NIST Technical Note 1803

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Thermal Exposure Sensor for Fire Fighters – Laboratory-Scale Performance Experiments

ABSTRACT

During structural fire fighting operations, fire fighters wear protective gear to insulate them from high temperature environments, including hot combustion gases, burning surfaces, and thermal radiation. Current turnout gear insulates the fire fighter to such an extent, encapsulating his/her entire body, that it is difficult for each individual fire fighter to understand how hazardous or hot the thermal environment is. Therefore, the natural heat-sensing mechanism of the body is incapable of sensing the ambient temperature, possibly putting firefighters at risk. A thermal sensing 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 thermal sensing device was conducted in laboratory-scale (i.e., climatic chamber experiments) and in full-scale (i.e. fire experiments in ISO room) environments. This report describes the laboratory-scale experiments and a second report describes the full-scale fire 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 experiments.

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 Laboratory
BTU/ft^3	BTU per cubic feet
cm	Centimeter
Cr	Chromel
^oC	Degrees Centigrade
DAQ	Data Acquisition System
DV	Digital Video
E#	Experiment Number
ft	foot/feet
^oF	Degrees Fahrenheit
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
TC	Thermocouple
TC #	Thermocouple number
TI	Temperature Inside
TO	Temperature Outside
TSU	Thermal Sensing Unit
UBC	Uniform Building Code
V	Volt
%	Percentage

1.0 INTRODUCTION

Firefighters and first responders wear protective gear to insulate them from high temperature conditions including hot combustion gases, burning surfaces, and thermal radiation. While it is critical to protect fire fighters from adverse fire conditions, it is also important that fire fighters be able to continuously assess the fire environment in which they are working. A rapid increase in temperature may alert a fire team to worsening conditions or a cooling of the environment may indicate successful suppression. Being able to constantly assess their environment allows fire fighters to work more safely and more effectively. Current turnout gear, including boots, pants, coat, hood, helmet, and gloves, effectively insulates a fire fighter from their environment. This gear encapsulates their entire body and that makes it more difficult for fire fighters to sense or understand how hot or intense the conditions are that envelop them. A smoke filled room prevents a fire fighter from visually evaluating their environment. Before the current personal protective equipment was widely available, fire fighters often utilized exposed skin, such as ears, to sense or track the fire conditions around them. While current protective equipment may have reduced the number of burns, especially to the ears, fire fighters still need to be able to assess fire conditions.

Thermal sensing technology can provide fire fighters with the ability to monitor their thermal surroundings. However, in order to be effective, this technology must both be able to detect the thermal environment, and must make the fire fighter aware of the thermal conditions in a manner that is timely and understandable. At this time, it is not clear whether tracking gas temperatures will provide better data than monitoring heat flux rates. While measuring temperatures or heat fluxes will provide important information, it may also be necessary to track the gradient or change in these quantities. The specific temperature may be important, but how quickly that temperature is achieved may provide additional insight into the developing fire environment.

Thermal sensing technology including thermocouples or thermistors, and heat flux gauges can be incorporated into existing protective equipment or as stand-alone monitors. Multiple manufacturers of Personal Alert Safety System (PASS) devices offer models with thermal sensors incorporated into each device. If the temperature being monitored exceeds pre-set limits, the alarm signal is activated. At this time, thermal sensors have only been incorporated into non-integrated PASS devices and are not available on PASS devices that have been integrated into self-contained breathing apparatus (SCBA). Other fire safety equipment manufacturers offer stand-alone thermal sensing units which can be utilized to monitor temperatures in several different location inside or outside turnout gear. Early stand-alone systems such as Life Vest*[*] or Life Shirt, appeared to focus on temperature inside a fire fighter's turnout coat. While these

[*] Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose

sensing units may provide warning of potential burn injuries or heat stress, these temperature monitors do not provide much data on changing conditions surrounding a fire fighter.

Thermal sensors, such as the Fire-Eye (Figure 1) have been developed to track external gas temperatures and display this data directly to each fire fighter. Fire-Eye's sensing unit and display mounts directly to the clear viewing section of the SCBA mask. As the temperature monitored near the face piece exceeds pre-determined values, a series of red and green light emitting diodes (LED) alert the fire fighter to changing conditions. 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.

While thermal sensing technology has already been included in different pieces of safety equipment, there are currently no standards or testing protocols with which to assess the performance of these thermal exposure sensors. While it is commendable that manufacturers seek to include more technology in order to increase the safety of fire fighters, the fire service does not have the resources to evaluate the thermal exposure sensor performance in stand-alone or integrated systems devices. There is a need for a well-designed testing protocol that would include different fire conditions that fire fighters typically encounter. This would allow the fire service to understand better the performance characteristics of the thermal sensors. In addition, a standardized testing protocol would allow the manufacturers to match the performance of their devices with the requirements of the fire service.

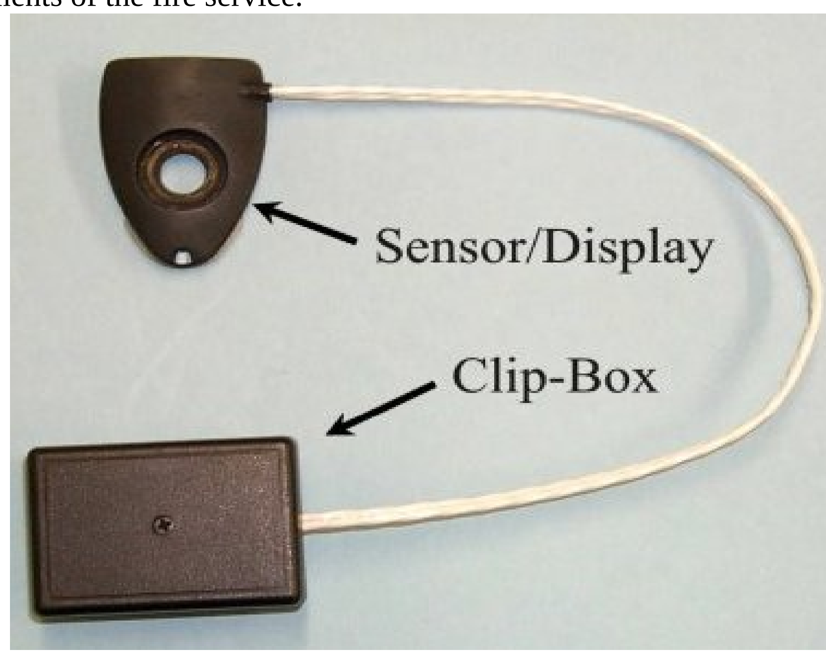

Figure 1. Example of personal awareness tool, a Fire-Eye device along with the clip-box electronics unit.

1.1 Heat Transfer Mechanism in the Fire Fighter Environment

The experimental series included the different thermal conditions that fire fighters typically encounter. Within a fire scenario, 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 the most efficient modes of transfer of heat energy across gas-filled volumes and it is the dominant mode in a typical fire.. A fire scenario may involve the transfer of heat energy with any combination of the three mechanisms. Therefore, it was necessary to evaluate the performance of a temperature-warning device in experimental conditions representing each of the three mechanisms. In order to validate the performance of the device in keeping with the elements above, the experimental matrix included examining the device in laboratory and full-scale experiments utilizing conductive, convective and radiative modes during the controlled exposure conditions.

1.2 Situational Awareness Information Displays

Timely display of fire ground data such as gas temperature, thermal flux values, and gas concentrations, is as important as collecting the data itself. This situational information must be displayed to the fire fighter quickly and in an understandable form. Firefighters and emergency responders are covered with protective gear while conducting firefighting or response activities; therefore, one possible method is to provide a visual warning which is directly in their line of sight. One method for providing this information to the fire fighter is through a visual display on or near the face piece. Manufacturers of personal protective equipment are beginning to introduce equipment with head mounted displays (HMDs) in which the information is conveyed to them through a Head-Up Display (HUD) or Head-Down Display (HDD). 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. There have been multiple applications of HMDs in fire department 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 hazardous material 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 Performance of Thermal Sensing Units Under Laboratory-Scale Conditions

This study examines the performance of a stand-alone thermal sensing unit in a series of laboratory scale experiments that were designed to document the response of an externally mounted monitor that was located at the top of the facepiece lens. The performance of several thermal sensing devices of the same design were monitored through a series of carefully controlled heated oven and radiant panel exposures. After completion of the laboratory experiments, these same thermal sensing devices will be included in a series of full-scale experiments. The full-scale experiments are described in a separate report (Deshmukh et al. 2013).

2.0 EXPERIMENTAL APPARATUS

The experimental set-up for the laboratory-scale experiments included instrumented headforms and thermal sensing units, respirator facepieces, and a data acquisition system. The headforms and thermal sensing units were exposed to thermal conditions in a static oven, flow loop, and radiant panel apparatus.

2.1 **Instrumented Headform**

The headforms used in the laboratory experiments were made from white closed-cell foam. 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}C), a large portion of the headform surface was covered with fiberglass 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 video camera along with its power cord, the headform was drilled at an angle of 40 ° facing up from rear side. Upon insertion of the bullet camera inside the headform, the monitor screen of the video recording unit was used to verify that the camera would capture current state and any change in status of the the warning indicator lights of the mounted thermal sensing device. The headform was then covered completely with a Nomex cloth head cover to protect the headform from 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 fire fighters), only the face of the headform (again, covered with heat resistant tape) was visible, as shown in the right side of Figure 2.

