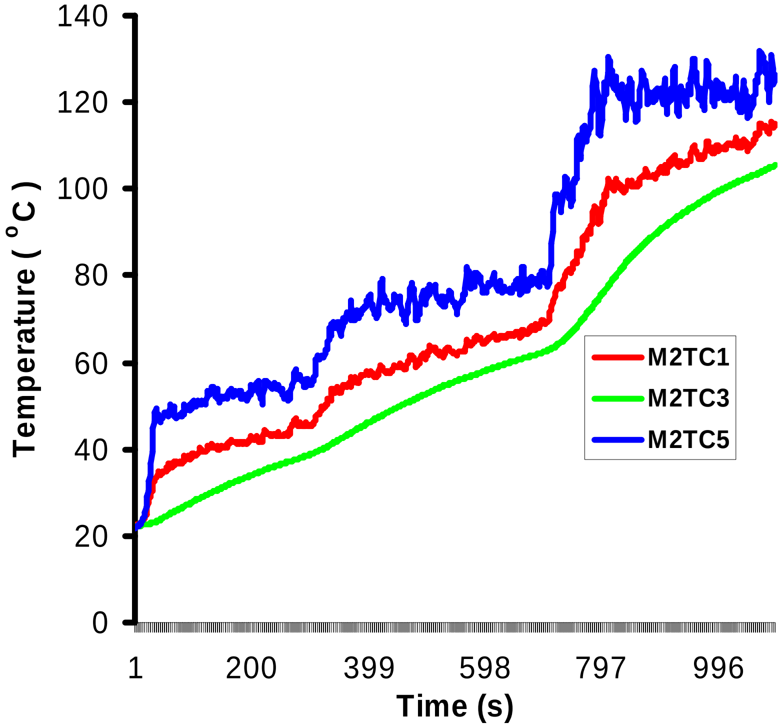


Figure 84. Temperatures at Mask 2 for Natural Gas Test #1.

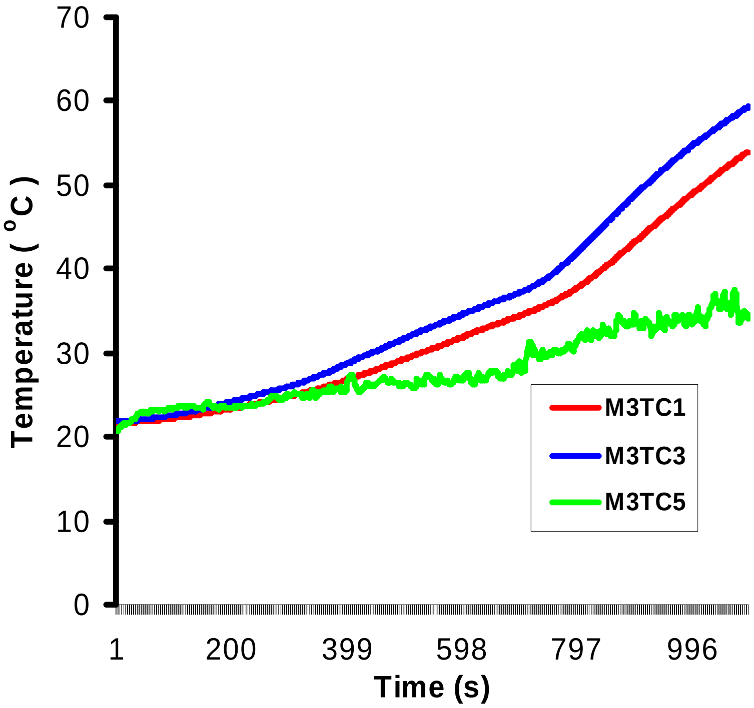


Figure 85. Temperatures at Mask 3 for Natural Gas Test #1.

The timeline and the test details for Natural Gas Test #2 are shown in table 23 and table 24.

Table 23. Timeline and details for Natural Gas Test #2.

Natural Gas Test 2	**Mask 1**	**Mask 2**	**Mask 3**
Test begin time	0:00	0:00	0:00
Time at ignition	0:10	0:10	0:10
Blinking Green	6:24	7:18	12:04
Solid Green	11:58	13:02	No change
Solid Red	13:30	No change	No change
Blinking Red	14:30	No change	No change
Test end time	14:40	14:40	14:40

Table 24. Performance of the three Fire-Eye devices in Natural Gas Test # 2

Natural Gas Test2	**Mask1 (Fire-Eye#5)**		**Mask2 (Fire-Eye#4)**		**Mask3 (Fire-Eye#6)**	
Temperature (^oC)	M1TC1	M1TC3	M2TC1	M2TC3	M3TC1	M2TC3
Blinking Green(^oC)	64.85	68.05	66.18	68.05	57.21	53.21
Solid Green (^oC)	105.79	114.14	111.24	103.43	No change	No change
Solid Red (^oC)	101.39	117.18	No change	No change	No change	No change
Blinking Red (^oC)	86.97	101.95	No change	No change	No change	No change

The graphs in Figure 86- 88 show the temperature profiles at the TC's attached to the Fire-Eye devices located at different mask location.

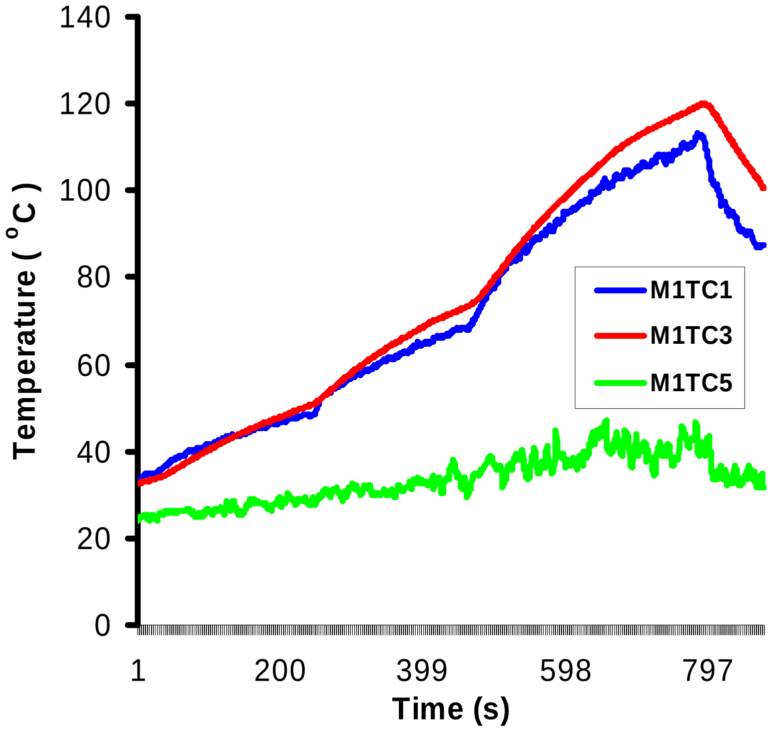


Figure 86. Temperatures at Mask 1 for Natural Gas Test #2.

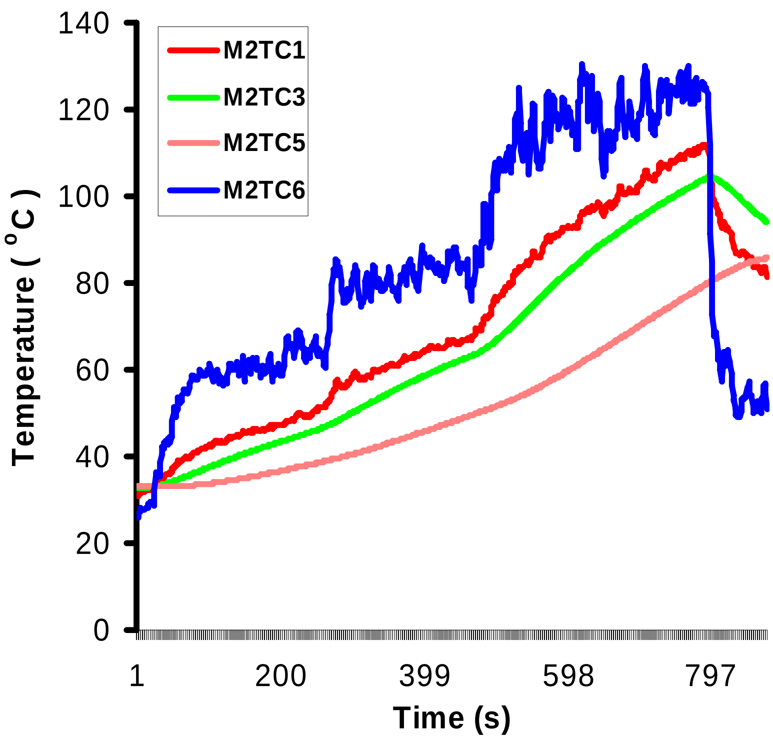


Figure 87. Temperatures at Mask 2 for Natural Gas Test #2.

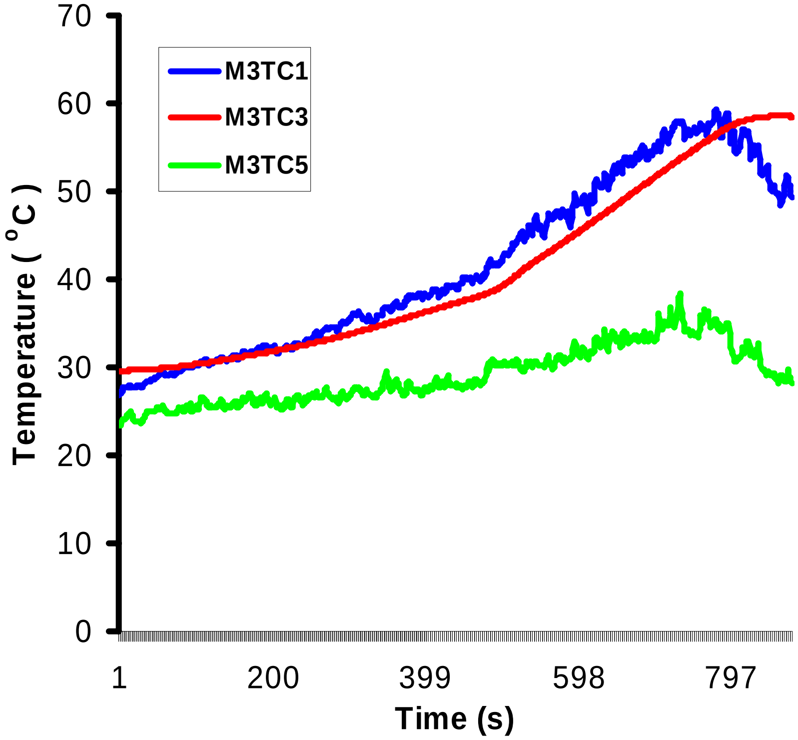


Figure 88. Temperatures at Mask 3 for Natural Gas Test #2.

5.4 Results of the Heptane Tests

The Heptane test flame height from the surface of the burner was between 3 and 4 feet for both tests (see Figure 61). The ignition time was begun just after the test begin time as there was a time lag between the fuel flow rate and the actual HRR recorded at the burner.

The timeline and the test details for Heptane test #1 are shown in table 25. The temperatures at the Fire-Eye devices attached to each mask for Heptane test #1 are diagrammed in Figures 89-91.

Table 25. Timeline and details for Heptane Test #1.

Heptane Test 1	Mask 1	Mask 2	Mask 3
Test begin time	0:00	0:00	0:00
Time at ignition	1:25	1:25	1:25
Blinking Green	2:35	2:30	8:35
Solid Green	12:09	9:55	No change
Solid Red	13:20	12:12	No change
Blinking Red	14:37	13:15	No change
Test end time	17:05	17:05	17:05

Table 26 shows the specific temperatures at TC1 and TC3 for specific Fire-Eye devices, when the warning indicators changed their blinking status during the test.

Table 26. Performance of the three Fire-Eye devices in Heptane Test # 1

Heptane Test 1	**Mask 1 (Fire-Eye#5)**		**Mask 2 (Fire-Eye#4)**		**Mask 3 (Fire-Eye#6)**	
Temperature (°C)	M1TC1	M1TC3	M2TC1	M2TC3	M3TC1	M2TC3
Blinking Green(°C)	61.35	70.04	73.23	67.13	30.89	53.26
Solid Green (°C)	116.97	119.84	124.7	107.6	No change	No change
Solid Red (°C)	112.46	121.76	43.03	123.85	No change	No change
Blinking Red (°C)	104.46	109.52	149.58	130.03	No change	No change

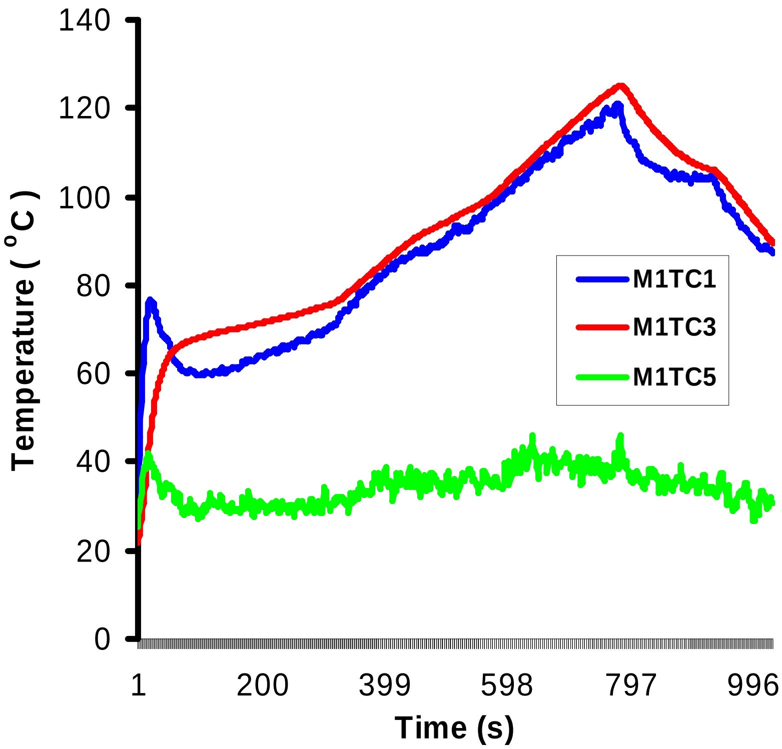


Figure 89. Temperatures at Mask 1 for Heptane Test #1.

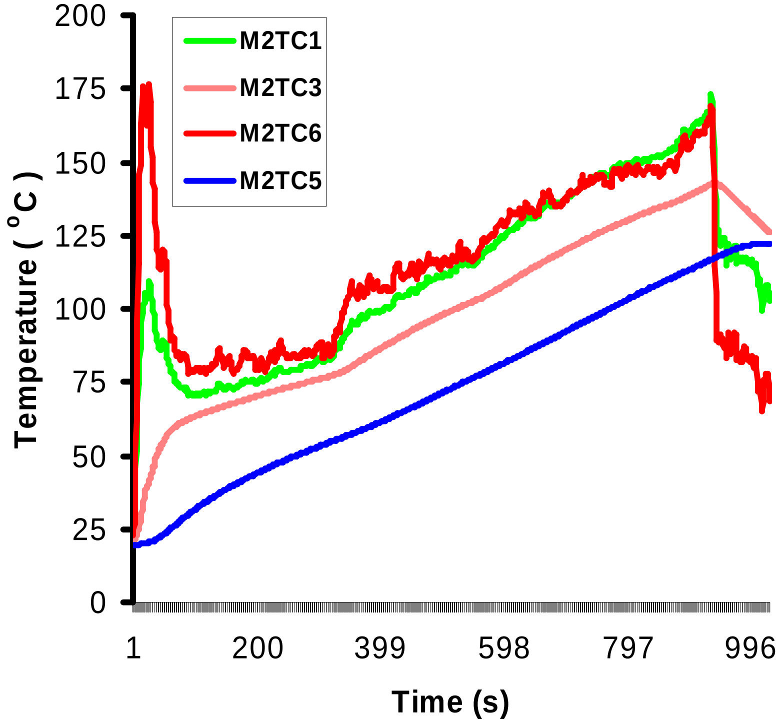


Figure 90. Temperatures at Mask 2 for Heptane Test #1.