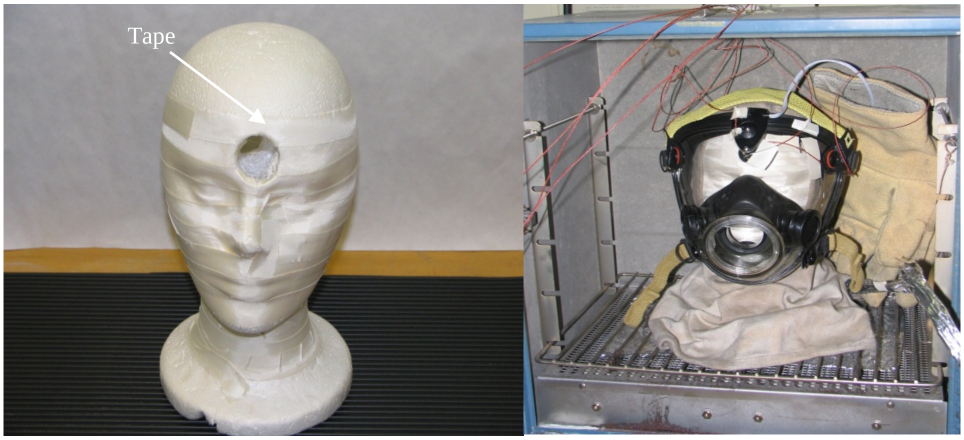

Figure 2. The left photograph shows the headform covered with heat- resistant tape and drilled for bullet camera insertion. The right photograph shows the Nomex cloth-covered headform equipped with an SCBA facepiece and a thermal sensing device.

2.2 Thermocouples

The thermocouples used for the laboratory-scale experiments were Type K nickel-Chromel/nickel Alumel (Ni-Cr/Ni-Al) (Figure 3). The operating temperature range of a Type K thermocouple is from -269 °C to 1260 °C. The diameter of the sensing junction bead on each thermocouple was approximately 1 mm. Typically, as the mass of the sensing junction bead increases, the time response of the thermocouple also increases. The time constant for these 1 mm diameter bare thermocouple beads was estimated at 2 seconds (Omega). The length of each thermocouple used for the laboratory-scale experiments was maintained at an average of 20 feet.

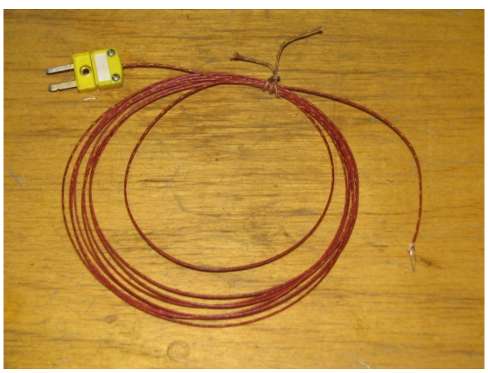

Figure 3. A thermocouple as used in experiments.

These thermocouples were attached directly to the surface of the SCBA facepiece and to the thermal sensing unit using heat-resistant tape and flame-resistant thread having a maximum diameter of 0.254 mm (0.010 in). The time constant for these 0.254 mm diameter bare thermocouple beads was estimated at 0.2 seconds (Omega). In order to ensure surface temperatures were recorded, care was taken to keep the thermocouple beads in direct contact with the surface of the SCBA facepiece and of the thermal sensing device.

Six thermocouples were used to record temperatures in each experiment for the static oven, flow loop, and radiant panel series in utilized in the laboratory-scale experiment matrix. The description of the location of each thermocouple is outlined in Table 1. The first five thermocouples were associated with the thermal sensing device or the SCBA facepiece. The sixth thermocouple was attached and placed at a 25.4 mm (1 in) distance from the thermal sensing device. 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 thermal sensing device and SCBA facepiece.

2.3 Thermal Sensing Unit Selection and its Nomenclature

Six thermal sensing devices were used for the laboratory-scale experiments. Each thermal sensing device was marked with its assigned number ranging from 1 through 6 on the top panel in the front of each device. Five thermal sensing devices (Numbers 1, 2, 3, 5, and 6) were instrumented with two thermocouples, one touching the front surface and the other touching the rear surface of each thermal sensing 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 experiment or if they malfunctioned.

Table 1: Nomenclature for the thermocouples used in the laboratory-scale experiments.

Thermocouple Label	Description of Thermocouple Location	Channel Name in Data Acquisition System
TC1	Thermocouple registering the temperature on the front surface of thermal sensing device	TSU FT TC1
TC2	Thermocouple registering the temperature on the rear surface of the thermal sensing device	TSU 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 Thermal sensing device	TSU IE TC5
TC6	Thermocouple registering the ambient temperature at a distance of 1 inch from thermal sensing device attached to the facepiece	TC6

Thermal sensing device #4 was instrumented with three thermocouples: one in front, one in the rear, and one inserted inside the thermal sensing device and next to the platinum thermal sensor to track the temperature in its vicinity. Thermal sensing device #4 was opened to position TC5 close to the platinum sensor itself. The thermal sensing device numbers, along with the manufacturer's serial number and thermocouple placement, are shown in Table 2.

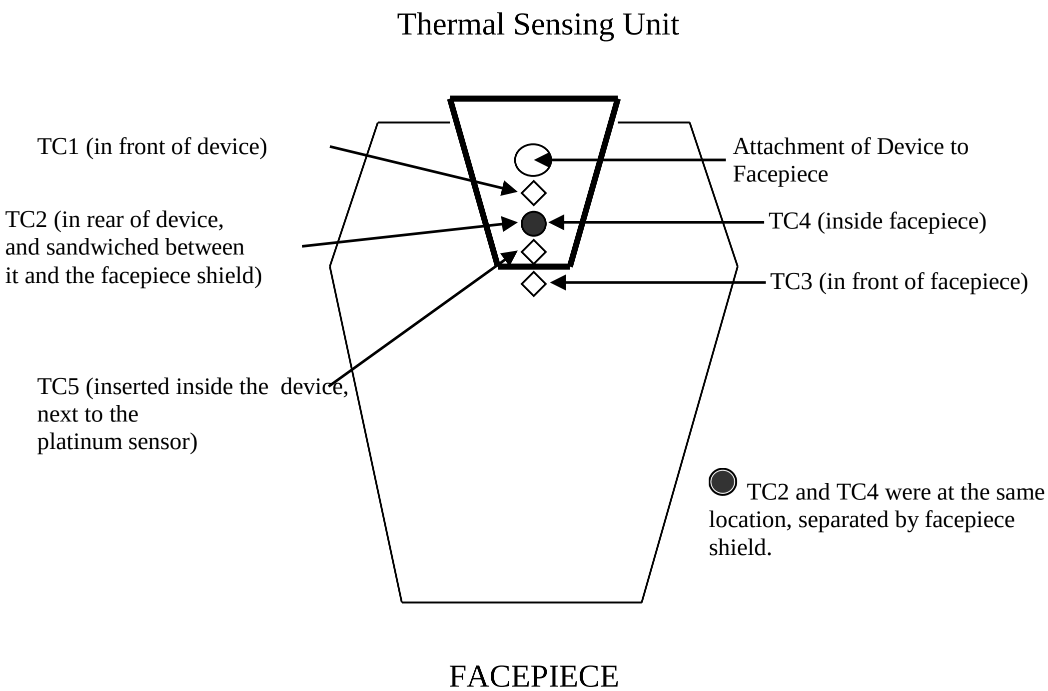

Figure 4. Location of thermocouples on the facepiece and thermal sensing unit.

Table 2: Nomenclature for the thermal sensing devices.

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

2.4 Facepiece Selection and Nomenclature

The thermal sensing device was interfaced with a Scott AV Face Mask 2000 model facepiece and three such facepieces were procured for the laboratory-scale experiments. The manufacturer's serial numbers along with the designated face piece numbers for experimental purpose are listed in Table 3.

Table 3. 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. TC3 and TC4 were positioned on top of each other and separated by the facepiece lens.

2.5 Digital Video Recording

A bullet camera manufactured by Sony Electronics Inc. and powered by a 30V battery was used to record the status changes indicated by the warning lights of the thermal sensing 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. In order to withstand the high temperature in the experimental scenarios, the wire connecting the bullet camera to the battery, which passed through the headform and facepiece, was covered with the heat-resistant tape.

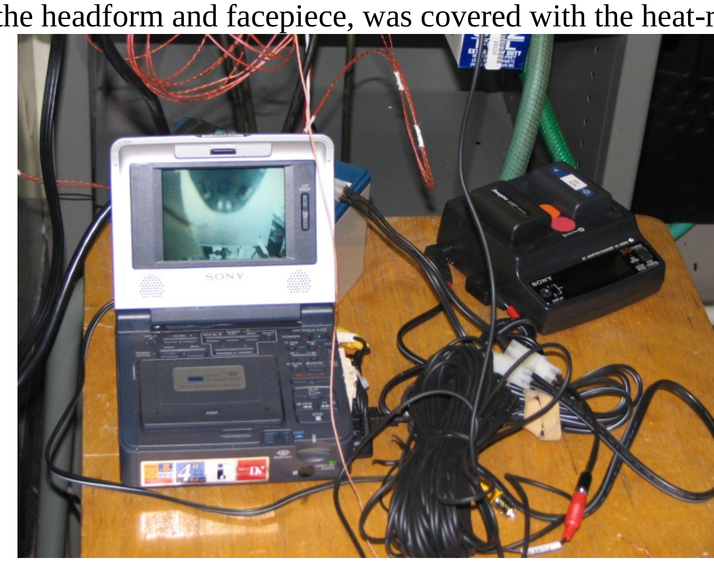

Figure 5. The mini-DV digital video recording unit.

Figure 6. The Sony bullet camera used to record thermal sensing device indicators.