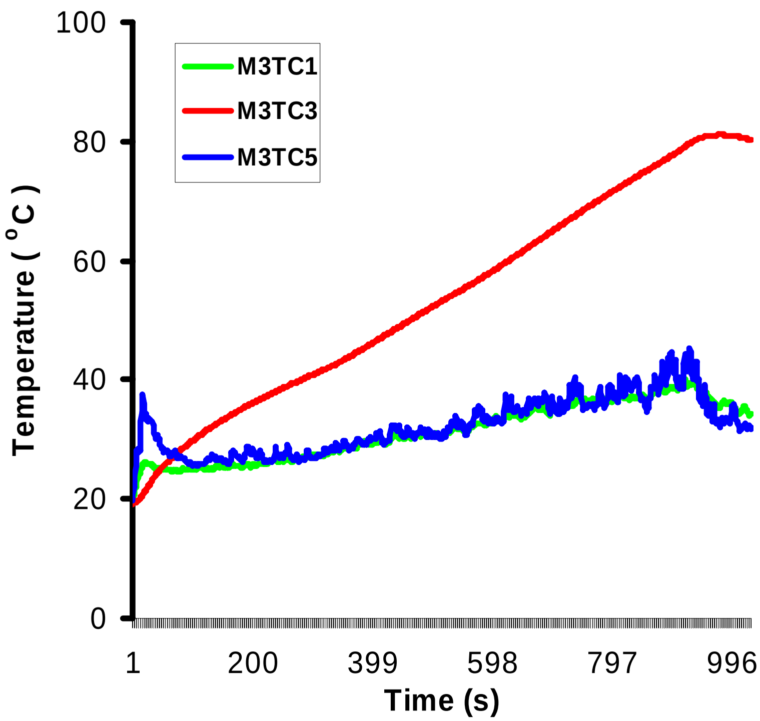


Figure 91. Temperatures at Mask 3 for Heptane Test #1.

The timeline and the test details for Heptane Test #2 are shown in table 27 and table 28. The temperatures at each mask for Heptane Test #1 are diagrammed in Figures 92-94

Table 27. Timeline and details for Heptane Test #2.

Heptane Test 2	Mask 1	Mask 2	Mask 3
Test begin time	0:00	0:00	0:00
Time at ignition	0.00	0.00	0.00
Blinking Green	3:40	No response	7:15
Solid Green	10:20	No response	No change
Solid Red	11:10	No response	No change
Blinking Red	No change	No response	No change
Test end time	12:00	12:00	No change

Table 28. Performance of the three Fire-Eye devices in Heptane Test # 2

Heptane Test 2	Mask1 (Fire-Eye#5)		Mask2 (Fire-Eye#3)		Mask3 (Fire-Eye#2)	
Temperature (^oC)	M1TC1	M1TC3	M2TC1	M2TC3	M3TC1	M2TC3
Blinking Green (^oC)	60.08	62.69	No Response	No response	27.36	48.87
Solid Green (^oC)	106.23	111.02	No response	No response	No change	No change
Solid Red (^oC)	111.88	117.33	No response	No response	No change	No change
Blinking Red (^oC)	No change	No change	No response	No response	No change	No change

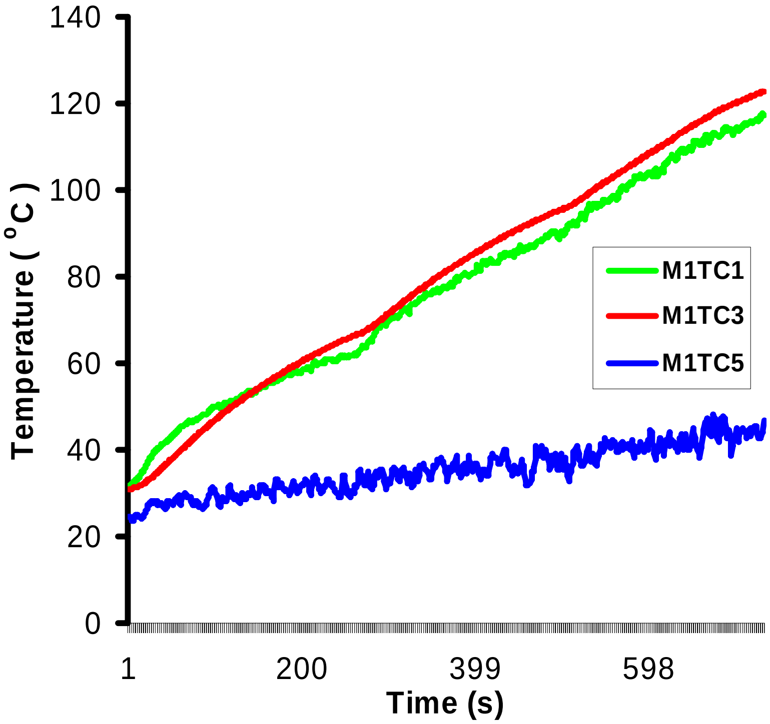


Figure 92. Temperatures at Mask 1 for Heptane Test #2.

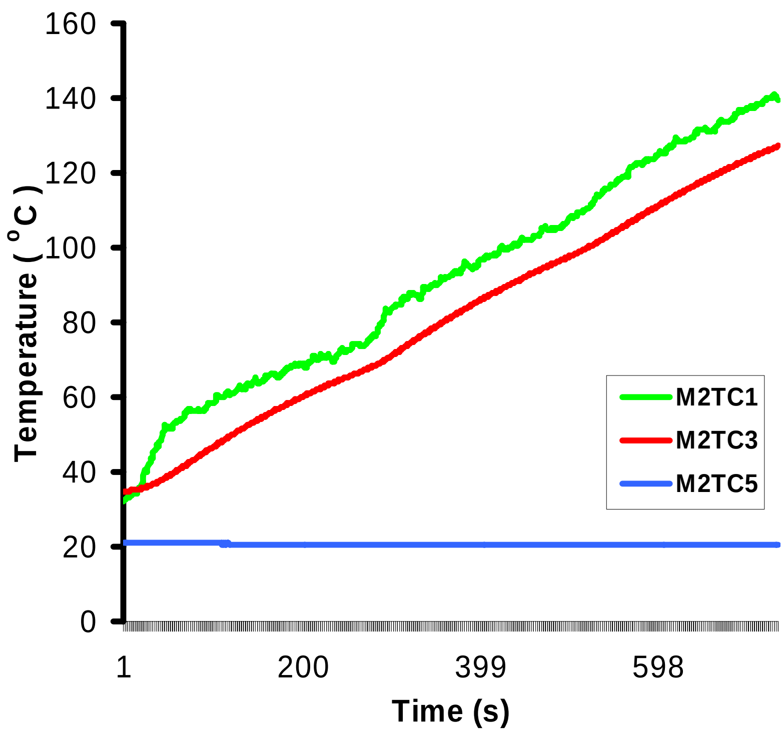


Figure 93. Temperatures at Mask 2 for Heptane Test #2.

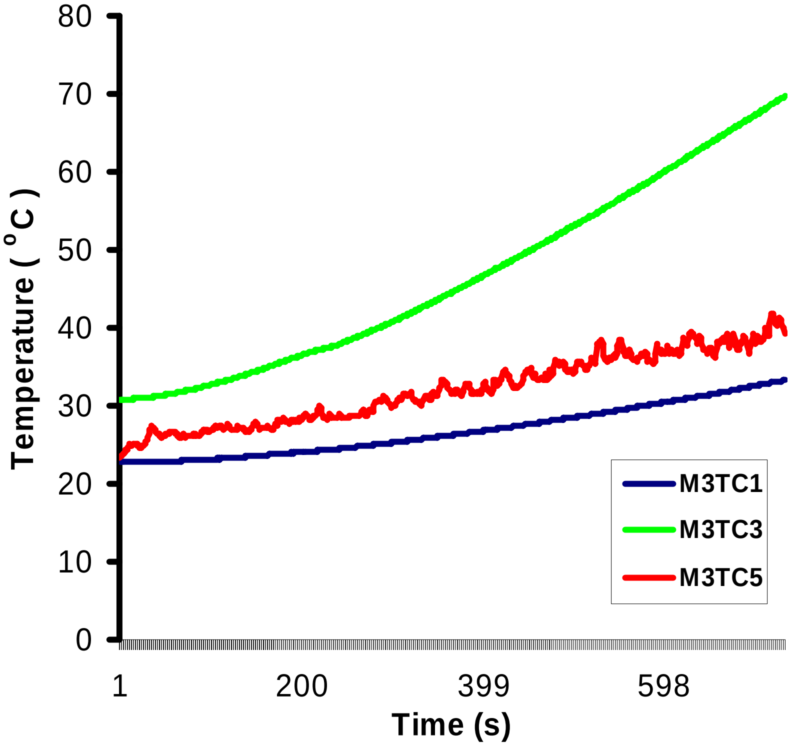


Figure 94. Temperatures at Mask 3 for Heptane Test #2.

5.5 Results of the Living Room Fire Tests

The living room fire tests were the shortest tests conducted in the ISO room, with durations of three minutes and two minutes, twenty seconds. As explained earlier, these tests were short in an effort to avoid the flashover temperatures that could have damaged the infrastructure of the ISO room as well as the masks and Fire-Eye devices. Even though care was taken to avoid flashover temperatures, the temperatures in the upper layer of the room were measured to reach above 600^{o} C. The flame height from the couch was measured to be in the range of 4-5 feet from the floor. The timeline and the test details for living room fire Test #1 are shown in table 29. The temperatures at each mask for living room Test #1 are diagrammed in Figures 95-97.

Table 29. Timeline and details of Living Room Test #1.

Living Room Test 1	Mask 1	Mask 2	Mask 3
Test begin time	0:00	0:00	0:00
Time at ignition	0:40	0:40	0:40
Blinking Green	2:33	2:23	3:20

Solid Green	Skipped	Skipped	No change
Solid Red	2:45	2:25	No change
Blinking Red	No change	No change	No change
Test end time	3:00	3:00	3:00

Table 30 shows the specific temperatures at TC1 and TC3 for specific Fire-Eye devices, when the warning indicators changed their blinking status during the test.

Table 30. Performance of the three Fire-Eye devices in Living Room Test # 1

Living Room Test 1	**Mask 1 (Fire-Eye#5)**		**Mask 2 (Fire-Eye #4)**		**Mask 3 (Fire-Eye#2)**	
Temperature (°C)	M1TC1	M1TC3	M2TC1	M2TC3	M3TC1	M2TC3
Blinking Green (°C)	63.18	77.69	102.7	92.09	43.13	49.49
Solid Green (°C)	No change	No change	No change	No change	No change	No change
Solid Red (°C)	59.32	75.44	94.98	92.6	No change	No change
Blinking Red (°C)	No change	No change	No change	No change	No change	No change

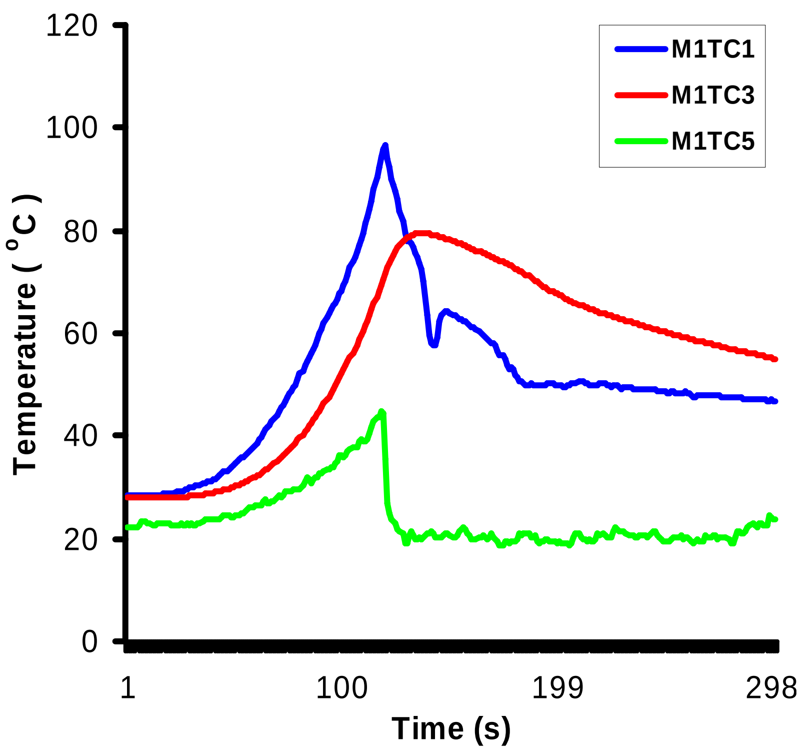


Figure 95. Temperatures at Mask 1 for living room Test #1.

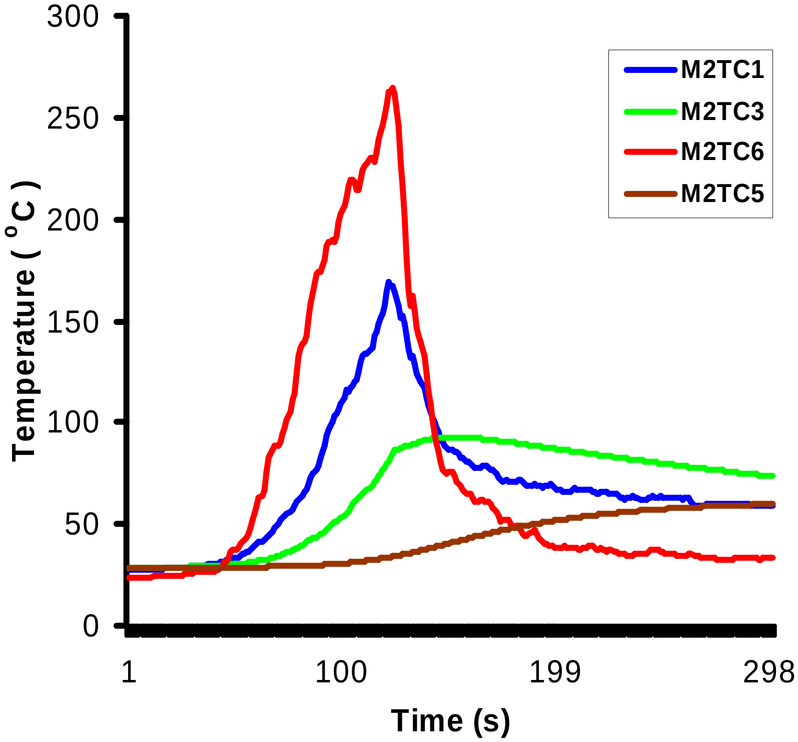


Figure 96. Temperatures at Mask 2 for living room Test #1.

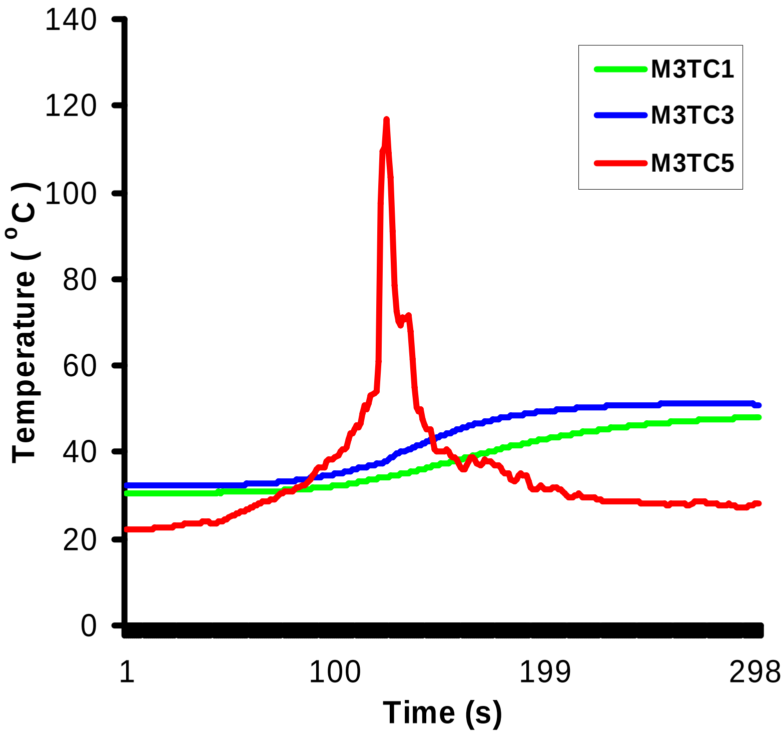


Figure 97. Temperatures at Mask 3 for living room Test #1.

The timeline and the test details for living room fire Test # 2 are shown in table 31. The temperatures at each mask for living room Test #2 are diagrammed in Figures 98-100.

Table 31. Timeline and details for Living Room Test #2.

Living Room Test 2	**Mask 1**	**Mask 2**	**Mask 3**
Test begin time	0:00	0:00	0:00
Time at ignition	1:00	1:00	1:00
Blinking Green	3:00	2:58	3:12
Solid Green	Skipped	Skipped	Skipped
Solid Red	3:11	3:09	3:25
Blinking Red	No change	No change	No change
Test end time	3:35	3:45	3:45

Table 32. Performance of the three Fire-Eye devices in Living Room Test #2.

Living Room Test 2	**Mask 1 (Fire-Eye#5)**		**Mask 2 (Fire-Eye#4)**		**Mask 3 (Fire-Eye#6)**	
Temperature (^{o}C)	M1TC1	M1TC3	M2TC1	M2TC3	M3TC1	M2TC3
Blinking Green (^{o}C)	51.93	89.21	115.60	138.47	40.63	53.85
Solid Green (^{o}C)	No change	No change	No change	No change	No change	No change
Solid Red (^{o}C)	55.54	80.93	106.77	136.51	43.33	55.68
Blinking Red (^{o}C)	No change	No change	No change	No change	No change	No change

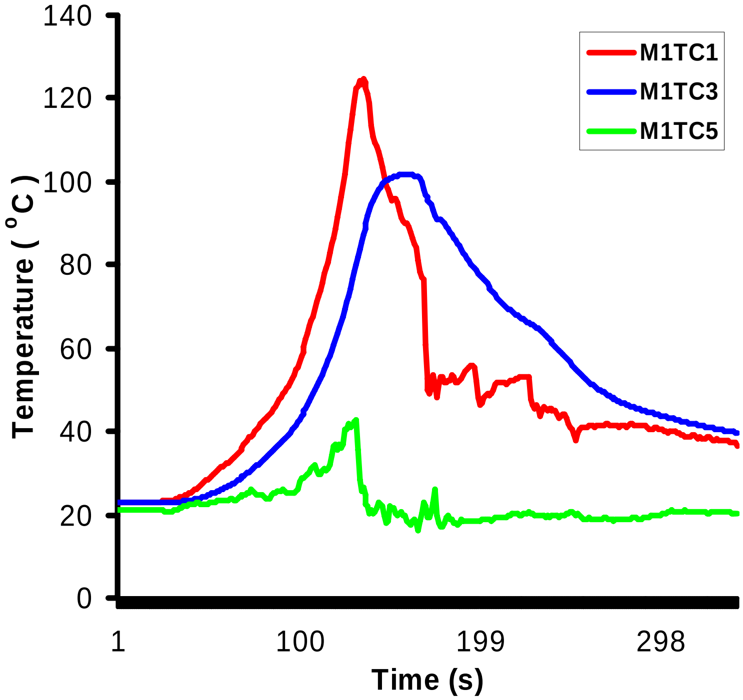


Figure 98. Temperatures at Mask 1 for living room Test #2.

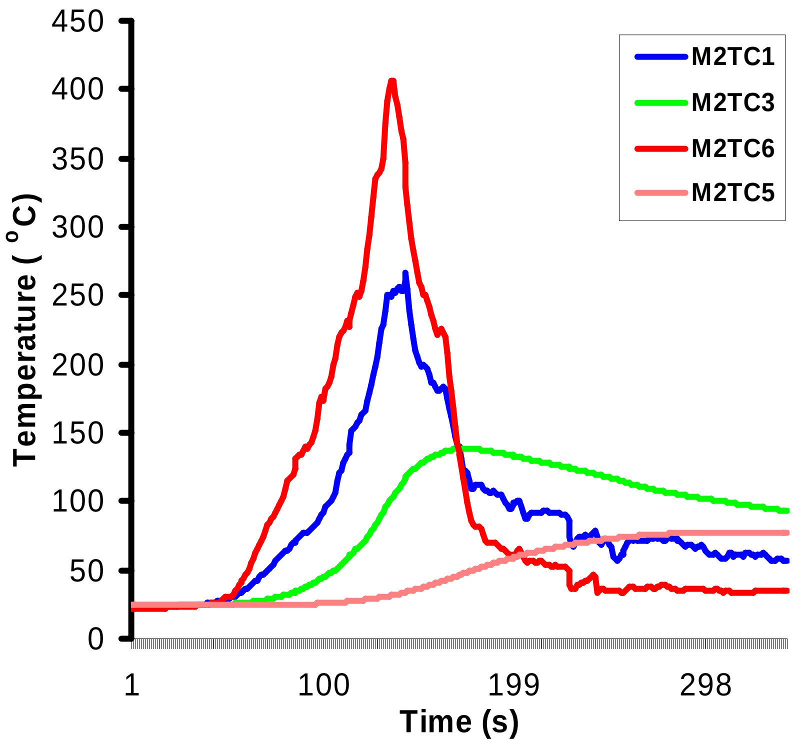


Figure 99. Temperatures at Mask 2 for living room Test #2.

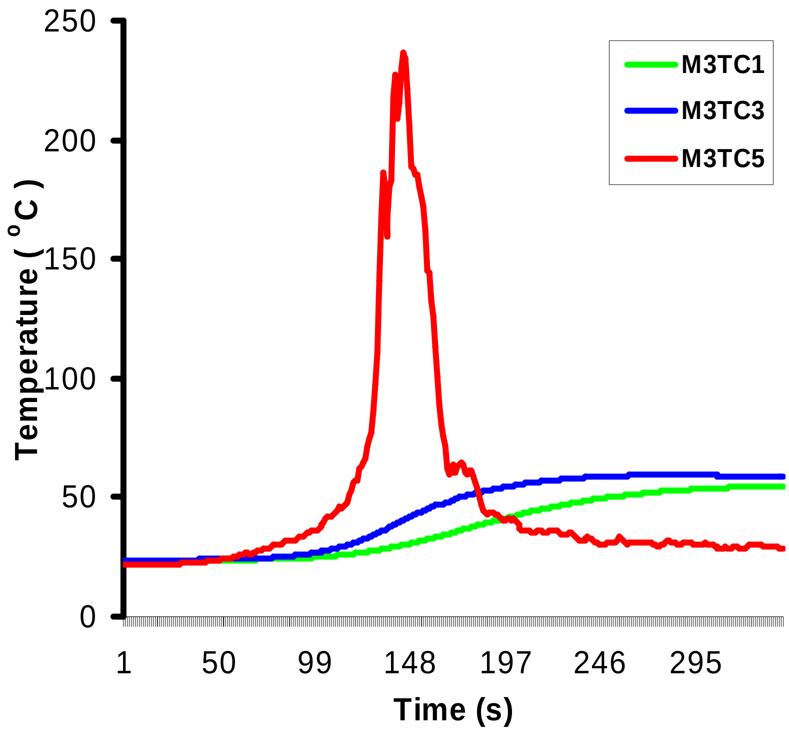


Figure 100. Temperatures at Mask 3 for living room Test #2.

6.0 DISCUSSION

The response of the Fire-Eye devices across the three tests was different, depending upon the intensity and the rate of increase of heat in a particular test. None of the Fire-Eye devices deformed or melted in any of the Full-scale fire tests. However, some surface marks and scratches were noticed on Fire-Eye #5 and Fire-Eye #4 at the conclusion of the living room fire tests. This was likely due to the fact that the temperatures for those tests increased drastically within several seconds, perhaps demonstrating one of the most hazardous conditions for firefighters and their protective gear. Fire-Eye device #5 (located at mask 1, see Figure 55 for location) survived the complete test regimen. Fire-Eye device #'s 2, 4, 5, and 6 were noted to indicate 'sudden hot conditions' through actuation of their solid red indicator immediately after the green blink indicator, when the temperatures increased to more than 200^{o} C within a few seconds during the living room fire tests.

As stated earlier, Mask 1 represented the position of Fire-Eye device when exposed to intense radiation. Fire-Eye device #5 was tested for reproducible performance at Mask 1 in all three of the tests. That device consistently indicated ‘blinking green’ for both of the Natural Gas tests between the temperatures of 60^{o} C—65^{o} C. Fire-Eye device #5 also produced a ‘blinking green’ indicator between the temperatures of 68^{o} C—73^{o} C for both of the Heptane tests, whereas the same device produced a ‘blinking green’ indicator between the temperatures 68^{o} C—73^{o} C momentarily in the living room fire test.

The Fire-Eye device # 5 at mask 1 responded first in both of the Natural Gas tests, followed by the devices at mask 2 and mask 3. The Fire-Eye device #’s 3 and 4 at mask 2 responded first in the first Heptane test and the two living room fire tests, followed by the Fire-Eye device # 5 at mask 1 and Fire-Eye device # 2 and 6 at mask 3. The most likely reason for the response of mask 1 in the Natural Gas test was that the intense radiant heat that was incident upon the mask was due to the height of the burner and the mask being the same, exposing it to increased radiative heat when compared to mask 2 and mask 3.

The Fire-Eye device at mask 2 responded earlier than the FE device at mask 1 in the Heptane test # 1 due to a hot upper layer of gases formed in the ISO room after ignition. The Heptane burns produced large amounts of soot that led to the formation of a heated gas layer in the topmost, empty space of room. The hot soot layer was seen up to 4 feet from the roof of the room. In this hot soot layer, mask 2 was at a height of 5 feet from floor, just at the appropriate height where the soot layer was noted to accumulate. These hot layers of gases resulted in a convective heat transfer to mask 2, which led to it being heated and its attached Fire-Eye device indicators actuating earlier than for mask 1 or mask 3. Mask 1 was located at a distance of a foot from the floor, so it was lower in space than was the Heptane burner height by 6 in. This may have been a possible rationale as to why mask 1 did not experience radiation as intense as was the case in the Natural Gas tests. The Fire-Eye device at mask 3 responded later in the Heptane tests as well.

The Fire-Eye device at Mask 2 responded earlier than the device at mask 1 in the living room fire tests as well, but the difference in the response time of the two devices was between 5 to 10 seconds. The couch was set on fire from the rear leftmost point in the room, leading to large amounts of soot production from the left corner to the nearest ‘cooler region,’ which was located in the top space of ISO room. The hot layer of sooty gases in the living room fire tests were noted to be at a height of 4 feet from the floor of the room, resulting in the condition that half of the room was filled with hot gases. This hot layer resulted in increased convective heat transfer to mask 2, leading to display of the 'blinking green' indicator. Interestingly, mask 1 and mask 2 did not display the 'solid green' indicators and instead went straight to the 'solid red' indicators within 10 seconds, suggesting the development of hazardous conditions within two minutes after the test ignition time.

The Fire-Eye device at Mask 3 also responded quickly in the two living room fire tests when compared to the Natural Gas or Heptane tests, likely due to the intense heat and smoke that was generated within a two minute time period, and was noted to actuate the 'solid red' indicator within 10 seconds of actuating the 'blinking green' indicator, providing a 'validation' of sorts regarding the hazardous scenario that was existing in the ISO room at that time. Further, the Fire-Eye device at mask 3 was noted to actuate only the 'blinking green' indicator in the Natural Gas and Heptane tests due to the (comparatively) limited conductive heat transfer endemic to those tests. As such, the 'slowest' indicator response was from the Fire-Eye device at mask 3 in 4 of the 6 tests conducted in the ISO room, whereas the devices at mask 1 and mask 2 responded quickly depending upon the intensity, the rate of increase of temperature, and the hot upper layer of gases created in the ISO room. Figure 101 shows the post-test condition after living room fire test #2. Fire-Eye device #3 failed to indicate *any* warning indicators in Heptane test #2 at the location of mask 2. The cause of this apparent malfunction was unknown.

Figure 101. Post-test condition of the ISO test room for the living room fire test.

Figure 102 displays the post-test condition of the three masks exposed to the fire during living room fire test #2, one of the most intense tests conducted in the ISO room. The mask on the left of the image was the most damaged; it was located 5 feet from the floor, and its damage was due to convective heat transfer. The mask on the right side of Figure 102 was the least damaged mask, and its placement primarily represented the conditions of conductive heat transfer. The mask in the middle was only moderately damaged.

Figure 102. The post-test condition of the three masks after living room fire test #2.

Figure 103 shows Fire-Eye device #4 mounted on mask #2 at a height of 5 feet from the floor (this was the most damaged mask after the living room fire test). Figure 104 displays Fire-Eye device #5, which was at a height of 1 foot from the floor, and closest to the source of the fire (this device was exposed to the most heat from the source that due to radiation heat-transfer). Fire-Eye device #5 was deformed, but was not as heavily damaged as the FE device # 4 that was positioned at a height of 5 feet from the floor.

Figure 103. Deformed and damaged mask #2 resulting from convective heat-transfer, and which was positioned at a distance of 5 feet from the room floor.

Figure 104. Deformed mask #1, located at a height of one foot from the room floor, and closest to the source of the fire.

7.0 STATISTICAL DATA ANALYSIS

The dependent variable in this research effort was *temperature* and it has been measured to the smallest SI unit of time, i.e. per second for each test. The temperature recorded in each test was a three second mean recorded at the change of each warning indicator. The Fire-Eye device usually transits through blinking green, solid green, solid red and then blinking red in a normal fire situation. It should be noted that the blinking red indicator is an indication that environment is cooling but it plays an important role in recognizing the period of time over which the preceding solid red indicator is active. The solid red indicator means the environment is consistently heating. The device has also been programmed to transit directly to solid green, skipping the blinking green stage, when the environment suddenly heats up to more than 20^{o}C in less than a minute. Therefore, in the case of a blinking red indicator as well as for all other indicators, the first instance at which the indicator begins blinking has been recorded. The blinking red indicator was observed multiple times in many tests and was also recorded in the laboratory observation notebook, but the temperature of blinking red indicator at the first instance has only been reported in this report. Since that temperature at first instance of blinking red was deemed to be the significant step in understanding the environment.

It is also important to note that there are no manufacturer-specified values of specific temperatures that will bound these warning indicators. The manufacturer specified the hierarchy of warning indicators which will occur over a wide range of temperatures from 125^{o}F to 400^{o}F. The manufacturer has not given any upper bound or lower bound temperature for any of the warning indicators as a part of the device's specification. This makes it impossible to compare the recorded test temperatures of these four indicators with any manufacturer-suggested benchmark temperatures.

7.1 Descriptive Statistics

Table 33 shows the average and the standard deviation of temperature at each warning indicator type, listed in the order of their occurrence from blinking green, solid green, solid red, and blinking red, for each type of test method. The statistic shows a comprehensive picture of the performance of the Fire-Eye devices in each method.

Table 33. Average and standard deviation of temperatures for different warning indicators in different test methods.

Warning Indicators		Blinking Green	Solid Green	Solid Red	Blinking Red
	Type of Test	Avg. (St. Dev)	Avg.(St. Dev)	Avg.(St. Dev)	Avg.(St. Dev)
Laboratory -scale Tests	Static Oven Test	66 (11)	92 (12)	97 (15)	111 (13)
	FEE Test	61 (5)	101 (8)	106 (8)	116 (12)
	Radiant Panel I	53 (9)	73 (18)	74 (19)	78 (21)
	Radiant Panel II	67 (17)	88 (23)	94 (23)	102 (26)
	Overall Lab-scale	**62 (6)**	**89 (12)**	**93 (14)**	**102 (17)**
Full-scale Tests	Natural Gas Test	62 (5)	109 (2)	111 (8)	108 (18)
	Heptane Test	51 (20)	116 (9)	122 (18)	127 (32)
	Living-room Test	70 (32)	N/A	72 (27)	N/A
	Overall Full-scale	**61 (10)**	**113 (5)**	**102 (26)**	**118 (13)**
Overall Statistics		**61 (7)**	**97 (16)**	**97 (19)**	**107 (17)**

The laboratory-scale results show that the average blinking green indicator occurred between 53 ^oC through 67 ^oC, with an average of 62 ^oC for the overall laboratory-scale tests, whereas the Full-scale tests showed the range of average temperature for blinking green indicator between 51 ^oC through 70 ^oC, with an average of 61 ^oC. The average solid green indicator occurred between the range of 73 ^oC through 101 ^oC in all the laboratory-scale tests, whereas the solid green indicator occurred during the range of 109 ^oC through 116 ^oC. The average for laboratory-scale solid green indicator is 89 ^oC, whereas the average of Full-scale tests for solid green indicator is 113 ^oC. The average solid red indicator occurred during the range of 74 ^oC through 106 ^oC in the laboratory-scale test, whereas the average solid red indicator occurred during 72 ^oC through 111 ^oC in the Full-scale tests. These results show that the range of solid green indicator and solid red indicator overlapped in the laboratory-scale tests as well as in the Full-scale tests. The average blinking red indicator occurred during the range of 78 ^oC through 116 ^oC in the laboratory-scale tests, whereas the same blinking-red indicator occurred during 108 ^oC through 127 ^oC in Full-scale tests.

Based on the observations of the temperature readings in Table 33, the overall average temperature of the blinking green indicator across all methods is 61^oC, the overall average temperature of solid green and solid red indicators across all methods is 97 ^oC, and the overall average temperature of blinking red across all methods was recorded to be 107 ^oC.

The standard deviation values in Table 33 increase as the temperatures increased and as the devices progressed through the later stages of warning indicators in the case of laboratory-scale testing. The standard deviation is lowest for the blinking green indicators, whereas the value for standard deviation for the solid green and solid red is more than that of blinking green for all laboratory-scale tests. The results in Table 33 also indicate that the standard deviation values are more dynamic in the Full-scale tests and do not follow any trend worthy pattern as in case of laboratory-scale tests.

7.2 Models for Analysis of Variance (ANOVA)

An important part of any experimental design problem is conducting an analysis of variance commonly referred as ANOVA. In this quantitative analysis of performance of the Fire-Eye device at four levels of warnings indications, it is important to understand the variance in the performance between the various laboratory-scale methods as well as between laboratory-scale and Full-scale testing methods. ANOVA allows the comparison of multiple methods and multiple device performance in a step by step way. The steps involved in ANOVA include specifying the model, determining the sum of squares for each component in the model, and the number of degrees of freedom associated with each sum of squares along with constructing an appropriate test statistic.

Therefore, ANOVA was used to conduct inferential statistics in order to detect differences among the four laboratory-scale methods as well as to compare the performance between the laboratory-scale and Full-scale methods. The first model that was used was the one way ANOVA model and the second model was the two-way ANOVA model.