2.6 Data Acquisition System

The CR23X system, manufactured by Campbell Scientific Inc., and shown in Figure 7, is a self-contained compact data logger that measures multiple sensor types (such as temperature and heat flux), communicates via modems, reduces data, controls external devices, and stores data. 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 touched. 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 voltage data indicating a change in status of warning lights of the thermal sensing device (Figure 8). This channel was referred to as the ‘marker channel.’

The marker channel was also used to mark certain important experiment parameters, such as the beginning of a experiment, the end of a experiment, and to note the change of warning status (e.g., from blinking green to solid green). The marker channel created a spike of 20 V in the data when it was actuated, leading to a change in status from 0 V to 20 V in the real-time data. A laptop computer, which was connected to the data logger system, is shown in Figure 9. The data acquisition software allow the temperatures to be displayed numerically and graphically in real time during each experiment.

Figure 8. Marker channel power supply and switch.

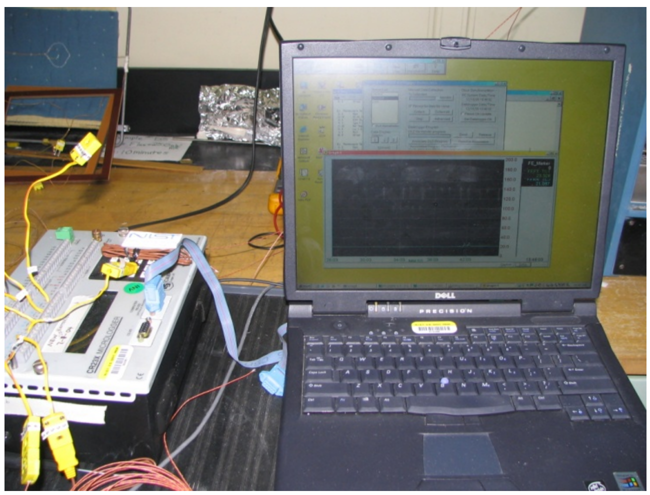

Figure 9. Laptop computer connected to the data acquisition system.

In order to record the temperature at each thermocouple location, the channels were programmed to specify the maximum temperature limit of 204 °C (400 °F) and the minimum temperature of -12 °C (10 °F). The data acquisition system was programmed to collect data every two seconds. The temperature data was an instantaneous temperature value; it was not averaged of 2 s and reported every 2 s. For a 30 minute experiment, the data system would generate approximately 900 data points.   At the end of each experiment, the data for that experiment was labeled and stored as a separate file indicating the date, time, and the name of the experiment.

2.7 Static Oven Description

A static oven utilizing conduction-type heat transfer was used during the first set of laboratory-scale experiments of the thermal sensing 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 0.30 m x 0.31m x 0.23 m (11 in x 12 in x 9 in). The external dimensions of the oven were 0.31 m x 0.33 m x 0.43 m (12 in x 13 in x 17 in). The internal capacity of the oven was approximately 0.0421 m^3 (1.5 ft^3). The circular thermostat knob allowed control of the temperature between the range of 40 °C (105 °F) to 200 °C (390 °F). The small opening on the top of the oven was used to insert the thermocouple wires attached to the facepiece and the thermal sensing device. This opening was also used to insert a glass thermometer, which confirmed the temperature in the oven. A thermocouple that monitored gas temperature was also inserted through the same opening and positioned in front of the facepiece.

Figure 10. Static oven sealed with a temporary calcium silicate board wall/door.

The static oven door was replaced by a temporary door made of calcium silicate material (Marinite I) containing a small glass viewing window whose dimensions were 11.4 cm (4.5 in) x 29.2 cm (11.5 in). The glass window was fixed in place by four screws around the glass and by additional calcium silicate board. The glass viewing window allowed the experimenter to monitor the experiment as well as record the status change of the warning indicators in the thermal sensing device.

2.8 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 thermal sensing devices. The FEE was designed and constructed to simulate moving hot gas conditions encountered by fire fighters. The FEE is able to reach a temperature of 300 °C with a total thermal flux of 20 kW/m^2, which is considered to be the radiation flux at the onset of flashover (Lawson et al. 1952). 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.

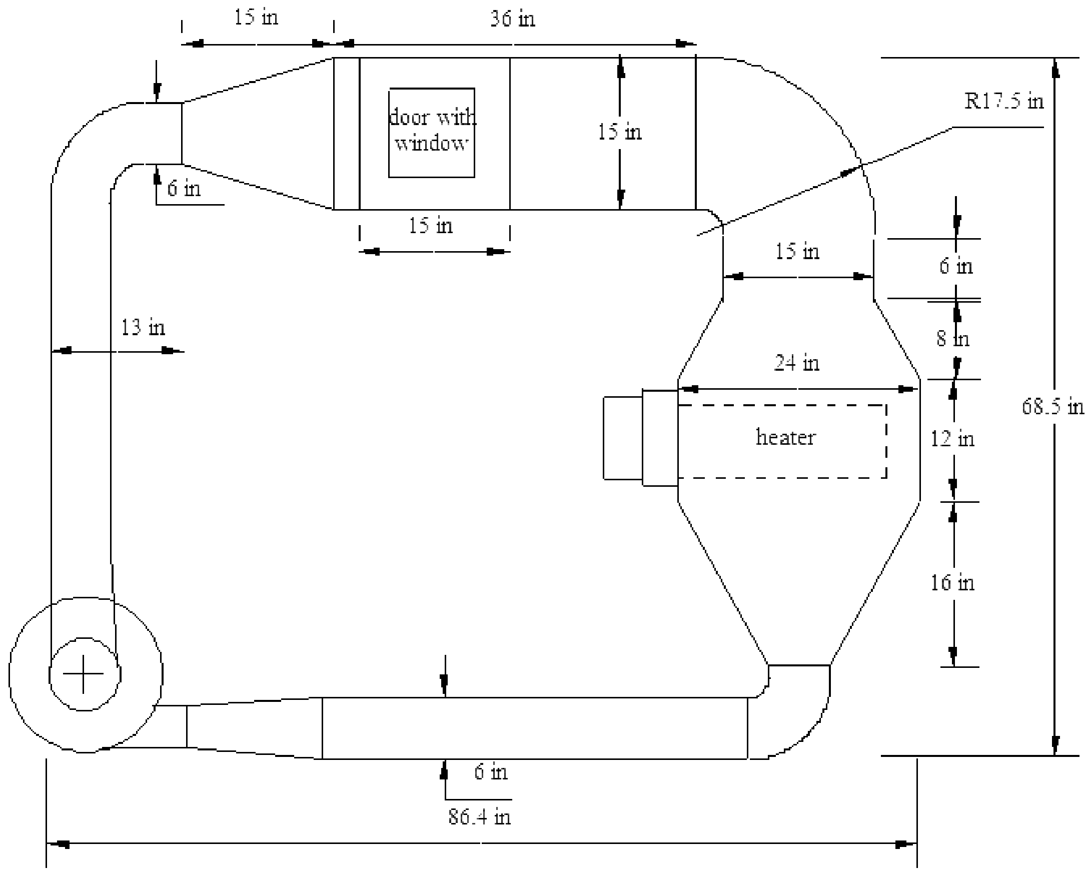

Figure 11. Specifications and dimensions of a FEE tunnel (Donnelly, Davis, Lawson, and Selepak, 2006).

The FEE consists of a stainless steel closed circuit flow loop and a fan driver. The flow loop's dimensions are 220 cm x 174 cm x 38 cm. The test chamber of the FEE is 91 cm (36 in) long by 38 cm (15 in) square, and can be expanded to fit larger equipment specimens if needed. In case of this set of laboratory experiments, the existing chamber dimensions were appropriate to expose the headform along with facepiece and thermal sensing 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) flow loop.

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 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 loop, and the photograph to the right shows the heat flow controls and graphical display of temperatures in the flow loop.

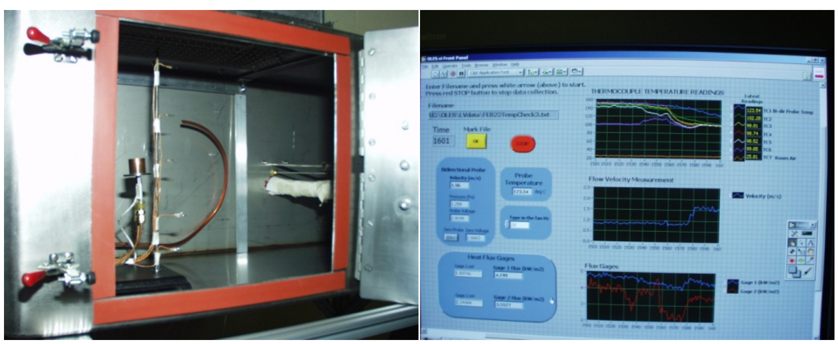

Figure 13. The FEE test section and a display of the temperature and heat controls in the FEE flow loop.

Temperature and velocity were two parameters that were controlled during the experimental procedures using the FEE flow loop. 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 to simulate smoke movement experienced by fire fighters in structural fires.

2.9 Radiant Panel Description

Fire fighters' burn injuries occur from exposures to the radiant heat energy produced by fire. In other cases, fire fighters can be 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 characterize the performance of the thermal sensing device under controlled and reproducible radiant heat conditions (see Figure 14).

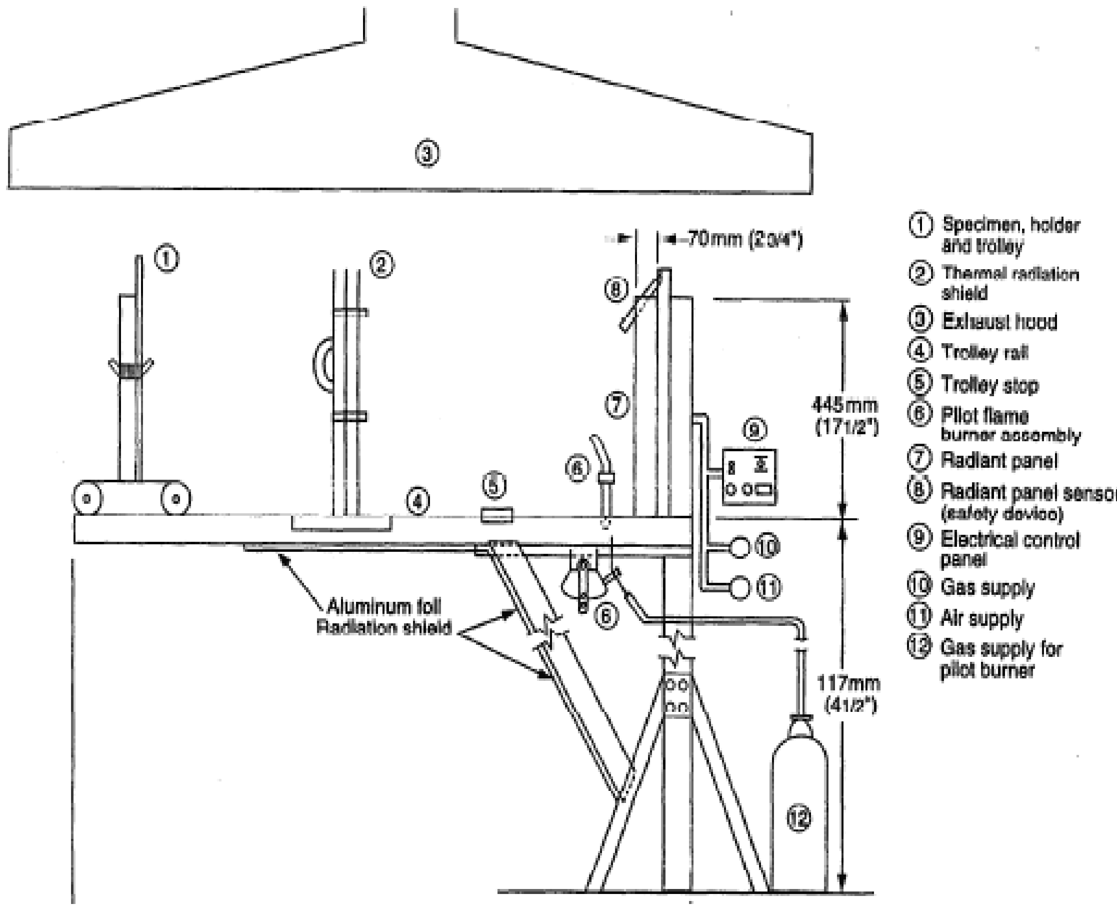

Figure 14. Side view of the radiant panel test apparatus (Lawson and Twilley, 1999).

A natural gas-fired radiant panel that is detailed in American Standards for Testing Materials (ASTM) standard (E 162–98) was the radiant heat source for the laboratory-scale experiments. The 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 experimental 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 310 mm x 460 mm (12 in x 18 in). The panel is equipped with a 'venturi-type aspirator' for mixing gas and air at approximately atmospheric pressure, a centrifugal blower to provide 50 L/s (100 ft^3/min) air at a pressure of 700 Pa (2.8 in of water), 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 $^oC \pm 4$ ^oC (1240 $^oF \pm 7$ ^oF). A propane gas pilot line burner allowed the researcher to initiate natural gas/air mixture across radiant panel width.

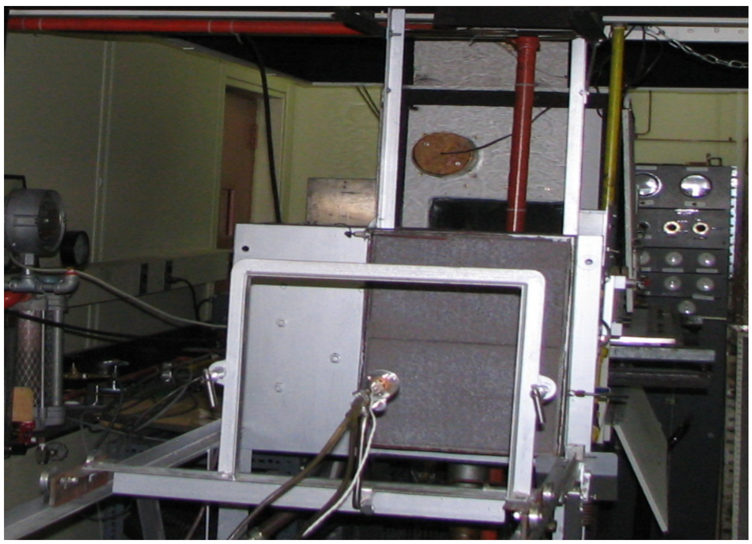

Figure 15. Radiant panel assembly.

The thermal sensing unit device was mounted on the movable trolley assembly and was attached to the radiant panel experiment frame as shown in Figure 16. Positioning of the trolley allowed for adjustment of radiant flux exposures and provided the ability to expose specimens to radiant energy environments that could be increased or decreased during the experiment (ASTM, 1997).

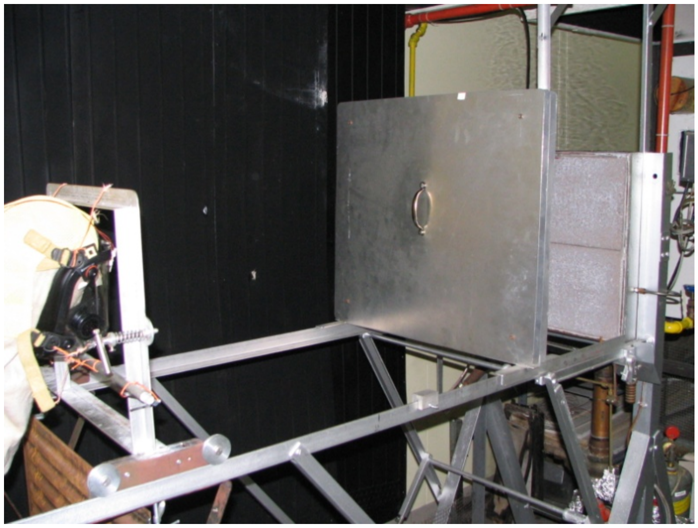

Figure 16. Side view of the radiant panel with a heat-shielding aluminum partition and the specimen holder mounted with a headform and facepiece.

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 kW/m^2 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 in) in diameter and had a metal flange located 25 mm (1 in) down its body, and away from the sensing surface (ASTM, 1997).

2.10 Batteries

Thermal sensing devices operate using two AAA batteries (1.5 V, 1100 mAh). Prior to each exposure, the thermal sensing devices were fitted with new AAA alkaline batteries. Through this procedure, the potential of low battery power influencing the research results was minimized.

3.0 EXPERIMENTAL PROCEDURE

3.1 Experimental Exposure Matrix

Six thermal sensing units were utilized during the three sets of laboratory-scale experiments. The exposures were designed to simulate the following conditions that fire fighters experience:

1) Static Oven Experiments representing the conductive heat effects of working in a hot environment,

2) Fire Equipment Evaluator Experiments to recreate the convective heat flow when moving through a hot environment or when having smoke and hot gases flow past a fire fighter, and
3) Radiant Panel Experiments representing exposure to significant thermal heat flux as experienced by a fire fighter in a burning room or under a flaming upper layer.

Repeatability and reproducibility were incorporated into the experiment regimen for the three sets of laboratory experiments. In order to examine the performance of the thermal sensing device through reproducibility, a particular device was exposed three times within the same experiment conditions. Conducting three repetitions also helped to spotlight any 'abnormal performance' that might have presented during one of the three experiments, such as a specimen malfunction. Thermal sensing device 5 (TSU #5) was selected for experimenting under this protocol for not only the laboratory-scale experiments, but also for the full-scale experiments described in a second report (Deshmukh et al. 2013). In order to validate the repeatability of a range of thermal sensing devices in identical experimental conditions for the laboratory-scale experiments, five devices were selected. Four devices (TSU #1, TSU #2, TSU #3, and TSU #6) were instrumented identically, whereas device 4 (TSU #4) was instrumented with an additional thermocouple close to the platinum sensor and inside the device. This research plan for reproducibility and repeatability is shown in Tables 4 and 5.

Table 4: Research plan to examine the reproducibility of the thermal sensing device.

Description	**Static Oven**	**Fire Equipment Evaluator**	**Radiant Panel**	
			Flux 1	Flux 2
TSU # 5 – Experiment 1	Repetition 1	Repetition 1	Rep 1	Rep 1
TSU # 5 – Experiment 2	Repetition 2	Repetition 2	Rep 2	Rep 2
TSU # 5 – Experiment 3	Repetition 3	Repetition 3	Rep 3	Rep 3

Table 5. Research plan to examine the repeatability of the thermal sensing device.