The dependent variable for ANOVA analysis was the temperature, which was a 3 second mean, recorded at the time of change in status of the warning indicator. There are four different hierarchical statuses of the warning indicators: blinking green, solid green, solid red, blinking red. Therefore, an analysis has been done independently for all four statuses of the warning indicators with respect to different temperatures recorded for each status.

For comparison purposes among the laboratory-scale tests, the four methods used in testing are listed below:

1) Static Oven tests representing conductive heat: Cd
2) Fire Equipment Evaluator tests representing convective heat: Cv

3) Radiant Panel tests at heat flux of 1.6 kW/m^2 representing radiative heat: Rad1

4) Radiant Panel tests at heat flux of 4.5 kW/m^2 representing radiative heat: Rad2

One-way ANOVA Model

Depending upon the objectives of the experiment, an appropriate ANOVA model is important for the selection of appropriate F-tests. An ANOVA structural model indicates a mathematical statement expressing all of the possible components of variation in a specific experiment. The source of variation is a list of all possible effects in the ANOVA design that can be estimated. The first model used for the analysis purpose was the fixed-effect one-way ANOVA model. In the fixed-effect model, the fixed effects α_i will be same in each replication of the experiment.

Model, $Y_{ij} = \mu + \alpha_i + \varepsilon_{ij}$, where

Y = observation,

μ = overall average of the particular samples at all possible locations,

α = independent variable,

ε = random error,

i, j etc. = level of factor, etc.

Null hypothesis: Group means are equal: given that $\sum \alpha_i = \sum (\mu-\mu_i) = 0$. In the case of this model, conclusions are made only to the one factor level involved in the experiment.

Two-way ANOVA model

The second model which has been used in the analysis was a two factor ANOVA model. Two independent variables were considered at fixed levels. The two factor ANOVA model is as listed as:

Model, $Y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk}$, where

Y = observation,

μ = overall average of the particular values of dependent variables at all locations,

α = independent variable with i levels,

β = independent variable 2 with j levels,

$\alpha\beta$ = interaction effect of the i^{th} independent variable in j^{th} location,

ε = random error,

i, j etc. = level of factor, etc.

Assumptions for ANOVA

In order to proceed with hypotheses testing, following assumptions were made related to the data at a confidence level of 95% ($\alpha = 0.05$).

1. The measurements in each cell were selected randomly from a normal distribution.
2. The distributions from the cells have same standard deviation.
3. The value of each cell comes from independent samples.
4. The same number of measurements were taken in each cell.

7.3 Hypothesis Testing

As stated earlier, the statistical analysis is conducted for two different hypotheses, and they are analyzed in details as follows.

Hypothesis 1. *There is no difference in the performance of Fire-Eye device for between and within test conditions among the different laboratory-scale methods.*

The four laboratory-scale methods have already been listed. The above hypothesis has been divided into two parts: between device analysis and within device analysis. Between device analysis will consider the data collected for the four devices (FE # 2, 3, 4 and 6), whereas within device analysis will consider the data collected in three replications for FE device # 5.

Part I. Two Way ANOVA for Between Device Test Condition

The data related to FE Device # 2, 3, 4, and 6 was used for between device test condition tested in the four laboratory-scale tests. A two way ANOVA was conducted for between device tests using Minitab™ statistical software. The ANOVA results of between-device testing for the four sets of tests are arranged as per the four warning status indicators. There are two independent variables in this analysis:

Independent Variable 1: Device (4 independent devices), Independent Variable 2: Method (4 laboratory-scale methods), and

Dependent Variable: Temperature. (^{o}C)

Since this was a two factor design, there were three separate pairs of hypotheses. These hypotheses are common for all four stages of warning indicators and are listed below.

H_0: There is no difference in the performance of the Fire-Eye device.

H_1: At least two devices have a different performance based on variation in devices.

H_0: There is no difference in performance of Fire-Eye device based on variation in method.

H_1: At least two devices have a different performance based on variation in method.

H_0: There is no difference in performance of Fire-Eye device based on the interaction between the device and method.

H_1: At least two devices have a different performance based on the interaction between the device and method.

Condition 1. Blinking Green Indicator

Table 34. Two way ANOVA Data for Blinking Green Indicator

Method / Device	Device # 1	Device # 2	Device # 3	Device # 4
Conduction	83	75	65	56
Convection	50	60	65	59
Radiation 1	44	48	61	39
Radiation 2	44	67	74	43

The result obtained from the two way ANOVA analysis for blinking green indicator is shown below.

Summary of Fit

R Square	0.6457
R Square Adj.	0.4095
Root Mean Square Error	9.9153
Total Number of Obs.	16.00

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Device	3	688.19	229.396	2.39	*0.136*
Method	3	955.69	318.563	3.32	*0.071*
Error	9	863.56	95.951		
Total	15	2507.44			

Result: The *p*-value (0.071 > 0.05) for *method* indicates that there was no significant evidence against the null hypotheses. The *p*-value (0.136> 0.05) for *device* indicates that there was no significant evidence against the null hypothesis. There was *no interaction* effect.

Condition 2. Solid Green Indicator

Table 35. Two way ANOVA Data for the Solid Green Indicator

Method / Device	Device # 1	Device # 2	Device # 3	Device # 4
Conduction	95	90	114	91
Convection	84	100	105	102
Radiation 1	87	57	85	40
Radiation 2	69	90	101	45

The result obtained from two way ANOVA analysis for the solid green indicator is as follows:

Summary of Fit

R Square	0.7085
R Square Adj.	0.5142
Root Mean Square Error	14.9153
Total Number of Obs.	16.00

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Device	3	2024.19	674.729	3.03	*0.086*
Method	3	2840.19	946.729	4.26	*0.039*
Error	9	2001.06	222.340		
Total	15	6865.44			

Result: The *p-value* (0.039 < 0.05) for *method* indicates that there was a significant evidence against the null hypotheses. The *p-value* (0.086> 0.05) for *device* indicates that there was no significant evidence against the null hypothesis. There was *no interaction* effect.

Condition 3. Solid Red Indicator

Table 36. Two way ANOVA Data for Solid Red Indicator

Method / Device	Device # 1	Device # 2	Device # 3	Device # 4
Conduction	123	90	115	90
Convection	87	108	107	108
Radiation 1	88	62	86	38
Radiation 2	81	97	107	47

The result obtained from two way ANOVA analysis for solid red indicator is as follows:

Summary of Fit

R Square	0.6922
R Square Adj.	0.4869
Root Mean Square Error	16.9800
Total Number of Obs.	16.00

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Device	3	2328.75	776.25	2.69	*0.109*
Method	3	3508.75	1169.58	4.05	*0.045*
Error	9	2596.25	288.47		
Total	15	8433.75			

Result: The *p-value* (0.045 < 0.05) for *method* indicates that there was a significant evidence against the null hypotheses. The *p-value* (0.109> 0.05) for *device* indicates that there was no significant evidence against the null hypothesis. There was *no interaction* effect.

Condition 4. Blinking Red Indicator

Table 37. Two way ANOVA Data for Blinking Red Indicator

Method / Device	Device # 1	Device # 2	Device # 3	Device # 4
Conduction	135	109	120	102
Convection	92	118	107	119
Radiation 1	96	58	89	40
Radiation 2	99	101	126	48

The result obtained from two way ANOVA analysis for blinking red indicator is as follows:

Summary of Fit

R Square	0.6624
R Square Adj.	0.4373
Root Mean Square Error	20.5800
Total Number of Obs.	16.00

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Device	3	2576.20	858.73	2.03	*0.180*
Method	3	4899.20	1633.06	3.86	*0.050*
Error	9	3810.60	423.40		
Total	15	11286.00			

Result: The *p-value* (0.050 = 0.05) for *method* indicates that there was a significant evidence against the null hypotheses. The *p-value* (0.180> 0.05) for *device* indicates that there was no real evidence against the null hypothesis. There was *no interaction* effect.

<u>Summary of Two Way ANOVA Results for Between Device Test Condition</u>

Table 38. Summary of p-values for between device test condition in four laboratory methods

#	Comparison of Results	*p value*: Device	*p value*: Method
1	Blinking Green	0.136	0.071
2	Solid Green	0.086	0.039
3	Solid Red	0.109	0.045
4	Blinking Red	0.180	0.050

The results from Table 38 indicate that there is a significant difference (*p value* < 0.05) for the *method* factor in three of the four warning indicators and the results are consistent. Interestingly, the *p value*s for the *device* factor are suggestive of little to no significant difference (*p value* >0.05) for the four warning indicators in the laboratory-scale methods. The *p value* (p= 0.086) is almost approaching the level of significance ($p < 0.05$) at the solid green warning indicator for device factor, indicating that the recorded performance is approaching a significant difference for the device factor too.

<u>Part II. One way ANOVA for within devices data</u>

As said earlier, FE device # 5 was used for the within-test condition in the four laboratory-scale methods. A one way analysis of variance was conducted for within device tests using JMP^{TM} statistical software. The FE device # 5 was tested three times in same test method.

The null hypothesis and the alternative hypothesis for the second part of the first hypothesis are:

H_0: There is no difference in the performance of Fire-Eye device # 5 based on variation in laboratory-scale methods.

H_1: The Fire-Eye device # 5's performance varies in different laboratory-scale methods.

<u>Condition 1. Blinking Green Indicator</u>

Table 39. One way ANOVA Data for Blinking Green Indicator

Device	Fire-Eye device # 5		
Method	Repetition 1	Repetition 2	Repetition 3
Conduction	58	73	53
Convection	62	61	67
Radiation 1	55	59	62
Radiation 2	78	81	83

The result obtained from one way ANOVA analysis for blinking green indicator is as follows:

Summary of Fit

R Square	0.7730
R Square Adj.	0.6879
Root Mean Square Error	5.7238
Total Number of Obs.	12.0000

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	3	892.73	297.58	9.08	*0.0059*
Error	8	262.09	32.76		
Total	11	1154.83			

Result: The result (p = 0.0059 < 0.05) indicates that there is a significant evidence to reject the null hypothesis.

Condition 2. Solid Green Indicator

Table 40. One way ANOVA Data for Solid Green Indicator

Device	Fire-Eye device # 5		
Method	Repetition 1	Repetition 2	Repetition 3
Conduction	86	90	79
Convection	104	106	107
Radiation 1	72	85	87
Radiation 2	106	103	102

Summary of Fit

R Square	0.8690
R Square Adj.	0.8199
Root Mean Square Error	5.1879
Total Number of Obs.	12.0000

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	3	1428.60	476.20	17.69	*0.0007*
Error	8	215.31	26.91		
Total	11	1643.92			

Result: The result ($p = 0.0007 < 0.05$) indicates that there is a significant evidence to reject the null hypothesis.

Condition 3. Solid Red Indicator

Table 41. One way ANOVA Data for Solid Red Indicator

Device	Fire-Eye device # 5		
Method	Repetition 1	Repetition 2	Repetition 3
Conduction	90	105	82
Convection	111	110	114
Radiation 1	73	87	87
Radiation 2	112	109	105

Summary of Fit

R Square	0.7982
R Square Adj.	0.7226
Root Mean Square Error	7.3657
Total Number of Obs.	12.0000

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	3	1717.78	572.59	10.55	*0.0037*
Error	8	434.03	54.25		
Total	11	2151.82			

Result: The result ($p = 0.0037 < 0.05$) indicates that there is a significant evidence to reject the null hypothesis.

Condition 4. Blinking Red Indicator

Table 42. One way ANOVA Data for Blinking Red Indicator

Device	Fire-Eye device # 5		
Method	Repetition 1	Repetition 2	Repetition 3
Conduction	109	110	94
Convection	131	121	120
Radiation 1	77	94	89
Radiation 2	117	115	107

Summary of Fit

R Square	0.8327
R Square Adj.	0.7700
Root Mean Square Error	7.4463
Total Number of Obs.	12.0000

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	3	2209.13	736.37	13.28	*0.0018*
Error	8	443.58	55.44		
Total	11	2652.72			

Result: The result ($p = 0.0018 < 0.05$) indicates that there is a significant evidence to reject the null hypothesis.

Summary of One Way ANOVA Results for FE Device # 5 for Within Device Test Condition

The one way ANOVA results of within device testing for four set of tests are arranged as per the four warning status indicators. The results of ANOVA for laboratory-scale within device tests in four test methods are shown in Table 43. The results show that there is a significant ($p < 0.05$) difference among the four methods for all four levels of warnings indicators. Post-hoc analysis using Tukey's HSD test was conducted for each of the four levels of warning indicator in order to identify the difference among the four methods.

Table 43. Summary of ANOVA for laboratory-scale within device tests in four test methods

Ser. #	Comparison of Results	*P value*	Significance
1	Blinking Green	0.0059	*
2	Solid Green	0.0007	*
3	Solid Red	0.0037	*
4	Blinking Red	0.0018	*

Note: * = $p < 0.05$ and ** = $p > 0.05$

Table 44 shows the results from post-hoc analysis conducted using Tukey's HSD test for the four test methods. The post-hoc analysis indicate that the results for solid red and blinking red was the same and they can be divided into two groups Cd, Cv, Rad2 in group 1 and Cd and Rad1 in group 2. For the blinking green indicator, the results showed that there was no significant difference among Cd, Cv, Rad1, but the three are different than Rad2. For the solid green warning indicator, the results show that the results can be divided into two different groups indicating that Cd and Rad1 can be classified into one group while Cv and Rad2 can be classified into other group.

Table 44. Results of post-hoc Analysis for within device test for four laboratory test methods.

Method	Blinking Green	Solid Green	Solid Red	Blinking Red
Cd	B	B	A B	A B
Cv	B	A	A	A
Rad1	B	B	B	B
Rad2	A	A	A	A

Note: Levels not connected by same letter are significantly different.

<u>Hypothesis 2.</u> *There is no difference in the performance of Fire-Eye device in the laboratory-scale test and Full-scale fire tests in identical heat exposure conditions.*

In hypothesis 2, there were three types of heat conditions that were utilized in the laboratory-scale tests as well as in Full-scale tests. The performance of Fire-Eye device is compared at each of the three locations. In certain conditions, there are unequal numbers of observations to compare, which were entered in the JMP software and it adjusted the missing values and completed the one way ANOVA analysis.

H_0: There is no difference in the performance of Fire-Eye device between laboratory-scale and Full-scale test at an identical heat transfer condition such as radiation, convection and conduction.

H_1: The Fire-Eye device performs differently between laboratory-scale and Full-scale test at an identical heat transfer condition such as radiation, convection and conduction.

<u>Case 1. Radiant Type Heat Location</u>

The data recorded in the radiant heat location was recorded for Fire-Eye device #5 for the within test conditions. Therefore, the data indicates that same device was tested in the laboratory-scale radiation-1 tests as well as in the Full-scale radiant heat location. The distance of the Fire-Eye device from the heat source was the same in the laboratory-scale and the Full-scale methods. Therefore, ANOVA was conducted for the within test condition for the same Fire-Eye device.

<u>Blinking Green Indicator</u>

The data recorded in the two methods is listed in Table 45.

Table 45. Blinking green data at radiant heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	55
2	Lab Scale	59
3	Lab Scale	62
1	Full-scale	62
2	Full-scale	65
3	Full-scale	61
4	Full-scale	60
5	Full-scale	63
6	Full-scale	52

Summary of Fit

RSquare	0.874263
RSquare Adj	0.497052
Root Mean Square Error	2.960484
Mean of Response	59.93667
Observations	9

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	1	8.86	8.86	0.4752	*0.5128*
Error	7	130.54	18.64		
Total	8	139.40			

Result: The result (p = 0.5128 > 0.05) indicates that there is no sufficient evidence to reject the null hypothesis.

Solid Green Indicator

Table 46. Solid green data at radiant heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	72
2	Lab Scale	85
3	Lab Scale	87
1	Full-scale	108
2	Full-scale	106
3	Full-scale	117
4	Full-scale	106
5	Full-scale	No change
6	Full-scale	No change

Summary of Fit

RSquare	0.859944
RSquare Adj	0.831933
Root Mean Square Error	6.615356
Mean of Response	97.32714
Observations (or Sum Wgts)	7

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	1	1343.52	1343.52	30.69	*0.0026*
Error	5	218.81	43.76		
Total	6	1562.33			

Result: The result (p=0.0026 > 0.05) indicates that there is significant evidence to reject the null-hypothesis.

Solid Red Indicator

Table 47. Solid red data at radiant heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	73
2	Lab Scale	87
3	Lab Scale	87
1	Full-scale	115
2	Full-scale	101
3	Full-scale	112
4	Full-scale	112
5	Full-scale	59
6	Full-scale	56

Summary of Fit

RSquare	0.051017
RSquare Adj	-0.08455
Root Mean Square Error	23.71057
Mean of Response	89.09667
Observations (or Sum Wgts)	9

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	1	211.56	211.56	0.3763	*0.5590*
Error	7	3935.33	562.19		
Total	8	4146.90			

Result: The result (p = 0.5590 > 0.05) indicates that there is no sufficient evidence to reject null-hypothesis.

Blinking Red Indicator

Table 48. Blinking red data at radiant heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	77
2	Lab Scale	94
3	Lab Scale	89
1	Full-scale	116
2	Full-scale	87
3	Full-scale	104
4	Full-scale	No change
5	Full-scale	No change
6	Full-scale	No change

Summary of Fit

RSquare	0.385193
RSquare Adj	0.231491
Root Mean Square Error	11.91683
Mean of Response	94.635
Observations (or Sum Wgts)	6

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	1	355.89	355.89	2.50	*0.1886*
Error	4	568.52	142.01		
Total	5	923.93			

Result: The result (p = 0.1886 > 0.05) indicates that there is no sufficient evidence to reject null-hypothesis.

Case 2. Convection Type Heat Location

Blinking Green Indicator

Table 49. Blinking green data at convective heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	60
2	Lab Scale	65
1	Full-scale	66
2	Full-scale	66
3	Full-scale	73

4	Full-scale	No change
5	Full-scale	102
6	Full-scale	116

RSquare	0.257905
RSquare Adj	-0.11314
Root Mean Square Error	22.87455
Mean of Response	78.42286
Observations (or Sum Wgts)	7

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	2	727.38	363.69	0.69	*0.5507*
Error	4	2092.98	523.24		
Total	6	2820.40			

Result: The result ($p = 0.5507 > 0.05$) indicates that there is no sufficient evidence to reject null-hypothesis.

Solid Green Indicator

Table 50. Blinking green data at convective heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	100
2	Lab Scale	105
1	Full-scale	110
2	Full-scale	111
3	Full-scale	125
4	Full-scale	No change
5	Full-scale	No change
6	Full-scale	No change

Summary of Fit

RSquare	0.626457
RSquare Adj	0.252914
Root Mean Square Error	8.002681
Mean of Response	110.238
Observations (or Sum Wgts)	5

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	2	214.80	107.40	1.67	*0.3735*
Error	2	128.08	64.04		
Total	4	342.89			

Result: The result ($p = 0.3735 > 0.05$) indicates that there is no sufficient evidence to reject null-hypothesis.

Solid Red Indicator

Table 51. Solid red data at convective heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	108
2	Lab Scale	107
1	Full-scale	116
2	Full-scale	No change
3	Full-scale	143
4	Full-scale	No change
5	Full-scale	95
6	Full-scale	107

Summary of Fit

RSquare	0.066307
RSquare Adj	-0.55616
Root Mean Square Error	20.45819
Mean of Response	112.55
Observations (or Sum Wgts)	6

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	2	89.88	44.58	0.1065	*0.9022*
Error	3	1255.61	418.53		
Total	5	1344.78			

Result: The result ($p = 0.9022 > 0.05$) indicates that there is no sufficient evidence to reject null-hypothesis.

Blinking Red Indicator

Table 52. Blinking red data at convective heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	118
2	Lab Scale	107
1	Full-scale	120
2	Full-scale	No change
3	Full-scale	150
4	Full-scale	No change
5	Full-scale	No change
6	Full-scale	No change

Summary of Fit

RSquare	0.557796
RSquare Adj	-0.32661
Root Mean Square Error	20.90915
Mean of Response	123.7
Observations (or Sum Wgts)	4

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	2	551.88	275.73	0.63	*0.665*
Error	1	437.52	437.19		
Total	3	988.66			

Result: The result ($p = 0.665 > 0.05$) indicates that there is no sufficient evidence to reject null-hypothesis.

Case 3. Conduction Type Heat Location

Blinking Green Indicator

Table 53. Solid green data at conductive heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	83
2	Lab Scale	56
1	Full-scale	54
2	Full-scale	57
3	Full-scale	31
4	Full-scale	27
5	Full-scale	43
6	Full-scale	41

Summary of Fit

RSquare	0.674909
RSquare Adj	0.544873
Root Mean Square Error	11.95687
Mean of Response	49.0125
Observations (or Sum Wgts)	8

ANOVA Summary Table

Source	**DF**	**SS**	**MS**	***F***	***P***
Method	2	1484.04	742.31	5.19	*0.0603*
Error	5	714.83	142.96		
Total	7	2198.87			

Result: The result ($p = 0.0603 > 0.05$) indicates that there is no sufficient evidence to reject null-hypothesis.

Important Note: There is insufficient data for the warning indicators solid green, blinking red, and solid red in order to conduct ANOVA. Tables 54, 55 and 56 show the exact data available for these three warning indicators in the two test methods.

Solid Green Indicator

Table 54. Blinking green data at conductive heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	91
2	Lab Scale	No change
1	Full-scale	No change
2	Full-scale	No change
3	Full-scale	No change
4	Full-scale	No change
5	Full-scale	No change
6	Full-scale	No change

Solid Red Indicator

Table 55. Solid red data at conductive heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	123
2	Lab Scale	90
1	Full-scale	No change
2	Full-scale	No change
3	Full-scale	No change
4	Full-scale	No change
5	Full-scale	No change
6	Full-scale	43

Blinking Red Indicator

Table 56. Blinking red data at conductive heat location data in laboratory-scale and Full-scale tests

Number	Type	Temperature
1	Lab Scale	135
2	Lab Scale	102

1	Full-scale	No change
2	Full-scale	No change
3	Full-scale	No change
4	Full-scale	No change
5	Full-scale	No change
6	Full-scale	No change

<u>Summary of ANOVA results for comparison between LAB Scale test and Full-scale tests</u>

The summarized ANOVA results for each type of heat locations are listed below.

Table 57. ANOVA results summary of within device testing for radiative heat location

Ser. #	Comparison of Results	*P value*	Significance
1	Blinking Green	0.512	**
2	Solid Green	0.002	*
3	Solid Red	0.559	**
4	Blinking Red	0.188	**

Note: * = $p < 0.05$ and ** = $p > 0.05$

The results in Table 57 indicate that except for blinking green indicator, there is no significant difference in the performance of Fire-Eye device # 5 at the radiative heat condition in the Full-scale and laboratory-scale tests.

Table 58. ANOVA results summary of between device testing for convective heat location

Ser. #	Comparison of Results	*P value*	Significance
1	Blinking Green	0.550	**
2	Solid Green	0.373	**
3	Solid Red	0.902	**
4	Blinking Red	0.67	**

Note: * = $p < 0.05$ and ** = $p > 0.05$

The results in Table 58 indicate that there is no significant difference for any of the warnings indicators in the performance of Fire-Eye device # 3 and # 4 at the convective heat location in the Full-scale and laboratory-scale tests.

Table 59. ANOVA results summary of between device testing for conductive heat location

Ser. #	Comparison of Results	*P value*	Significance
1	Blinking Green	0.06*	Ns
2	Solid Green	N/A *	-
3	Solid Red	N/A	-
4	Blinking Red	N/A	-

Note 1: * = $p < 0.05$ and ** = $p > 0.05$
Note 2. N/A represents that no results were obtained due to lack of data.

The results in Table 59 indicate that there is no significant difference for the blinking green indicator for Fire-Eye device # 2 and # 6 at the conductive heat location in the Full-scale and laboratory-scale tests.

7.4 Discussion

Average and Standard Deviation

Based on the averages and standard deviations shown in Table 33, blinking green was most consistent among the four laboratory methods, with the lowest value being 39^{o}C in the Radiant Panel I test and the highest value being 83 ^{o}C in the Static Oven test. This data indicates that depending upon the type and intensity of heat, the blinking green indicator activated differently and the activation cannot be generalized for any fire scenario. The blinking green indicator also activated between varying range of temperature based on the location of the device inside the fire, especially in the Full-scale tests. The blinking red indicator was the least consistent indicator in the laboratory-scale tests with the lowest value being 40 ^{o}C in the Radiant Panel I test and 134 ^{o}C being the highest in the Static Oven test. Overall, the warning indicators were consistent in activating as per the hierarchy suggested by the manufacturer.

Interestingly, there was little or no difference among the average for each indicator between the laboratory-scale and Full-scale tests. 'Blinking green' averaged between the two methods was most consistent with 62 ^{o}C in laboratory-scale and 61 ^{o}C in Full-scale tests. The difference between the average was most for the solid green indicator in the laboratory-scale tests (89 ^{o}C) and Full-scale tests (97 ^{o}C). The difference between the averages for solid green between the laboratory-scale and the Full-scale testing can be understood by the fact that the Full-scale tests had an instant (in less than a minute) increase in temperature of more than 20-25 ^{o}C, which Fire-Eye device recognizes by indicating the solid green indicator instantly-without transiting in the blinking green phase. Therefore, the average for the solid green indicator in the Full-scale test was much higher (113 ^{o}C) than the laboratory-scale average (89 ^{o}C). The average for the solid red in the laboratory-scale and Full-scale test differed just by 9 ^{o}C, whereas the average for blinking red in the laboratory-scale and Full-scale test differed by 16 ^{o}C.

Overall, the average and standard deviation calculations suggest that the Fire-Eye devices followed a defined pattern of warnings based upon their location and the type of heat they were exposed to. As stated earlier, since there was no specific range of temperature for these four warning indicators, the results obtained by the descriptive statistics suggest that Fire-Eye device activates in a well-defined pattern, whereas the consistency of warning indicators in identical conditions remains an issue. Further study is proposed to study the aspect of consistency of the device in identical fire situations, even though it is difficult to replicate the exact fire scenarios used herein.

Analysis of Variance

Hypothesis I. The results obtained from the ANOVA generally do not support the first hypothesis that there was no difference in the performance of Fire-Eye device among the different laboratory-scale methods. The first hypothesis was divided into two parts based on the between device and within device test conditions.

The between-device condition involved two factors, *method* and *device,* for conducting the two way ANOVA. The results showed that three of the four warning indicators of the four devices performed significantly different in the four laboratory-scale-methods, thereby suggesting that method factor was significant, whereas the device factor was insignificant in the testing. The difference for the blinking green indicator was also approaching a significance level since the difference was negligible ($p = 0.71 > 0.05$). The probable reason for such a behavior is not known; therefore, further testing is suggested to obtain more consistent results.

The within-device condition involved only one factor, the *method*, for conducting one way ANOVA for device #5. The results indicated that there was a significant difference among the four test methods. Post-hoc analysis was conducted to further categorize the four methods into groups. The post-hoc analysis indicated that there were two well-defined groups for the solid red and blinking red warning indicators, with Cd, Cv and Rad2 in one group and Cd and Rad1 in other group. But the other two warning indicators could not be categorized similarly. The reason for the solid red and blinking red consistency suggests a need for further research to study this pattern.

Hypothesis II. The results obtained from the second hypothesis reiterate that, overall, there was no significant difference between the laboratory-scale testing and Full-scale testing for all three heat conditions, except for the blinking green indicator in the radiative heat condition. The reason for this is due to the built-in programming of the Fire-Eye device. When the environment temperature instantly increases more than 20°C in less than a minute, the warning hierarchy avoids the blinking green indicator altogether and transits directly into the solid green indicator status. This happened only in the radiation location for FE device #5 which was at the closest location to the fire and was therefore exposed to the most radiant heat than any other location.

The statistical data analysis indicates that overall the Fire-Eye device warns differently based on the type of fire and the location of the device. As said earlier, fire consists of three types of heat: radiation (@ 70%); convection (15-18%) and conduction (10-12%). Each kind of heat has it own characteristics of transferring energy to the objects that come in contact with it. Therefore, when the Fire-Eye device was exposed to such varying heat conditions, the warning indicators will behave differently, depending on the intensity and the type of heat. The results obtained from the statistical analysis also confirm to this theory that the devices will behave differently in different methods, rather than similarly in all methods. But further studies, especially replications of tests in identical thermal environments are needed to establish the reliability and consistency of the Fire-Eye device. The results obtained from this experiment may serve as a building block for future well-planned studies guided by a specific purpose.

8.0 COMPARISON OF THE LABORATORY-SCALE AND FULL-SCALE FIRE TESTS

8.1 Mask 1 – Radiant Heat

As said earlier, FE device #5 at mask 1 (which was tested for reproducibility at this location in the Full-scale fire tests) represented the location that was exposed to the maximum radiant heat in the three types of Full-scale fire tests. This device was located purposefully at a distance of 33 in from the radiant heat source in an effort to mirror the laboratory-scale test setting while conducting the 1.6 kW/m^2 Radiant Panel exposures. Fire-Eye device #5 at mask 1 indicated 'blinking green' between the temperatures of 62 °C-64 °C in the Natural Gas tests as the mask was at the same level as that of the Natural Gas burner. The Radiant Panel tests at 1.6 kW/m^2 for Fire-Eye device #5 triggered the 'blinking green' indicators between the temperatures of 55 ^{o}C-61 ^{o}C. The 'solid green' indicators in the Natural Gas tests activated between the temperatures of 105 ^{o}C-108 ^{o}C, whereas the 'solid green' indicators in the Radiant Panel tests activated between the temperatures of 71 ^{o}C-87 ^{o}C. The 'solid red' indicators in the Natural Gas tests activated between the temperatures of 101 ^{o}C-114 ^{o}C, whereas the 'solid red' indicators in the Radiant Panel test activated between the temperatures of 72 ^{o}C-87 ^{o}C. Therefore, it is interesting to note that the temperature at which the 'blinking green' started was within +/- 5 ^{o}C in both test methods, but the 'solid green' and 'solid red' indicators were not. These results may be due to the fact that the Full-scale tests were conducted in a *dynamic* environment wherein many factors could have influenced the ambient temperature, whereas the Radiant Panel tests were conducted in a stable, controlled laboratory environment at room temperature.

Comparison of the reproducible performance of Fire-Eye device #5 in the Heptane fire tests with the Radiant Panel tests were also interesting. In the Heptane fire tests, Fire-Eye device #5 activated its 'blinking green' indicator between the temperatures of 106 ^{o}C-116 ^{o}C, whereas the Radiant Panel test activated the blinking green indicator in the range of 78 ^{o}C-82 ^{o}C at a flux level of 4.0 kW/m^2. The 'solid green' indicators activated at a temperature range of 106 ^{o}C-116 ^{o}C in the Heptane test, whereas they activated at a temperature range of 101 ^{o}C-105 ^{o}C in the Radiant Panel test at a flux level of 4.0 kW/m^2. Further, the 'solid red' indicator activated at a temperature range of 111 ^{o}C-112 ^{o}C in the Heptane test, whereas the 'solid red' indicator activated at a temperature range of 105 ^{o}C-112 ^{o}C at a flux level of 4.0kw/m^2. Therefore, the activation of the 'solid green' and 'solid red' indicators in both test conditions were similar.

In the living room fire tests, the temperatures increased drastically, leading to intense fire dynamics in the ISO room. Therefore, Fire-Eye device #5 did not transition through the regular order of status indicators, and instead immediately displayed the 'solid red' (within 60 to 90 seconds from the start of the test). That is, the 'blinking green' and 'solid green' indicators were bypassed in the living room tests, indicating extremely hazardous conditions that developed rapidly. Such conditions were not generated at any point during the Radiant Panel tests, but Fire-Eye device #5 *did* present its 'solid red' indicator for a few seconds soon after the device was exposed to an intense flux of 4.0 kw/m2 in the first 60-90 seconds of the test. The 'solid red' indicator in the Radiant Panel tests was momentarily noted to activate, and the device changed its indicators again to 'blinking green' and then transitioned through its hierarchy of warning indicators, suggesting that the conditions were hot, but were not as hazardous as compared to the living room fire tests.

8.2 Mask 2 – Convective Heat

Mask 2 was installed with Fire-Eye devices #3 and #4 in the Full-scale fire tests, and was located at a height of 5 feet from the floor of the ISO room in an effort to expose the Fire-Eye devices to the hot layer of gases formed at that higher elevation. Fire-Eye device #3 at mask 2 indicated 'blinking green' at 66 ^{o} C in Natural Gas test #1, and Fire-Eye device #4 indicated 'blinking green' in the range of 66 ^{o} C -73 ^{o} C in the Natural Gas and Heptane tests. Fire-Eye devices #3 and #4, however, indicated 'blinking green' at 60 ^{o} C and 65 ^{o} C, respectively, in the FEE test with convective heat flow. Fire-Eye device #3 could only be tested in Natural Gas Test #1 because it later malfunctioned in Heptane test #2. Fire-Eye device #3 indicated 'solid green' at 110 ^{o} C in the NG test and Fire-Eye device #4 indicated 'solid green' in the range of 111 ^{o} C-124 ^{o} C in the NG and Heptane tests, whereas Fire-Eye device #3 indicated 'solid green' at 100 ^{o} C and Fire-Eye device #4 indicated 'solid green' at 104 ^{o} C in the FEE tests. FE device #3 indicated 'solid red' at 116 ^{o} C in the NG tests, and Fire-Eye device #4 indicated 'solid red' at 143 ^{o} C in the Heptane tests, whereas Fire-Eye devices #3 and #4 indicated 'solid red' at 107 ^{o} C and 106 ^{o} C, respectively, in the FEE tests. Fire-Eye device #3 did not display the 'solid red' and 'blinking red' indicators in Natural Gas test #2, likely because of insufficient heat with which to trigger the indicators.

Fire-Eye device #4 was exposed to both of the living room tests, and indicated 'blinking green' at 102 ^{o} C in test 1 and 115 ^{o} C in test 2. Fire-Eye device #4 directly activated its 'solid red' indicators due to the rapid increase in temperature to 95 ^{o} C in test 1 and 107 ^{o} C in test 2. The other warning indicators did not activate due to the hazardous conditions and the test was halted in time to avoid any structural damage to the ISO room.