Description	Static Oven (SO)	Fire Equipment Evaluator (FEE)	Radiant Panel (RP)	
			Flux 1	Flux 2
Experiment 1 – TSU # 1	SO- 1	FEE- 1	RP- 1	RP- 1
Experiment 2 – TSU # 2	SO- 2	FEE- 2	RP- 2	RP- 2
Experiment 3 – TSU # 3	SO- 3	FEE- 3	RP- 3	RP- 3
Experiment 4 – TSU # 4	SO- 4	FEE- 4	RP- 4	RP- 4
Experiment 5 – TSU # 6	SO- 5	FEE- 5	RP- 5	RP- 5

As mentioned earlier, the data set from thermal sensing device 6 (TSU #6) has been treated as a 'replacement dataset' should any of the other devices fail. Overall, there were seven Static Oven experiments, seven FEE experiments, and 14 Radiant Panel experiments at two different flux levels. Also as mentioned in the earlier discussion, radiation is a very efficient mode of energy transfer that may cause varying damage to the devices within a very short span of time. 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 experiments.

3.2 Procedure for Laboratory Experiments

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. Once the 'pre-experiment checklist' was completed, another checklist, 'during experiment checklist' was initiated. A third checklist was consulted after the completion of a particular experiment.

3.2.1 Static Oven Experiment Procedure

The headform with a facepiece installed with the sensing device, was mounted 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 headform in order to insulate the headform from direct heat. A glass thermometer was inserted through the small opening in the roof of the oven to track temperatures during the experiment. The modified insulating board oven door was closed.

The power was set to ON for the oven and the thermostat was set at 50 ^oC. Upon achieving an oven temperature of 50 ^oC, the experiment start time was recorded in the laboratory notebook, and the marker channel was actuated to create a spike in the voltage data that was recorded. The temperature was increased at an interval of 10 °C every 3 minutes by turning the thermostat knob. While the temperature in the oven was increasing, any change in status of the indicator lights was recorded by actuating the marker channel and also recording each event in the laboratory notebook. The temperature in the oven was increased until it reached 140 °C. A record was made in the laboratory notebook when the thermal sensing device displayed blinking red lights, indicating that the environment was 'still heating.' The static oven was turned off once the temperature reached 140 °C.

Figure 17. Instrumented setup for the static oven experiment.

The modified door panel was opened and a cooling fan was directed toward the facepiece for rapid cooling. The bullet camera and the experiment specimen were allowed to cool for at least 15 minutes at the end of each experiment. After the exposure series was completed for each specific thermal sensing unit, it was removed from the oven and the next device to be exposed was mounted in the oven. Before initiating the next experiment series, each wiring connection and thermocouple readout was verified. The static oven experiment was repeated using different sensing devices to complete the experimental matrix. Eight experiments were completed over a period of two days in this manner. In the first pilot experiment, the bullet camera overheated, leading to melting of an exposed portion of the bullet camera at the maximum temperature of 140 °C. As a result, all future experimenting in the static oven was halted at 140 °C.

3.2.2 Fire Equipment Evaluator Experiment Procedure

A thermocouple inside the experiment section area of the FEE was monitored to confirm ambient gas temperature. This temperature was used as the reference temperature for the experimental trial. The headform covered with the instrumented facepiece and the thermal sensor device was mounted in the center of the FEE's flow section. The headform was suspended in the center of the flow section using four small wires which were tied to steel rods attached to the walls of the flow section (similar to that of the static oven experiments, see Figures 18 and 19). The thermocouple connections were verified to ensure that the data acquisition system was reading all temperatures. The door of the test area of the FEE was closed and the temperature was increased to 50 ^{o}C. The experiment was started once the temperature of 50 ^{o}C was achieved. The experiment start time was recorded in the laboratory notebook and the marker channel was actuated. The temperature inside the FEE flow loop was increased at an interval of 10 ^{o}C every 3 minutes from the experiment start time (to simulate a gradual heating environment as in a real fire scenario). 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. In order to be consistent with the static oven experiment maximum temperature limit, the temperature in the FEE was also increased until it reached 140 ^{o}C. The FEE heater controls were turned off once the test area's temperature reached 140 ^{o}C. The thermal sensing device as well as the bullet camera were allowed to cool for fifteen minutes. The door of the test area was opened and the headform, facepiece, and thermal sensing device were removed. The FEE experiment was repeated using different thermal sensing devices to complete the research procedure. Eight FEE experiments were conducted over a period of two days, and the timeline for each experiment is listed in the results section.

Figure 18. Instrumented setup for the Fire Equipment Evaluator experiment.

3.2.3 Radiant Panel Experiment Procedure

Before conducting a radiant panel experiment, 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 experiments. 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 curve for the Schmidt-Boelter heat flux gauge, the millivolt output value was calculated for the selected incident heat flux. In order to achieve a uniform and steady heat flux, the radiant panel was calibrated each day prior to conducting experiments.

For the first set of experiments using radiant panel, a flux of 1.6 kW/m^2 was chosen as the target flux (i.e., the heat flux that fire fighters face while fighting a fire and that they can survive in for 30 minutes or less without developing skin burns (National Fire Protection Association (NFPA), 1971). To achieve a flux of 1.6 kW/m^2, the specimen holder was positioned at a distance of 83.8 cm (33 in) from a reference point of the radiant panel. A set of three aluminum panels was used to shield the thermal sensing device from the radiant heat while the headform, along with the instrumented facepiece, was mounted on the specimen-carrying movable frame (Figure 19). The headform and facepiece were mounted in the center of the movable frame such that the heat from the radiant panel was incident on the sensing device. The headform was tilted and tightened at an angle as shown in Figure 20, resulting in the thermal sensing 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.

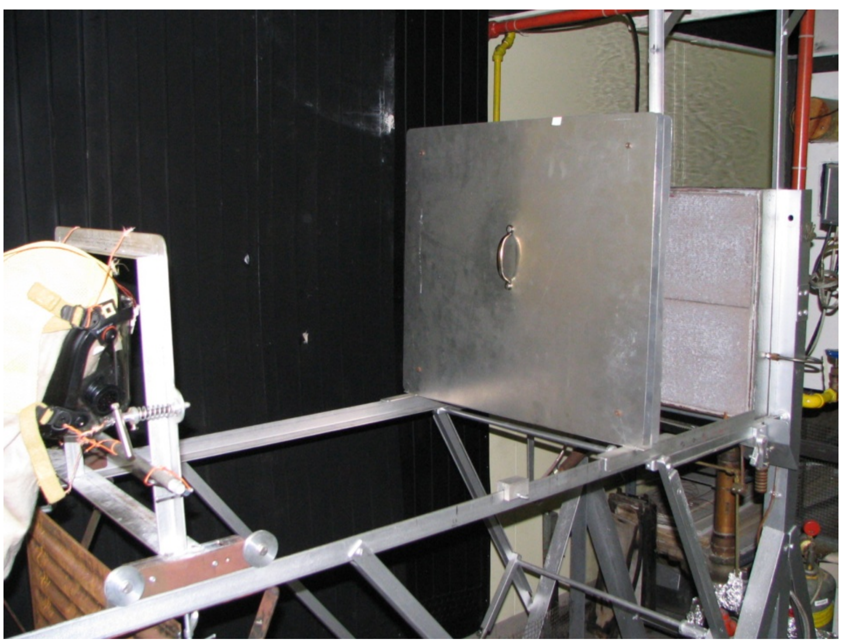

Figure 19. Side view of the radiant panel with a heat-shielding aluminum panels and the specimen holder mounted with a headform and facepiece.

The exposure was initiated by removing the heat shield and recording the time in the laboratory notebook and on the marker channel. Once the warning indicators on the thermal sensing unit demonstrated a continuous blinking red indicator, the thermal shield was inserted between the radiant panel and the facepiece. The movable specimen holder was moved away from the radiant panel to allow it to cool for fifteen minutes. The next device and facepiece were mounted for the next experiment. Eight experiments were repeated in the same fashion as above at a flux intensity of 1.6 kW/m2. A set of experiments 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 thermal sensing unit, positioned on the movable trolley, was hooked at a distance of 40.6 cm (16.0 in) from the radiant panel. Changes in status of indicator lights were recorded in the laboratory notebook as well as by actuating the marker channel. The timeline for each experiment is listed in the results section.

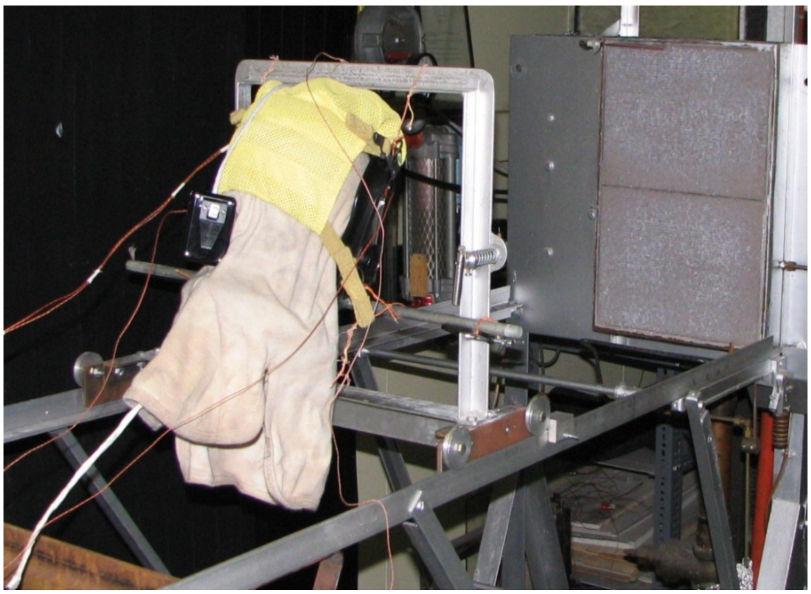

Figure 20. Instrumented setup for the Radiant Panel experiments.

4.0 RESULTS

4.1 Thermal Environment for Static Oven, FEE, and Radiant Panel Experiments

Figure 21 displays the thermal environment inside the static oven in which the situational awareness devices were examined across several thermocouple (TC) locations. TC6 recorded the ambient temperature during each experiment. The graph in Figure 21 shows the rate of increase of temperature per second for each static oven experiment. It indicates the maximum temperatures that the various thermal sensing units were exposed to in the enclosed static oven environment. Figure 22 shows the thermal environment inside the Fire Equipment Evaluator

In the case of the Radiant Panel experiments, the experiments were conducted in a laboratory without any enclosed environment as in Static Oven or FEE. The thermal environment in the radiant panel experiments is shown in Figure 23 and Figure 24.

4.2 Static Oven Experiment Results

Table 6 outlines the performance of various thermal sensing devices within the Static Oven, and Table 7 presents the same information for thermal sensing device (TSU #5). Figure 25 displays the graphical representation of the warning indicators of various thermal sensing devices in the Static Oven experiment, whereas Figure 26 shows the graphical representation of the warning indicators of unit 5 (TSU #5) in three Static Oven experiments.

Table 6. Performance of different devices in the Static Oven experiments.

Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
TSU #1	64	No Status	99	113
TSU #2	83	No Status	123	135
TSU #3	75	90	91	109
TSU #4	65	114	No Status	120
TSU # 6	56	91	90	102

Table 7. Performance of thermal sensing device #5 in the Static Oven experiments.

Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
TSU #5 – Rep 1	58	86	90	109
TSU #5 – Rep 2	73	90	105	110
TSU #5 – Rep 3	53	79	82	94

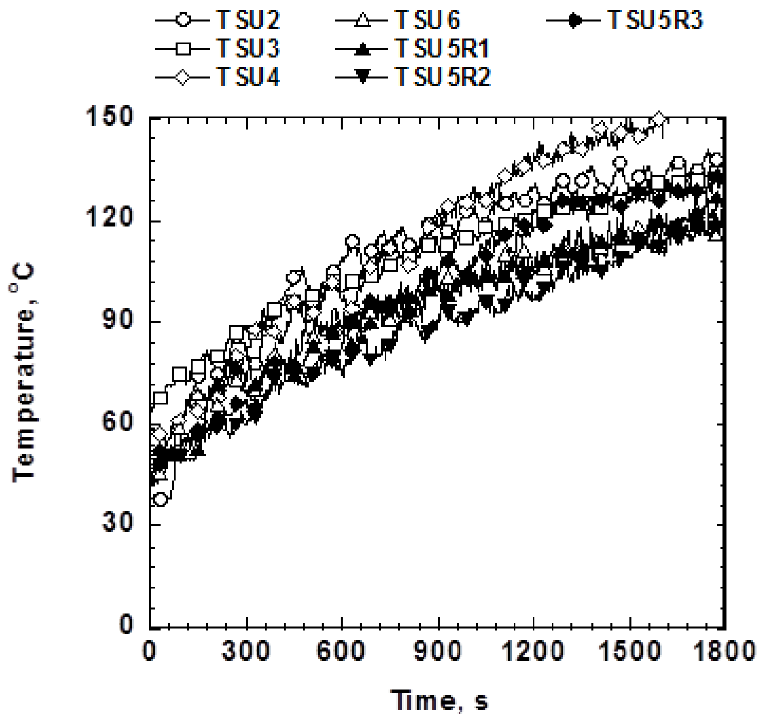

Figure 21. Thermal Environment in Static Oven experiments.

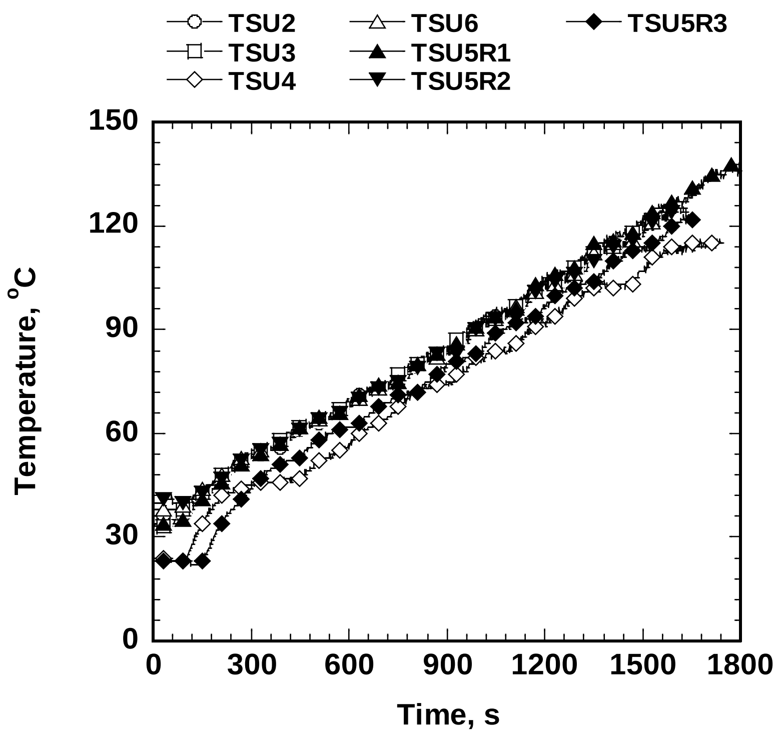

Figure 22. Thermal Environment in FEE experiments.

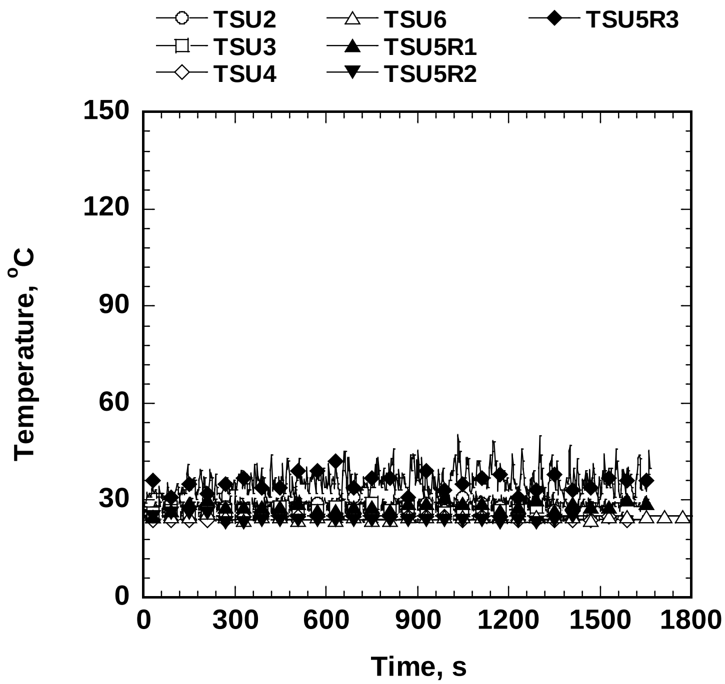

Figure 23**.** Thermal Environment in Radiant Panel experiments at heat flux of 1.6 kW/m^2.

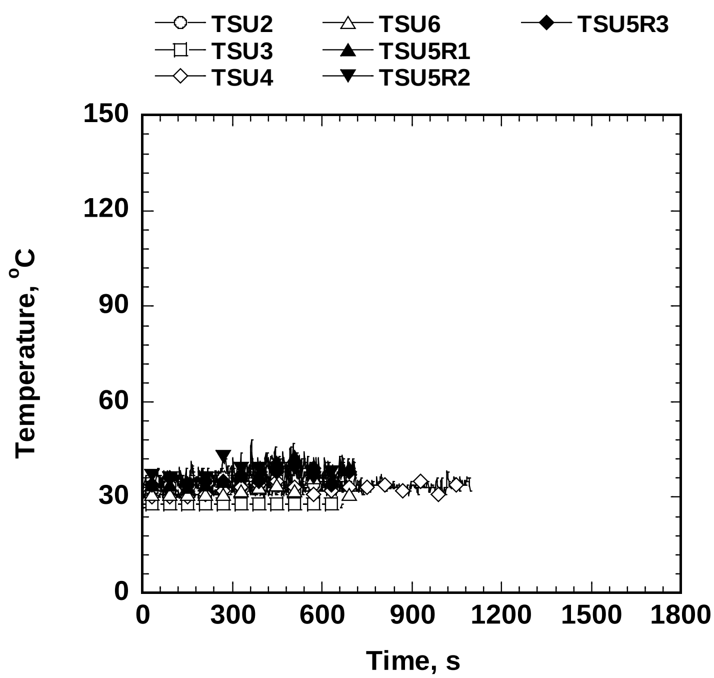

Figure 24. Thermal Environment in Radiant Panel experiments at heat flux of 4.0 kW/m^2.

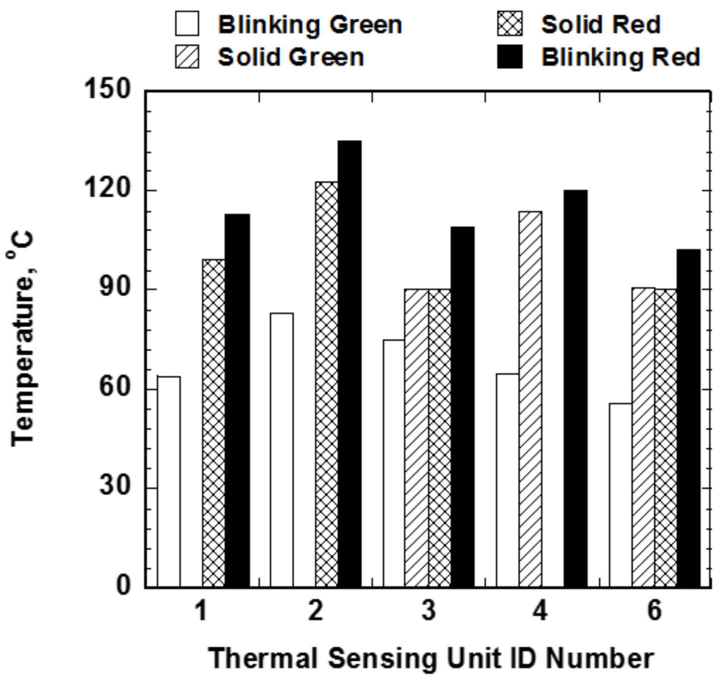

Figure 25. Measured onset temperature of sensors indicators for repeat experiments in the static oven series.