8.3 Mask 3 - Conductive Heat

Mask 3 was installed with Fire-Eye devices #2 and #6 in the Full-scale fire tests. These devices were located at a height of 3 feet from the floor of ISO room in order to expose them to the conductive-type of heat located at a distance from the fire source. Fire-Eye devices #2 and #6 indicated ‘blinking green’ at temperatures in the range of 27 ^{o} C- 54 ^{o} C and 30 ^{o} C -57 ^{o} C, respectively, in the Full-scale fire tests, whereas they activated their ‘blinking green’ indicators at 83 ^{o} C and 55 ^{o} C, respectively, in the Static Oven tests. In the Natural Gas and Heptane tests, Fire-Eye devices #2 and #6 did not continue through their hierarchy of indicators after presenting ‘blinking green’ due to insufficient heat transfer to mask 3’s location in the ISO room.

In living room test #2, Fire-Eye device #6 indicated ‘solid red’ within a few seconds of indicating ‘blinking green’ due to the extreme hot conditions. FE #6 indicated ‘solid red’ at a temperature of 44 ^{o} C due to the effect of radiative heat that was transferred from the heated walls and from the hot upper layer of gases that existed in the ISO room.

9.0 COMPARISON OF FIRE-EYE DEVICE IN FIRE USING DIFFERENT FUELS

The Fire-Eye devices performed consistently for all three types of fuels used in the Full-scale fire tests. The performance of the devices was based on the *heat* generated in each type of test rather than *the type of fuel* because of the nature of the heat sensors (i.e., they detect heat, no matter what is the source). Figures 65 through Figure 76 show the temperature profile in the ISO room at the two thermocouple trees. The figures indicate that the temperatures at higher elevations in the room reached a level of 400^{o} C -450 ^{o} C during the living room tests, whereas these temperatures were lowest in the Natural Gas tests (i.e., 200 ^{o} C-250 ^{o} C), with the Heptane test in between these two ranges. The heat flux that was generated in the six tests was in the range of 1 kW/m^{2} to 10 kW/m^{2}, as shown in Figures 77 through Figure 82. The heat flux of 6.4 kW/m^{2} causes the human skin to experience pain with a 1 second exposure and blisters the skin in 18 seconds with second-degree burn injury (NFPA, 1971). The heat flux of 10.4 kW/m^{2} , however, causes the human skin to experience pain with a 3 second exposure and blisters the skin in 9 seconds with second-degree burn injury. A heat flux of 12.5 kW/m^{2} causes wood volatiles to ignite with extended exposure and piloted ignition (NFPA, 1971). The earlier specified values of heat flux renders comparison of the heat flux values attained in the Full-scale fire tests relatively easy.

In the two Full-scale living room tests, the couch and the side table did not burn in the same manner. In the first living room test, the test-terminating criteria was exercised stringently, whereas the second living room test was allowed to continue further in order to assess the performance of the devices in extremely hot conditions, when the risk of the mask and the Fire-Eye device being destroyed was greater.

10.0 QUALITATIVE EVALUATION OF FIRE-EYE DEVICE BASED ON HUMAN FACTORS PRINCIPLES

Aspect I. Warnings in the Fire-Eye Device

Based on the literature review related to warnings in section 1.3.1, the warnings used in the Fire-Eye device were designed effectively to convey the nature of the hazard to the trained firefighter, including the consequences of the warnings if they are not heeded. Based on the video recording of the performance of warnings in different climatic chamber tests and Full-scale tests, the researcher suggests that the warnings have been integrated well with the user interface and the protective gear. The manufacturer (who is also a firefighter) has taken into account the user's reaction to the warnings as suggested by Maltz and Meyer (2001). This has led the manufacturer to design warnings indicators that are well understood by the user (firefighter) community. While observing the taped performance of devices, the numbers of nonvalid warnings were very low, thereby agreeing with Sorkin (1988), who suggested that firefighters will not have a chance to neglect or an option of ceasing to respond to valid warnings. Moreover, the dangerous conditions in which firefighters work will lead to a quick response and firefighters cannot afford to neglect the warnings.

According to Maltz and Meyer (2001), the use of warnings in attentionally-demanding tasks may create an impression that the warning relieves the user of part of responsibility of hazard detection, allowing the user to take greater risks. This is exactly the situation which is of intense concern whether or not firefighters decide to completely rely on warnings from the device and decide to take more risks without taking responsibility of hazard detection in the fire environment. Does this device impart reliability to such an extent that firefighters can avoid detecting hazards and take greater risk in their primary task? Certainly, intense and extensive testing of the software as well as the hardware will be required in order to develop the highest level of reliability.

As per Laughery (2006), design parameters that are most significant to warning success include format factors such as size, location, color /context, signal words and use of pictorials. The Fire-Eye device warnings are certainly succinct in size and the content changes dynamically based on the ambient temperature, and avoiding the factor of habituation which arises due to a static warning. The rest of the factors described by Laughery (2006) are described in the appropriate sections of this evaluation. Explicitness is also a key aspect of warnings, which is defined by Laughery and Smith (2006) as information that is specific, detailed, clearly stated, and leaving little or nothing implied. The information conveyed by the Fire-Eye device is certainly explicit to indicate the environmental characteristics to the user. It is also important to note that Wogalter (1995) has shown that greater familiarity leads to lower levels of compliance with warnings. This issue could not be confirmed in case of the Fire-Eye device due to the nature of work environment and as such needs further study to test such a hypothesis. It will also be important to test the importance of stress and time on the warning compliance decisions of firefighters.

Aspect II. Human Vision and Use of Color for Dynamic Warnings

As stated earlier by Pokorny et al., (1979) 8% of males and 0.5% of females in the population have congenital red-green color blindness. The Fire-Eye device uses red- and green-colored warning indicators to warn users. Usually, the firefighting profession is dominated by males; therefore, it is important that the firefighter population should be tested for their vision deficiency and only the red-green color normal population should be permitted to use the Fire-Eye device. Therefore, it is important to study the physiological parameters of the eyes of firefighters which recognize the warning signal and color. The researcher proposes further testing to evaluate the performance of color normal and color deficient firefighter population in order to evaluate the visibility and effectiveness of warnings.

There has been extensive research in the use of color in the warnings. The Fire-Eye device generates discrete output that is displayed as color coding of lights. Kahneman and Treisman (1984) have shown that the joint use of color and size in a single object can facilitate parallel processing of two variables at a perceptual level that will help both focused attention and integration. It has been shown by Derefeldt (1995) that use of color is more effective in dynamic displays than in static displays and color is of major importance in tasks that involve visual synthesis using the saccadic movements of the eye in a dynamic situation. It has also been shown that use of color enhances decision making as well as performance, especially in complex situation requiring intense information processing (Post, 1992; Post, 1997). Therefore, the use of color indicators in the Fire-Eye device is highly desirable given the conditions in which the device is proposed to be used.

Previous human factors research has indicated that different colors have different hazard connotations (Wogalter et al., 1998; Smith-Jackson and Wogalter, 2000). The Fire-Eye manufacturer has used the color red to indicate the emergency environment and green as a permissible environment. Typically, red color is perceived to be more hazardous and urgent than others, whereas green color is perceived relatively safe as compared to red. Therefore, the manufacturer has made an appropriate choice of color for warning indicators.

Aspect III. Fire-Eye device location

The location of a warning is an important aspect in warning design in dynamic scenarios. Firefighters and emergency responders are covered with protective gear; therefore, they can only attend to a visual warning that is directly in their line of sight. The Fire-Eye device is exactly located in the line of sight of firefighters; therefore, no extra effort is required to search for warnings. It is integrated in the form of binocular see-through HUD which is more relaxing to wear and has lower obtrusiveness, as per Melzer and Moffitt (1997).

The object attributes such as size, edge definition, brightness and background simplicity in the Fire-Eye provides adequate conspicuity to the warning indicators. These parameters have been observed by the researcher based on the observation of the device performance during the laboratory-scale tests as well as by viewing the taped performance of warning indicators.

Aspect IV. Situational Awareness

Fire-Eye effectively conveys the situational awareness to the firefighters but the researcher identifies a training requirement for the prospective users of the device. The users need to be trained to identify multiple changing intensity indicators of green as well as red color.

Since the device differentiates the warning indicators as 25% blinking green, 50% blinking green and 75% blinking green which will certainly need familiarization and practice to follow. In order to be expert in using such a device, firefighters will have to continue to practice and gain experience in varying work conditions.

Aspect V. Display Location and Display Characteristics.

Fire-Eye is mounted on the visor of the firefighter and it is located directly in the line of sight of the user. Display integration of the Fire-Eye device has been achieved by combining display components into a single object. According to Wickens and Carswell (1995), such displays may enhance performance when processing multiple properties of a single object required in determining whether an object is a threat based upon its location and identity.

Conclusions based on Qualitative Evaluation

Finally, the Fire-Eye device satisfies a majority requirements of a HMD for firefighters. It is easy to handle, simple to use and adjustable within few seconds. It is stable in front of the eyes during the firefighting operation. The integration with the visor is sufficiently rugged, safe, and it is resistant to heat and water, based on the observations from the laboratory-scale and Full-scale tests. In terms of price the device has been priced in the range of $450-500 per device, backed by a replacement plan which is probably a little on the expensive side. The device is usable with and without a breathing mask, with and without chemical suit, and only with a helmet or visor manufactured by prominent mask manufacturers such as Scott™. Therefore, the device satisfies all of the criterion of a HMD for firefighters.

11.0 LIMITATIONS

It was impossible to test human users of the Fire-Eye device in the Full-scale fire tests because of the high risk of potential injury involved. The effect of the human breathing inside of the mask could not be taken into account since an artificial respirator was not available nor was it feasible to conduct the testing with an artificial respirator.

Only three types of fuels were tested in this study, which would not be sufficient to generalize the results for all types of fuels that can cause a fire. Even though the Full-scale testing was conducted in an ISO room, the results cannot be generalized for certain fire scenarios such as that in a container fire, a ship fire, or a forest fire. The results can be generalized only for an enclosed space fire of the type studied herein. Multiple masks should have been used and placed at similar locations to test several of the devices at similar locations, whereas in this study, due to device and space limitations only one device was tested at one location for a particular test.

Finally, the author and the NIST laboratory technicians made every effort to maintain the experimental settings as well as the test conditions constant, but there is always some probability of human error in such testing which cannot be ignored.

12.0 RECAPITULATION AND GENERAL CONCLUSIONS

12.1 Laboratory-scale tests

As noted earlier, the laboratory-scale fire experiments were conducted at the National Institute of Standards and Technology's Building Fire Research Laboratory during December 13, 2006 through December 23, 2005. A total of seven Static Oven experiments and seven FEE experiments were conducted. Two sets of seven tests were conducted at two different heat flux levels using the Radiant Panel (i.e., fourteen total experiments). The experiments were conducted to validate the performance of the Fire-Eye device designed for fire fighters in conductive-, convective-, and radiation-type heat transfer conditions. The results from these laboratory-scale experiments produced warning indicators that actuated across a wide range of temperatures, and the extensive digital video footage that was captured of the Fire-Eye device's performance in these varying heat conditions provided evidence to this effect. The range of temperatures cataloged from these experiments, of both a repeatable and a reproducible nature, suggest that there are issues related to both types of criteria. That is, one would expect the same device to present data that was consistent across trials (i.e., reproducible), and one would further expect multiple devices comprised of identical components to present data that was consistent between them (i.e., repeatable). Among the various tests employed, the Fire-Eye device exhibited some inconsistencies in performance that give rise to questioning its reproducibility and/or repeatability under certain conditions.

12.2 Full-scale fire tests

The large-scale fire experiments were conducted at NIST's Full-scale fire facility during January 23, 2006 through January 24, 2006. A total of six experiments were completed over this time period, and were conducted to assist in the validation of the Fire-Eye device. The results from these pre-flashover fire experiments are an extensive set of data with a wide variety of measurements collected in a per-second basis, the smallest SI unit of time. All of the ISO room instrumentation, along with facepiece and the Fire-Eye device instrumentation, are represented in the data along with the three different fuels used in the six experiments. The data therefore have a considerable number of uses based on the significance of the environment in question. None of the Fire-Eye devices melted or deformed in the Full-scale tests, wherein the heat flux reached a maximum level of 10kW/m^2 for a few seconds. The devices also functioned consistently in the different kinds of environments generated by burning three different types of fuels. The results from the Full-scale testing suggest that the Fire-Eye device can withstand flame-resistant tests and can perform in highly convective and radiative heat environments, but the temperatures at which the warning indicators are triggered also vary considerably according to the characteristics of the environment in which they are tested. Similarly, there are some inconsistencies in the warning indicators subject to the exposure in similar environments. It was observed that the repeatability and reproducibility of the Fire-Eye device were questionable in the Full-scale testing as compared to the laboratory-scale experiments, likely due to the difference between the controlled and uncontrolled environments. The fire dynamics in an open space (i.e., ISO burn room) are very different and unpredictable when compared to fire dynamics in an enclosed environment or small space (i.e., radiant panel, static oven, FEE).

13.0 FUTURE RESEARCH

Global Discussion and Conclusions:

The results in the case study outline various design, manufacturing and compliance procedures followed by the SM and CM. As stated earlier, the results and findings of this case study are applicable to the overall PPE manufacturing industry. The SM may be considered to represent a group of small manufacturers who manufacture one or more PPE devices solely based on innovative and need-based entrepreneurship. The CM manufacturer may be considered to represent a broad group of PPE manufacturers who manufacturer a range of PPE devices. Such large manufacturers usually have a big, hierarchical and well-defined organization of employees and stream-lined design, manufacturing, and compliance processes. The large manufacturers are also well equipped financially and legally to provide any kind of support for their products as compared to small manufacturers.

In order to stay on top in their area of business, the large manufacturers are well established and motivated to adapt to any changes in the design, manufacturing, and compliance procedures based on their experience and overall capabilities. However, large manufacturers may also take longer to adapt to new practices due to the hierarchical nature of the organization and the length of time required to educate the employees may be long as well. On the other hand, small manufacturers have fewer employees to educate and a small organization, but they may lack financial and technical resources to stay on top in their business. Therefore, the dilemma still continues whether an innovator can also be a good manufacturer or he/she should sell the innovation to a large well-established manufacturer who is well capable of handling manufacturing and liability issues.

The Fire-Eye device is an excellent example of such innovators' dilemma since the product is being manufactured in batches in a garage of an electronic manufacturer and compliance procedures that are being followed are less effective as compared to the CM. The Fire-Eye manufacturer lacks a well-defined technical approach for certain procedures such as compliance and manufacturing, which may be due to lack of resources or technical capability. The SM is also not well equipped to handle the legal issues that may arise due to a malfunction or a failure of the Fire-Eye device in actual emergency situation. This raises questions about the reliability of the device as well as the liability capability of such a small organization.

Future research should involve more manufacturers in order to achieve a broad understanding of the processes and to compare the results across a number of manufacturers. In order to increase the reliability and validity of case study research, an effort can also be made to actively persuade the manufacturers to allow them to work in their manufacturing facilities in order to actually understand the various processes followed by them.

	Simple PPES	Complex PPES
Large Manufacturer	Future Research	Future Research
Small Manufacturer	Actual Evaluation	Future Research

The experimental part of the dissertation indicated that warnings could be evaluated effectively using two different simulated, controlled and uncontrolled environments for a PPE device. As shown in the adjoining figure, the Fire-Eye device is categorized as a simple device, manufactured by a small manufacturer, and was actually tested in the experimental set-up. The other boxes in the adjoining figure indicate a scope for future research for the simple and complex PPE devices manufactured by large manufacturer and a complex device manufactured by simple manufacturer. The results obtained from these proposed research initiatives will offer a chance to compare the performance of different PPE devices in similar environments. Such an effort may also help to establish the experimental procedure with which to evaluate products with warnings, as a standard human factors evaluation method, which is being used by other engineering disciplines.

The laboratory-scale experiments and the Full-scale fire tests were conducted in a relatively small period of time (24 days), resulting in a limited number of repetitions. An effort would be made to increase the number of repetitions to test the device more systematically. Also, an effort can be made to effectively map the environment in the ISO room by attaching more thermocouple trees at different locations. In this case, there were only two TC trees that were used to map the thermal environment in the room.

Finally, there is no standard specified by either the NFPA or NIOSH to test such a stand-alone PASS device as the Fire-Eye. Therefore, such comprehensive test procedures involving all types of heat transfer mechanisms, as outlined in this research, can be used to formulate a standard document incorporating procedures with which to test such devices.

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APPENDIX A – FIRE-EYE SPECIFICATIONS

Fire-Eye Firefighter's Temperature Encoder Specifications
Model FE-2000
U. S. Patents 6,118,382 and 6,417,774
Other Patents Pending

General Product Description: Light Indicating Thermometer. Fire-Eye consists of a Sensor/Display piece fitted at the top of the mask faceplate and an electronic Clip-Box worn clipped at the back of the mask webbing, under the Nomex(tm) hood.

Design Application: For use with Scott(tm) SCBA facemasks when fighting structure fires.

Temperature Sense Point: Near the center of the mask faceplate.