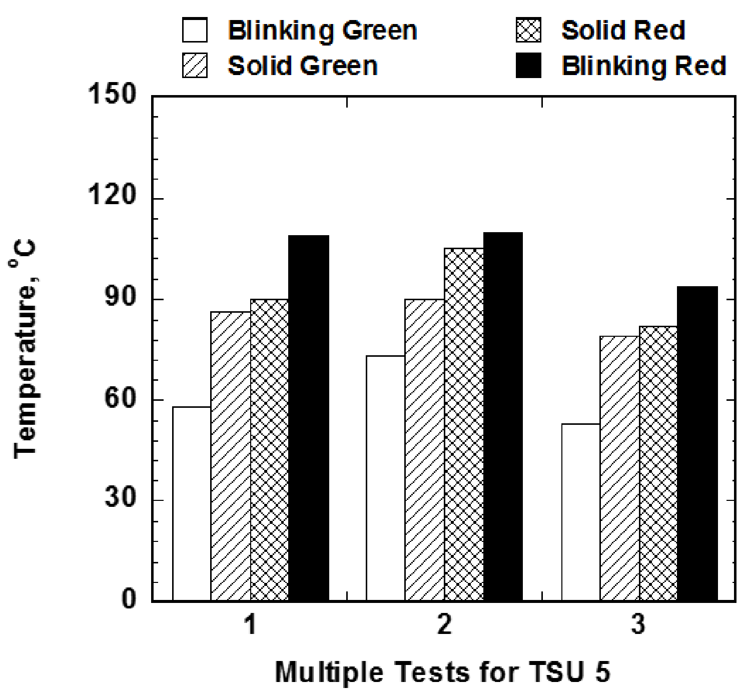

Figure 26. Measured onset temperature of device 5 (TSU #5) indicators for repeat experiments in the static oven series.

4.3 Fire Equipment Evaluator Experiment Results

Table 8 presents the results for the display indicator light conditions as a function of temperature, and Table 9 presents the same data for device 5 (TSU #5). Figure 27 displays the graphical representation of the warning indicators of various devices in the FEE experiment, whereas Figure 28 shows the graphical representation of the warning indicators of device 5 (TSU #5) in three FEE experiments.

As shown in Table 8 and Figure 26, device 1 (TSU #1) ceased to function in the FEE experiment.

Table 8. Performance of different devices in the FEE experiments.

Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
TSU #1	No Status	No Status	No Status	No Status
TSU #2	50	84	87	92
TSU #3	60	100	108	118
TSU #4	65	105	107	107
TSU #6	59	102	108	119

Table 9. Performance of thermal sensing device # 5 in three repetitions of the FEE experiment.

Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
TSU #5 – Rep 1	62	104	111	131
TSU #5 – Rep 2	61	106	110	121
TSU #5 – Rep 3	67	107	114	120

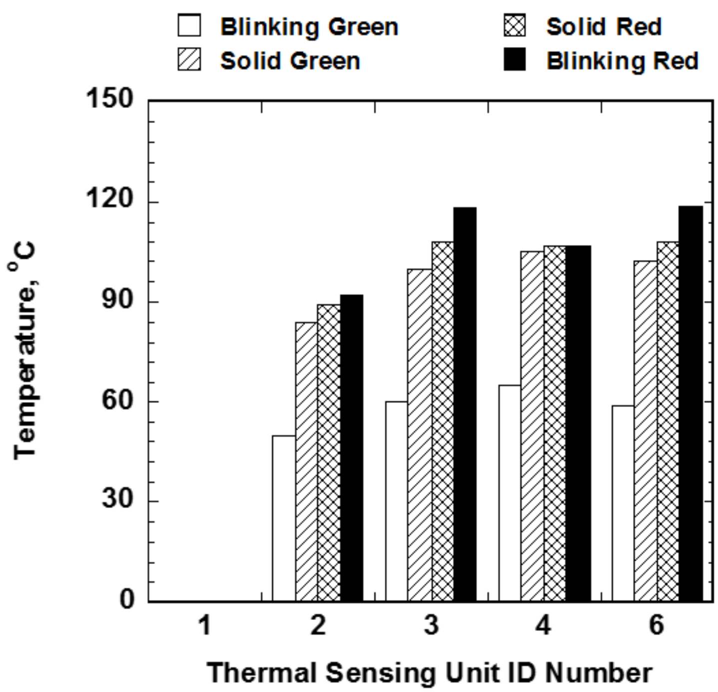

Figure 27. Measured onset temperature of sensors indicators for repeat experiments in the FEE experiments.

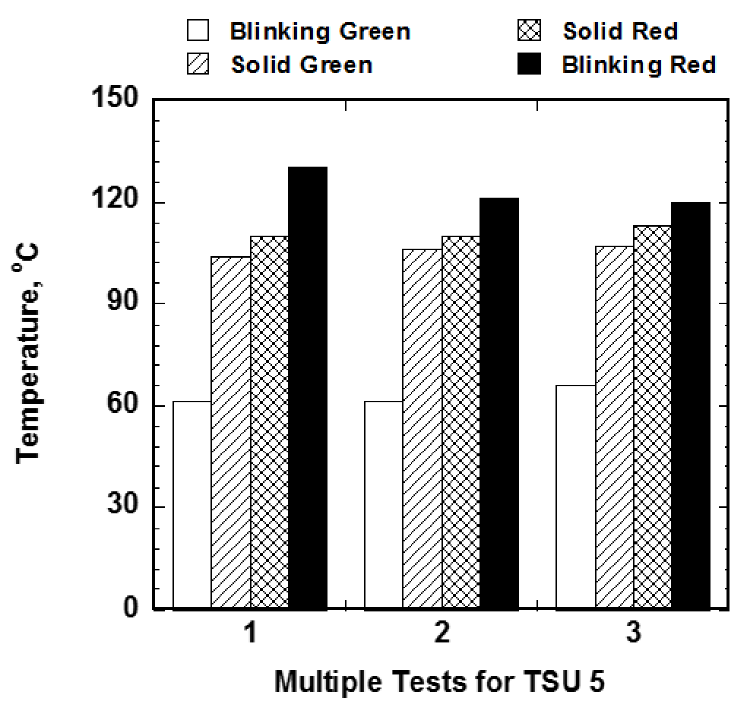

Figure 28. Measured onset temperature of device 5 (TSU #5) indicators for repeat experiments in the FEE series.

4.4 Radiant Panel Experiment Results

Table 10 presents the results for the display indicator light conditions as a function of temperature, and Table 11 presents the same data for device 5 (TSU #5). Figure 29 displays the graphical representation of the warning indicators of various devices in the Radiant Panel experiment at a heat flux level of 1.6 kW/m^2 , whereas Figure 30 shows the graphical representation of the warning indicators of device 5 (TSU #5) in three Radiant Panel experiments at a heat flux of 1.6 kW/m^2.

Table 10: Performance of different devices in radiant panel experiments at a heat flux of 1.6 kW/m^2.

Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
TSU #2	44	87	88	96
TSU #3	48	57	62	58
TSU #4	61	85	86	89
TSU #6	39	40	38	40

Table 11: Performance of thermal sensing device #5 in radiant panel experiments at a heat flux of 1.6 kW/m^2.

Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
TSU #5 – Rep 1	55	72	73	77
TSU #5 – Rep 2	59	85	87	94
TSU #5 – Rep 3	62	87	87	89

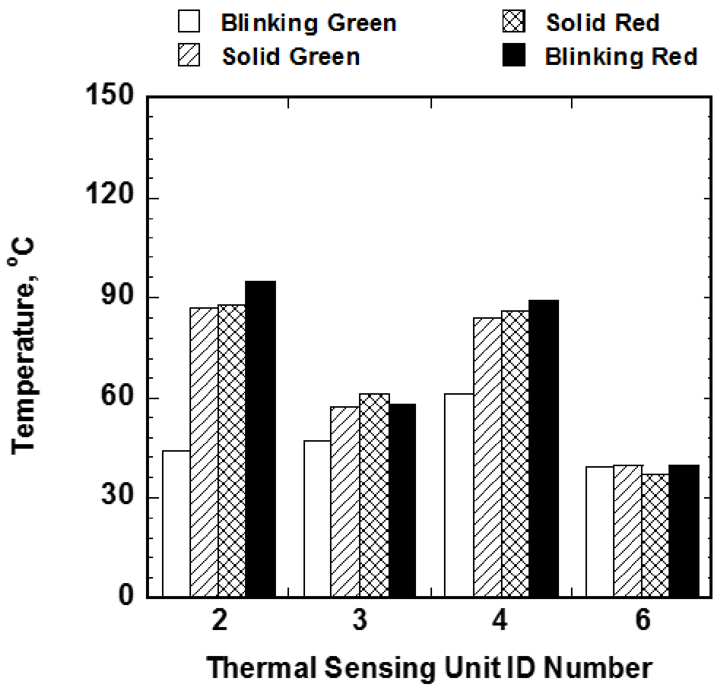

Figure 29. Measured onset temperature of sensors indicators for repeat experiments in the Radiant Panel series at a heat flux of 1.6 kW/m^2.