Temperature Sensing Element: Thin-film Platinum RTD on thin ceramic chip.

Temperature Sensing Rate: The sensor element is read four times per second when temperature conditions are being displayed.

Indicator Visibility: Green and Red indicator lights are visible through the facemask, centered just above the line of sight.

Indicated Temperature Conditions: The temperature conditions indicated depend on the environmental temperature, on the temperature of the surface of your protective gear and on the time spent at a particular temperature.

--- **No Lights (below 125° F):**
    Proceed normally. Victims can survive. Act according to your Department's training and policies.

--- **Green is Blinking and is mostly off:**
    You are in a warm environment and your fire protective gear should be safe. Unprotected victims can survive only a few minutes. Act according to your Department's training and policies.

--- **Green is Blinking and is 50% on:**
    The temperature is warmer and your fire protective gear should be safe. It is less likely that unprotected victims could survive. Act according to your Department's training and policies.

--- **Green is Blinking and is mostly on:**
    The temperature is very warm. You are depending on the thermal barrier of your fire protective clothing. Cool the environment and act according to your Department's training and policies.

--- **Solid Green:**
    The temperature is hot but your protective gear is safe for a few more minutes. Steam injury can occur. Unprotected victims cannot survive. Cool the area and act according to your Department's training and policies.

--- **Red (in general):**

Your gear is near its protection limit. Get lower. Cool the area immediately or move. Flashover is possible. Act according to your Department's training and policies.

--- **Red is blinking:**

The environment is hot but is cooling. Your gear is near its protective limit. Cool the area immediately or seek a cooler location. Act according to your Department's training and policies.

--- **Red is solid:**

The environment is hot and is still heating. The integrity of your protective gear is at risk. You are in serious jeopardy. Evacuate immediately to a cooler location. Flashover is likely. Act according to your Department's training and policies.

--- **Early Red:**

If the temperature increases very rapidly, Fire-Eye will display RED immediately without displaying all stages of GREEN. This warns quickly of extreme conditions. RED will be displayed until the rate of temperature increase slows.

--- **Heat-soak Red:**

If the temperature at the surface of your protective gear has been above 148F for more than 15 minutes, Fire-Eye will display RED. This condition indicates that the protective capacity of your gear is likely nearing exhaustion. RED will blink if the temperature is decreasing and will be solid if the temperature is increasing. RED will continue to be displayed until the temperature cools below 125F.

Temperature Accuracy: +/- 5^{o} Fahrenheit.

Temperature Response Rate: 2^{o} Fahrenheit per second when the temperature difference between the Fire-Eye Sensor and the environment is 20^{o} Fahrenheit. The higher the differential, the faster the response.

Battery Required: Two size AAA Alkaline cells.

Efficient Idle Mode: When the temperature is below 125^{o} F, Fire-Eye reads the thermal sensor once every eight seconds to prolong battery life.

Expected Battery Life: 4 Months

Recommended Battery Replacement Interval: 2 Months

Equipment Check Features:

--- Test Button for Electronics, Battery, and Lights

--- Continuously monitors battery voltage

--- Continuously monitors the connections to the temperature sensing element for open-circuit and short-circuit failures

--- Battery-low or sensor failure is indicated by blinking both lights continually or by both lights off

--- Built-in absolute calibration test for 0^{o} Centigrade standard

Absolute Calibration Check: Prepare a mixture of finely-crushed ice and water in an insulated container such as an 12-ounce foam cup. The water must be clean and must not contain any dissolved salts or sugars (i.e. no soft drinks). Immerse the Sensor/Display part of the Fire-Eye Temperature encoder in the ice/water mixture with the tip of the sensor near the center of the ice. Wait 5 minutes for the temperature to stabilize. Press and hold the test button. Both lights will blink 3 times and then the green light will blink if the Fire-Eye unit is accurately calibrated. The green light will continue to blink as long as the button is held and the temperature of the sensor remains between 30 and 34^{o} Fahrenheit.

Sensor/Display Operating Environment: Temperature 0 to 400^{o} Fahrenheit. Waterproof.

Clip-Box Operating Environment: Temperature 0 to 160^{o} Fahrenheit. Waterproof.

Temperature Endurance:
--- Black Plastic Parts: Reduced Strength at 450^{o}, Melts at 650^{o} Fahrenheit.
--- Clear Plastic Parts: Reduced Strength at 350^{o}, Melts at 680^{o} Fahrenheit.
--- Teflon(tm) Cable: 20,000 Hour Service Life at 400^{o} Fahrenheit.
Plastic Components:
--- Black Plastic Parts: GE ULTEM 1000, UL File Number E121562; UL-94 rated V-O for 0.016 inch thickness; UL-94 rated V-5A for 0.075 inch thickness; CSA File Number LS88480.
--- Clear Plastic Parts: GE LEXAN 4701R, UL File Number E121562; UL-94 rating HB for 0.058 inch thickness.

The calculated accuracy of the overall A/D and resistance comparison process yields a result of approximately 4^{o} Fahrenheit, including reference resistor and sensor tolerances. To be conservative, the Fire-Eye device's overall accuracy is advertised as +/- 5^{o} Fahrenheit.

The reference resistor is a precision metal-film resistor with a 0.1% accuracy specification with a very low temperature coefficient and is designed for long-term stability. (Panasonic: ERA-3YEBxxx, 1.5K Ohms)

The Platinum RTD is a thin-film / ceramic device (Minco S247PFY, 1.0K Ohms at 0 Centigrade). Its specifications are:

- Material: Platinum film on a thin aluminum oxide substrate with a fused-glass cover.
- Tolerance: 0.12% at 0 Centigrade. (About +/- 0.8^{o} F)
- Sensitivity: RTC = 0.00385 Ohms/Ohm/degree C. (About 0.2% per degree F)
- Repeatability: +/- 0.1^{o} C or better.
- Stability: Drift less than 0.1^{o} C per year
- Application temperature range: -70 to +600^{o} Centigrade.
- Vibration: Withstands 20 Gs minimum at 10 to 2000 Hz.
- Shock: Withstands 100 Gs minimum sine wave shock for 8 milliseconds.

Fire-Eye Software Design
Fire-Eye software for the Atmel AVR 4434 processor is executed from on-chip Flash Program

ROM. There is no operating system. The software is written as a continuous loop and uses on-chip timers to control the rate of cycling the loop. Most of the processor's time is spend in "sleep" mode to conserve power. Each cycle through the software's "main:" operational loop involves a sleep period, the length of which is dependent on conditions measured by the Fire-Eye's temperature sensor.

Startup…

When power is applied to the processor, it automatically begins execution at Program ROM address zero, the RESET interrupt location. The RESET location contains a jump instruction which begins executing instructions at an location called "RESET:". The RESET routine consists of code to initialize all program variables and processor status. At the end of the RESET code is a six-instruction "main:" program loop. Program execution just "falls" into the "main:" loop at the end of the RESET routine.

Main program loop…

The "main:" program loop performs three operations by calling subroutines. The first two instructions in the "main:" loop check the test button and, optionally, call a FLASH_LIGHTS:" subroutine. The subroutine functions to blink both Fire-Eye display lights three times, and is only called if the test button on the Fire-Eye has been pressed.
The second subroutine, "AD_CONVERT:", is unconditionally called by the "main:" program loop and does the great majority of the work each time the "main:" loop is executed.
The third subroutine, "POWER_SAVE:", is unconditionally called by the "main:" program loop and puts the processor into sleep mode for a certain time, specified by the "AD_CONVERT" routine.

After the processor wakes up in the "POWER_SAVE:" routine, control is returned to the "main:" program loop. A jump command at the end of the "main:" program loop causes execution to begin again at "main:".

AD_CONVERT subroutine…

> The "AD_CONVERT:" subroutine first makes sure that power is turned on to the temperature sensor and then sets up the A/D converter to measure the sensor. The processor is put into sleep mode for a fixed amount of time while the A/D conversion process happens. This mode of doing the A/D conversion while the processor sleeps is a feature of the AVR processor and contributes greatly to the precision of the conversion by eliminating electrical noise from digital processor execution. During the conversion, most interrupts are disabled so that the conversion process can be completed without disturbance.
>
> The A/D conversion hardware automatically sets the result of the conversion into two specific register bytes.

After the processor wakes up from the conversion process, a "HOW_HOT:" subroutine is called which compares the current temperature measured by the conversion process to programmed set points. The "HOW_HOT:" routine also takes temperature statistics and adjusts the GREEN/RED threshold appropriately. It finally sets a register variable to determine the status of the display lights and sets another register variable to determine the length of the next processor sleep cycle.

After the "HOW_HOT:" routine returns control to the "AD_CONVERT:" routine, most of the interrupts are enabled and the "DISPLAY:" subroutine is called.

The "DISPLAY:" routine interprets the "lights" register variable and controls the RED and GREEN lights appropriately.

After the "DISPLAY:" routine returns control to the "HOW_HOT:" routine, the status of the test button switch is dealt with and the test button interrupt is enabled. At the end of the "HOW_HOT:" subroutine, execution resumes in the "main:" program loop.

POWER_SAVE subroutine…

The "POWER_SAVE:" routine sets up an internal processor timer to control processor sleep time according to the "tmr2_scale" variable set by the "HOW_HOT:" subroutine. It then puts the processor into sleep mode. After the internal timer wakes up the processor, sleep mode is disabled and the subroutine ends.

APPENDIX B – Fire Test Safety Check List

Large Fire Facility
Building and Fire Research Laboratory

Project Name	Cost Center

Experimental Test Area

9 m x 12 m Hood	☐	Furniture Calorimeter	☐	50 kW Hood	☐
6 m x 6 m Hood	☐	Storage	☐	Other	

Test Description

Materials to be Tested: ________________________ Number of Tests:
________________________ Number of Tests:
________________________ Number of Tests:

Estimated Peak Heat Release Rate: ___________ kW Test Duration:
minutes

Ignition Method:

Narrative Description of Test Operation

Each test series will have a Test Supervisor (Project Personnel) and a Test Safety Officer (LFF Personnel). The Test Supervisor has ultimate responsibility for all aspects of safety surrounding the test, but may be assisted by a Test Safety Officer. Both of these individuals will have independent authority to shut down the experiment if hazardous conditions are encountered and to limit access to any portion of the test area.

Test Supervisor: ________________________________ Alternate:

-

Minimum Number of *Project Personnel* required to conduct the test:

Test Safety Officer: _____________________________ Alternate:
Minimum Number of *LFF Personnel* required to conduct the test:

In this document, we have provided an accurate and complete description of the foreseeable risks associated with this project and the measures we have taken to deal with them. For each major risk identified in this checklist, we have provided adequate measures to maintain safety or indicated why we believe that risk is irrelevant to this particular project. We know of no foreseeable hazards associated with this project other than those described in this document. We will ensure that the safety conditions reflected in this document remain in force at all times during the course of the experiments.

_________________________________ ____________

_________________________________ ____________

Test Supervisor Date Test Safety Officer Date

_________________________________ ____________

_________________________________ ____________

Large Fire Facility Supervisor Date **Fire Metrology Group Leader** Date

_______________________________________ ________________

Fire Research Division Chief Date

Instructions: Answer each question by checking the appropriate box. If a question is not applicable, check "N/A". "Unknown" is not an acceptable answer to any question.			
I. Fire Test Environment and Fire Control Procedures	**Yes**	**No**	**N/A**
1. Is **flameover** or **flashover** expected?			
2. Can the fire be **extinguished** at any time it is deemed necessary?			
If yes: (a) Describe provisions made, including method of extinguishment.			
3. Is remotely controlled extinguishment equipment required?			
(a) Has it been installed?			
(b) Is the activating device in a safe location?			
4. Is an **explosion** possible? (e.g. gas storage tanks or confined flammable mixtures)			

If yes: (a) Describe the source of the possible explosion. (b) Describe the methods that will be used to prevent an explosion and the methods that would be used to relieve an explosion if one occurred.			
5. Are there any **combustible materials** (e.g. gasoline or other liquid fuels) stored in or near the test environment?			
If yes: (a) Are all such materials stored in approved safety containers?			
(b) Are all such materials sufficiently distant from the fire to prevent accidental involvement?			

II. Exposure of Personnel to Hazardous Conditions	**Yes**	**No**	**N/A**
1. (a) Will any personnel need to be **in a burn compartment**?			
(b) Will any personnel need to be **exposed to fire, heat or products of combustion**?			
If yes to (a) or (b):			
(c) Will they have protective clothing and helmet with face shield?			
(d) Will they have self-contained breathing apparatus?			
(e) Will they have a back-up individual fully protected for rescue?			
(f) Justify need for exposure:			
2. Have provisions been made to protect and rescue investigators in the **event of collapse** while exposed to a fire environment?			
If yes: (a) Describe provisions.			
3. Are there any **other situations** that might expose a person to extraordinary hazardous conditions?			
If yes: (a) Describe situations.			

(b) Describe precautions to protect personnel in these situations.

III. Exposure of Personnel to Toxic Substances	**Yes**	**No**	**N/A**
1. Do you have **all necessary published information** (including, but not necessarily limited to, MSDS, report, label or container warning) on the toxicity of the materials to be tested?			
2. Have you determined the **types of toxic combustion products** to be expected when the materials are burned?			
3. Is some level of smoke or toxic gas **exposure unavoidable** for any test site personnel?			
If yes:			
(a) Is positive pressure air breathing apparatus provided for exposed personnel?			
(b) Have additional measures been taken to protect exposed personnel? If yes, describe them.			
4. Is it possible that **specialized medical assistance** (e.g., antidote) will be required if someone is exposed to a particular toxic gas or chemical associated with the test?			
If yes: (a) What condition(s) would require such assistance?			
(b) What type of assistance is provided to address these conditions?			
5. Does the test require the use of a **draft hood** for removing products of combustion?			

IV. Provisions for Injuries and First Aid	**Yes**	**No**	**N/A**
1. Do all test site personnel know that **injuries must be reported** to the medical unit as soon as possible?			

2. Have provisions been made for **handling emergency situation**, such as those requiring first aid? If yes, describe them.			
V. Familiarity with General Safety Procedures	**Yes**	**No**	**N/A**
1. Do all test site personnel **know who the Test Supervisor and Test Safety Officer are**?			
2. Have all test site personnel been **briefed on job responsibilities, possible hazards and safety procedures**?			
3. Have all test site personnel been **briefed on their responsibilities to use head, eye, and foot protection**?			
4. Has the Test Safety Officer established **rules for controlling and protecting visitors**? If yes: (a) What are the rules?			
5. Has **head and eye protection equipment** been provided for the protection of **test observers and visitors**?			

VI. Other/Miscellaneous	**Yes**	**No**	**N/A**
1. Do you have any **unusual safety problems** worthy of discussion with the NIST Safety Officer and/or the NIST Medical Officer If yes: (a) What are the unusual safety problems?			
(b) Have you discussed them with the appropriate NIST personnel?			
(c) Have special procedures and arrangements been made to address these problems? If yes: (a) Describe them.			

2. Are there any **other foreseeable safety problems**?			

If yes: (a) What are the problems?

(b) What procedures have been set up to deal with them?

APPENDIX C – Fire-Eye Full Scale Fire Test Checklist

Test: **Date:** **Time:**

Temp: C	**Humidity: %**
Key Test Variables: Temperatures in front and rear of fire-eye device and Facepiece, ambient temperature, heat flux at location of each mask.	
Test Objectives: To test the performance of fire-eye device in three different types of fuel and at three different locations for different heat exposure.	
Compare w/ tests: Radiant Panel, Convective Heat Flow and static oven as well as living room fire scenario.	
Figure: Please refer page 3 and page 4	
Hood Used:	Flow: kscfm
NOTES:	

PRETEST CHECKLIST

	THERMOCOUPLES
	FUEL SYSTEM
	HEAT FLUXES – remove caps
	LOAD CELL
	VIDEO
	PICTURES
	CHANNEL LIST
	BULLET CAMERAS

☐ **Ready to Ignite**

- **Video Start**
- **Ignite Pilot**
- **Record Test Start (fire ignition) Time:**
- **Start bullet camera recording**

☐ **TEST RUNNING CHECKLIST**

Time	Note

TO DO PRIOR TO THIS TEST		TO DO PRIOR TO NEXT TEST	
	Trouble shoot channels		
	Details of fuel and flow rate		
	Photographic footage pretest		

☐ **CHANNEL LIST**

☐ **PHOTOGRAPHS**

____ Specific test parameter(s) (ISO room, pan, nozzles, and location of masks)

- ISO room
- Video windows
- Fuel supply and burner pictures
- Location of burners
- Spray nozzle, flow meter, pans
- Exhaust arrangements
- Location of masks
- Data acquisition system
- Thermocouples and channel list
- Heat Flux gauges
- Thermocouple tree
- Exhaust flow and sucking system

EXPERIMENTAL DESIGN

DAY 1 –

FUEL 1 – NATURAL GAS

TEST 1 – MONDAY AM

M 1 M 2 M 3

FE 5 FE 3 FE 2

TEST 2 - MONDAY PM

M 1 M 2 M 3

FE 5 FE 4 FE 6

FUEL 2 - HEPTANE

TEST 3 – MONDAY PM

M 1 M 2 M 3

FE 5 FE 4 FE 6

TEST 4 – MONDAY PM

M 1 M 2 M 2

FE 5 FE 3 FE 2

DAY 2 – SOFA BURN IN ISO ROOM

SOFA BURN 1

TEST 5 – TUESDAY AM

M 1 M 2 M 3

FE 5 FE 3 FE 2

SOFA BURN 2

TEST 6 – TUESDAY PM

M 1 M 2 M 3

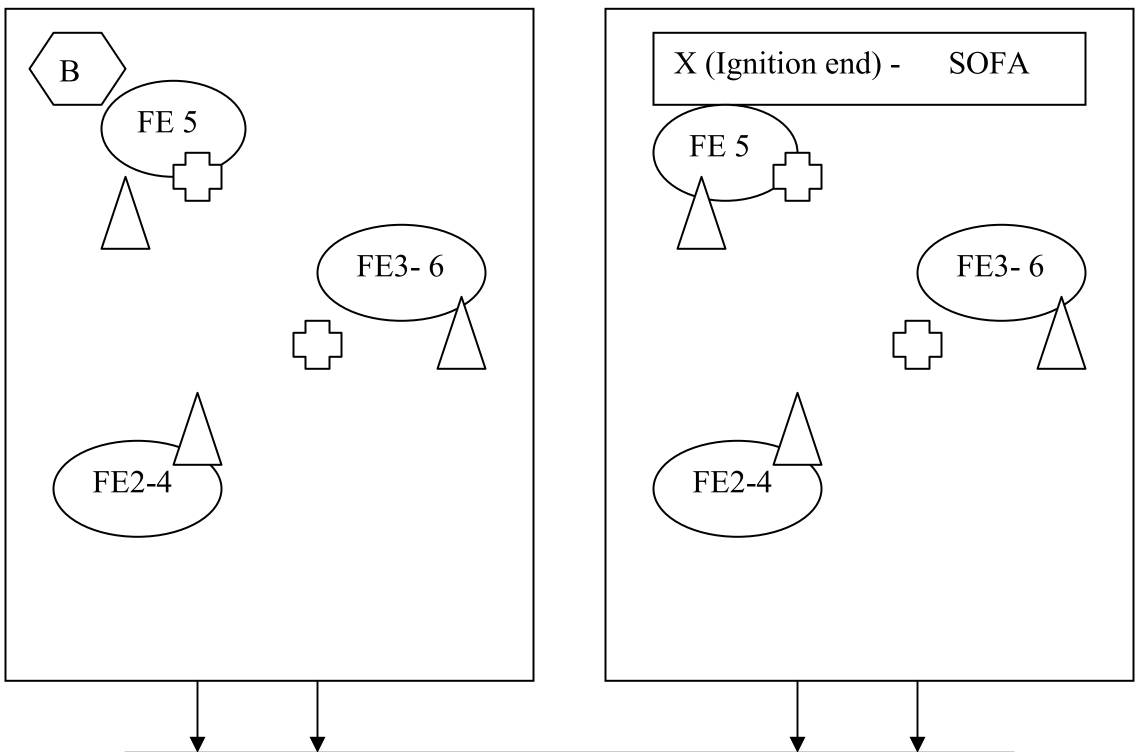
FE 5 FE 4 FE 6

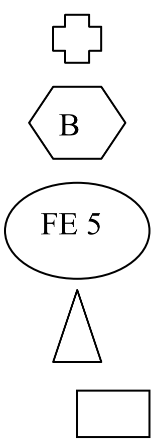
Description and location of masks and fire-eye devices

Mask Number	Type of Heat	Heat Flux Intensity	Fire-Eye devices mounted	Location
M 1	Radiation	High	# 5	Close to fire
M 2	Convection	Medium	# 3 and # 4	High up from fire
M 3	Conduction	Low	# 2 and # 6	Away from fire

ISO ROOM LAYOUT

DAY 1 – MONDAY **DAY 2 - TUESDAY**





Thermocouple Tree 1 and 2 Tree 1 – 2 ft x 2 ft from left and back wall Tree 2 – 5 ft x 5 ft from left and back wall
Burner using Natural Gas and Heptane Monday AM – Natural Gas and Monday PM - Heptane
3 masks mounted with fire-eye devices at different locations – Mask
Three heat flux gauges next to each mask

HEAT FLUXES

INSTRUMENTATION SETUP
INSTRUMENTATION CHECK
READY FOR TEST
CALIBRATION CURVES
TYPE OF FLUX GAUGES
___ Heater ON

___ Water ON

Checked	**Channel Number**	**Instrument Serial Number**	**Notes**

Flow meter settings (left to right):

☐ **VIDEO**

Camera	Viewing angle checked	Tapes in and labeled	Videos Recording	Tape Removed
SOUTH		FE012306Test1.DAT		
SOUTH EAST		FE012306Test2.DAT		
		FE012306Test3.DAT		
		FE012306Test4.DAT		

☐ **BULLET CAMERAS**

Camera #	Viewing angle of Fire-Eye	Tapes in and labeled	Camera recording	Tape Removed
Camera # 1				
Camera # 2				
Camera # 3				

DOCUMENTATION

____ Test documented

- Dimensions of the ISO room
- Room lining and room construction (make)
- Dimension of the location of burner
- Dimension of the location of thermocouple trees
- Dimension of the location of heat flux gauges
- Dimension of the location of masks
- Fuel Flow rate
- Pan size
- Exhaust Flow details and sucking system

- Sampling rate of data acquisition system

PRETEST CHECKLIST

	CALORIMETRY
	FUEL SYSTEM
	HEAT FLUXES –remove caps
	MASKS AND INSTRUMENTATION
	FIRE-EYE DEVICES AND INSTRUMENTATION
	DATA ACQUISITION SYSTEM
	VIDEO
	BULLET CAMERAS
	PICTURES
	CHANNEL LIST

___ SAFETY BRIEF

- **Call LAUREAN for safety briefing**
- **Personnel roles /positions and responsibilities**
- **Sequence of events**
- **Safe viewing distance**
- **Test terminating criteria**
    1. Fire Size
    2. Damage to ceiling fixture
    3. FGCS damage
    4. Excessive smoke in Room 205
    5. Erratic Fire Behavior
    6. ALL VISITORS MUST WAIT FOR TEST DIRECTOR OR SAFETY OFFICER FOR CLEARANCE PRIOR TO REENTRY IN TEST AREA

___ READY TO IGNITE

- **Video start**
- **Ignite Pilot**
- **Record Test Start (fire ignition) Time:**

___ TEST RUNNING CHECKLIST

Time	**Action**	**Note**
	Ignite Propane Pilots	
	Fuel Ignition	

	Confirm Ignition	

Time *	**Fire**	**Perimeter**	**Video**	**Notes**

*** Time t = 0 fire ignition**

POST TEST

	Action	**Notes**
	Cover sensitive instrumentation	
	Turn off water	
	Cubical inspection	
	Instrumentation inspection	
	Post test photographic footage	
	Weigh components	

___ Backup Data

CURRICULUM VITAE - ATUL R. DESHMUKH

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Grado Dept. of Ind. and Sys. Engg.
250 Durham Hall
Virginia Tech Blacksburg, VA 24061
Cell Phone: 732 672 5077
Email: atdeshmu@vt.edu

EDUCATION

Ph.D.,	Virginia Polytechnic Institute and State University, November 2006
Major:	Industrial and Systems Engineering
Concentration:	Human Factors Engineering and Ergonomics
Adviser:	Dr. John G. Casali, Director, Auditory Systems Laboratory
Dissertation:	Product Evaluation and Process Improvement Guidelines for the Personal Protection Equipment Manufacturers Based on Human Factors, NIOSH Guidelines and System Safety Principles
M.S.,	Rutgers University, May 2002
Major:	Industrial and Systems Engineering
Concentration:	Industrial Engineering
Project:	Forecasting a Safety Risk-metric for an Aircraft Operator
Sponsor:	Federal Aviation Administration (FAA) Section: AAR – 490
B.S.,	University of Pune, India, January 1997
Major:	Civil Engineering
Thesis:	Wind Power Energy
Sponsor:	Maharashtra Energy Development Corporation, Govt. of Maharashtra

DISSERTATION

<u>Dissertation Part I</u>: <u>Product Evaluation and Process Improvement Guidelines for the PPE Manufacturers Based on Human Factors, NIOSH Guidelines and System Safety Principles</u>
Sponsor: National Personal Protective Technology Laboratory (NPPTL), Pittsburg PA

- Reviewed and analyzed the manufacturing, system safety, quality and compliance procedures documentation of two PPE manufacturers
- Referred existing compliance standards such as NFPA, UL, ANSI, NIOSH, ISO etc.
- Utilized Six Sigma and NIOSH Guidelines to conduct survey and interviews of the product designers and manufacturers
- Utilized system safety methods such as Failure Mode and Effects Analysis (FMEA), Human Factors Safety Analysis to document the safety and reliability of PPE

<u>Dissertation Part II: Performance Evaluation of a Thermal Sensor for Firefighters</u>
Sponsor: Fire-Eye Inc.

- Designed experiments and protocols to validate the reproducibility and repeatability of the performance of the Fire-Eye safety device
- Conducted series of laboratory-scale controlled environment experiments using static oven, radiant panel, and fire equipment evaluator to validate the performance
- Conducted large scale fire tests in ISO burn room to validate and compare the performance of the device obtained from laboratory scale experiments

PROFESSIONAL EXPERIENCE

Graduate Research Assistant, September 2004 – Present
- Assisted in research and development activities of the Auditory Systems Laboratory
- Coordinated and conducted research activities with undergraduate and graduate students

Guest Researcher, National Institute of Standards and Technology (NIST), Dec-Jan 2006
Building Fire Research Laboratory, Gaithersburg, MD
- Conducted series of laboratory-scale experiments
- Conducted full-scale fire tests in ISO 9705 room using fuels such as Natural Gas, Heptane, and Living-room furniture burn

Graduate Teaching Assistant for Human Factors Courses, August 2002 - May 2004
- Coordinated and instructed undergraduate human factors laboratories
- Corrected student exams, laboratory reports and papers and maintained their grades

Human Factors COOP, June 2002 – August 2002

L3 Communications Titan, Air Traffic Division, Mays Landing, NJ

- Project 1 – Human Factors Program Cost Estimation
  Client: AAR-100, Federal Aviation Administration (FAA), Washington DC
  - Composed a survey questionnaire and interview questions for the study participants
  - Surveyed and interviewed FAA human factors professionals
  - Conducted data analysis and interview analysis to estimate relationship between human factors costs and attributes of FAA acquisition program
  - Obtained feedback about the funding level and its adequacy for human factors activities on various acquisition programs at FAA

- Project 2 – Comparison of Conflict Detection and Resolution (CD & R) algorithms
  Client: L3 Communications Titan, Air Traffic Division, Mays Landing, NJ
  - CD & R, one of the Aviation Decision Support Tool (DST) is designed to allow airspace users to maintain separation
  - Conducted literature survey of different CD & R on air and ground side
  - Helped in comparing the effectiveness of these algorithms from human centered perspective

Graduate Research Assistant, September 1999 - May 2001
Center for Advanced Risk and Decision Analysis, Rutgers University, Piscataway, NJ
Client: AAR-490, Risk Analysis Branch, Federal Aviation Administration, Atlantic City, NJ
- Conducted research to develop statistical multiple regression models and hybrid econometric models for Event Rate using SPSS and NeuroShell II packages
- Neural Network models were built to observe trends in data and forecasting the Event Rate using monthly data of variables such as operations, maintenance, fleet size, inspections, credit rating, accidents, incidents, changes in key personnel etc.
- Risk analysis was performed for regional, cargo and major domestic airlines

PUBLICATIONS

1. Lancaster, Jeff A., Deshmukh, Atul R., and Casali, J.G., " Developing PPE Systems: Salient Issues Faced by Small and Large Manufacturers," Advanced Personal Protective Equipment : Challenges in Protecting the First Responders Conference, Blacksburg, VA, October 16-18, 2005
2. Deshmukh, Atul R., and Hewitt, Glen, "Human Factors Cost Estimation," Proceedings of the Human Factors and Ergonomics Society Annual Conference, Denver, CO, October 13-17, 2003
3. Luxhøj, James T. and Atul R. Deshmukh, "Forecasting of a Safety Risk Metric for an Aircraft Operator," The 2000 International Conference on Industry, Engineering, and Management Systems, Cocoa Beach, Florida, March 13-15, 2000

PROPOSAL & REPORT WRITING

Doctoral Research: Grado Department of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA (Advisor: Dr. John G. Casali)

- Assisted Auditory Systems Laboratory in writing research proposal to Fire-Eye Inc.
  - Identified a need for a structured test regimen for Fire-Eye device and proposed a systematic test plan to the PPE manufacturer

- Submitted reports to funding agencies
  - NIOSH - NPPTL : "Problems faced by the manufacturers of Personal Protective Equipment while applying NIOSH Guidelines"
  - FAA : " An Artificial Intelligence Approach to Forecasting the Event Rate for an Aircraft Operator"
  - FAA : "Human Factors Cost Estimation"
  - Fire-Eye Inc.: " Performance Matrix of a thermal sensor for firefighters" (In progress)

HONORS AND AWARDS

- John Lee Pratt Research Fellowship for Graduate studies during the year 2004
- Graduate Summer Research Fellowship awarded by DIMACS (Discrete Mathematics and Theoretical Computer Science consortium of Rutgers and Princeton University) in summer 1999 for a project titled, "An artificial intelligence approach to forecasting of the Event Rate for an aircraft operation"
- Awarded "National Merit Scholarship" in June 1990 thru January 1997 by the Federal Government of India. This is a scholarship awarded up to PhD level of education (valid for studies in India) based on the performance in high school

PROFESSIONAL AFFILIATIONS

Student Member, Human Factors and Ergonomics Society (HFES), 2003-present
Member, HFES Student Chapter, Virginia Tech
Member, American Society of Safety Engineers Student Chapter, Virginia Tech

COMPUTER SKILLS

O/S and Software – Windows XP, UNIX, Macintosh, MS Office, MS Visio
Statistical Packages – SPSS, SAS, Minitab, JMP

Modeling and Analysis – ARENA (Simulation), NeuroShell2 (Neural Networks), Mat Lab

ADDITIONAL CERTIFICATES

- Diploma in Export Management from National Institute of Export Management (NIEM), Chennai, India
- Advanced Diploma in Sales and Marketing from Apex Institute of Professional Training, Pune, India (A Tack Training Ltd, UK undertaking)

EXTRA CURRICULAR ACTIVITIES

- Conference Manager for “Advanced Personal Protective Equipment: Challenges in Protecting First Responder’s Conference during October 16-18, 2005 at The Inn, at Virginia Tech. The conference is cosponsored by NIOSH and Virginia Tech
- Safety Monitor, Extreme Makeover: Home Edition show of ABC Television, cosponsored by Virginia Tech in December, 2005
- President, International Students Affairs Committee of Rutgers University, September 1999–August 2000
- Workshop Assistant – 1st and 2nd National Workshop on “Risk Analysis and Safety Performance Measurement in Aviation” at FAA Technical Center and Rutgers University respectively. The National Workshops were cosponsored by Federal Aviation Administration and Sandia National Laboratories with Rutgers University.
- Founding Member - Rutgers Yoga and Meditation Club
- Volunteer - Bone Marrow Registration drive at Rutgers University for 3 semesters.
- Volunteer- Art of Living Foundation, a UN recognized non-profit spiritual organization working in over 100 countries for the upliftment of poor and uneducated
- Volunteer-International Students Orientation Group for Fall-1999 and Fall-2000 at the International Center at Rutgers University

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

November 24, 2006

Mr. Atul Deshmukh
Auditory Systems Laboratory
Grado Department of Industrial and Systems Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

Dear Mr. Deshmukh;

Per our discussion involving your request for permission to include material from our collaborative effort on Thermal Sensors for First Responders, you do not require any additional permission to include the materials in your thesis

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If you have additional questions, please feel free to contact me.

Sincerely yours,

Nelson Bryner

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NIST

FIRE EYE 4:40 PM February 9, 2007

To:
Atul Deshmukh
Jeff Lancaster
Auditory Systems Laboratory
Grado Department of Industrial and Systems Engineering
Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

This is to certify Fire-Eye Development, Inc.'s granting of permission for Atul Deshmukh and Jeff Lancaster and other authors from Auditory Systems Laboratory, Virginia Tech and Building and Fire Research Laboratory, and the National Institute of Standards and Technology (NIST) to publish and/or present the results from research proposal number 06-0837-11 , entitled, "Performance Evaluation of the Fire-Eye device at NIST".

It is understood that Fire-Eye Inc. will be disclosed in this publications and presentations as a manufacturer of the product that was tested and evaluated at the Building and Fire Research Laboratory of National Institute of Standards and Technology, Gaithersburg, MD. These publications and presentations will be restricted to the following: scientific articles in journals and conferences, NIST internal reports, Virginia Tech reports, and PhD dissertation of Atul Deshmukh. It is understood that the data will not be used in any type of product comparison or marketing sense.

Best regards,

Daren R. Appelt

Daren Appelt / President
Fire-Eye Development, Inc.

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