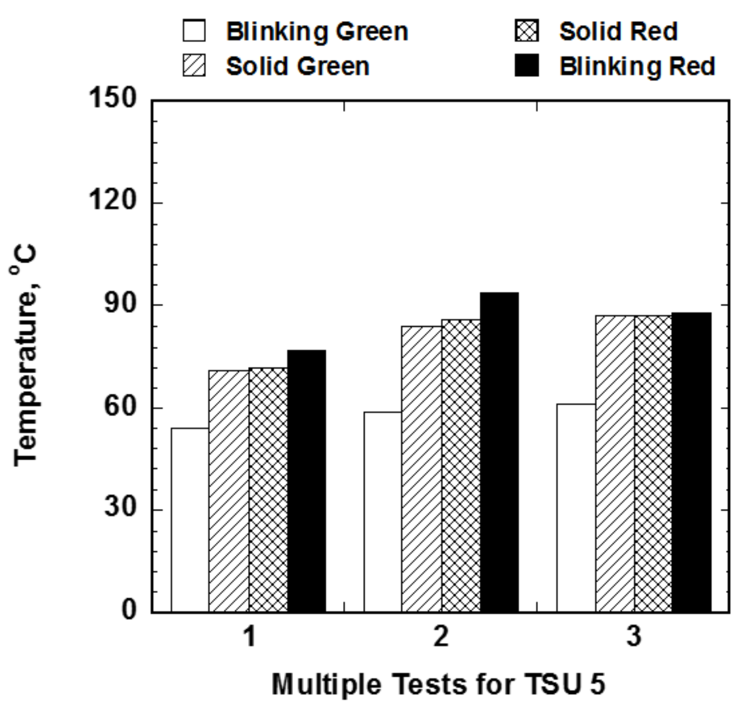

Figure 30. Measured onset temperature of device 5 (TSU #5) indicators for repeat experiments in the Radiant Panel series at a heat flux of 1.6 kW/m^2.

Table 12 presents the results for the display indicator light conditions as a function of temperature, and Table 13 presents the same data for device 5 (TSU #5). Figure 31 displays the graphical representation of the warning indicators of various thermal sensing devices in the Radiant Panel experiment at a heat flux of 4.0 kW/m^2 , whereas Figure 32 shows the graphical representation of the warning indicators of device 5 (TSU #5) in three Radiant Panel experiments at a heat flux of 4.0 kW/m^2.

Table 12: Performance of different devices in the radiant panel experiments at a heat flux of 4.0 kW/m^2.

Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
TSU #2	44	69	81	99
TSU #3	67	90	97	101
TSU #4	74	101	107	126
TSU #6	43	45	47	48

Table 13: Performance of thermal sensing device #5 in the radiant panel experiments at a heat flux of 4.0 kW/m^2.

Device #	Blinking Green (°C)	Solid Green (°C)	Solid Red (°C)	Blinking Red (°C)
TSU #5 – Rep 1	78	109	112	117
TSU #5 – Rep 2	81	103	109	115
TSU #5 – Rep 3	83	102	105	107

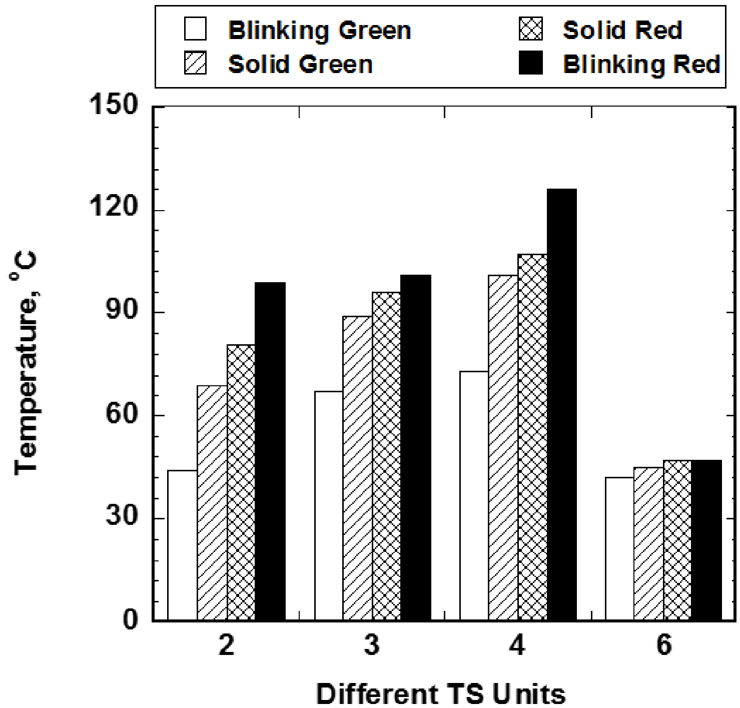

Figure 31. Measured onset temperature of sensors indicators for repeat experiments in the Radiant Panel series at a heat flux of 4.0 kW/m^2.

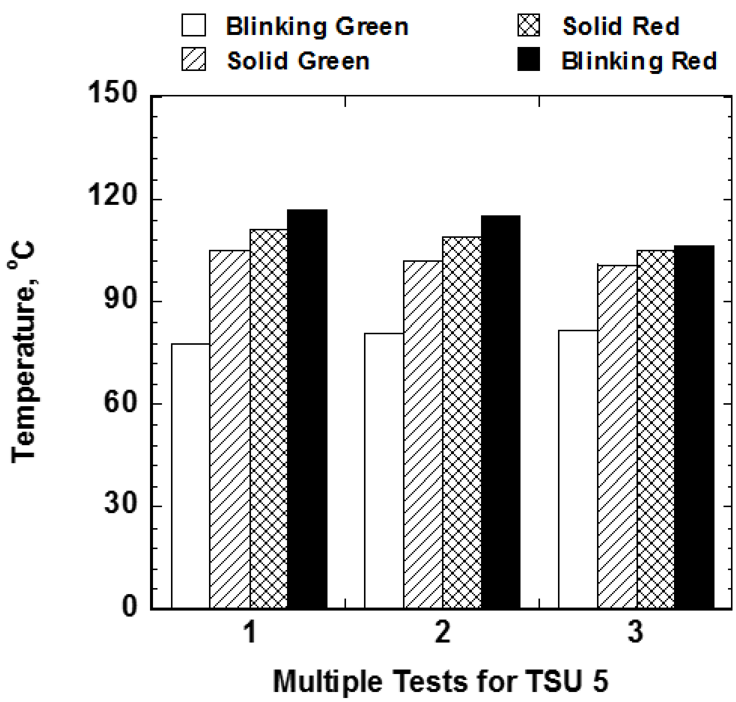

Figure 32. Measured onset temperature of device 5 (TSU #5) indicators for repeat experiments in the Radiant Panel series at a heat flux of 4.0 kW/m^2.

5.0 UNCERTAINTY

There are different components of uncertainty in the positioning, temperature, thermal flux, and time data reported here. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those which are evaluated by statistical methods, and Type B are those which are evaluated by other means [Taylor 1994]. Type B analysis of systematic uncertainties involves estimating the upper (+ a) and lower (- a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is essentially 100 %. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty. Multiplying the combined standard uncertainty by a coverage factor of two results in the expanded uncertainty which corresponds to a 95 % confidence interval (2σ).

Components of uncertainty are tabulated in Table 14. Some of these components, such as the zero and calibration elements, are derived from instrument specifications. Other components, such as radiative cooling/heating include past experience with thermocouples in high temperature environments.

The uncertainty in the air temperature measurements includes radiative cooling in each of the experiments series, but also includes radiative heating for the thermocouple located inside the facepiece. Gas temperature measurements were monitored up 140 ^{o}C. There were no temperature fluctuations of large magnitude and typically the temperature was incremented slowly. Thermocouples were located in hot and cool locations. When positioned in hot gases, the thermocouple beads would have radiated some energy to the cooler objects such as the facepiece or headform and this radiative cooling could have caused the recorded temperature to be lower than the actual gas temperature. On the other hand, a thermocouple positioned inside the facepiece would have been in a cooler environment, but radiation from the panel could had radiated some energy to the thermocouple bead and this could have cause radiative heating of the bead. This could have caused the recorded temperature to be greater than the temperature inside the facepiece. Calibration data was obtained from the thermocouple manufacturer and the measurements were very repeatable. This resulted in an estimate of -15 % to +12 % total expanded uncertainty for the laboratory-scale experiments.

Calibration of heat flux gauges was completed at lower fluxes and then extrapolated to higher values and this resulted in a higher uncertainty in the flux measurement. Combining all of component uncertainties for total heat flux resulted in a total expanded uncertainty of – 23% to + 23 % for the flux measurements. Estimating the uncertainty in the activation temperature for the static oven and flow loop experiments required the uncertainties in air temperature, alarm activation, and repeatability to generate a total expanded uncertainty range of –27 % to +29 %.

In all the experimental experiment series, positioning or locating instrumentation such as thermocouples or heat flux gauges was estimated to have the lowest total expanded uncertainty of ± 11 %.

Table 14: Uncertainty in lab scale experimental data.

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Air Temperature Calibration Radiative Cooling Radiative Heating Repeatability [1] Random [1]	 ± 1 % - 5 % to + 0 % - 0 % to + 2 % ± 5 % ± 3 %	- 8 % to + 6 %	- 15 % to + 12 %
Total Heat Flux Calibration Zero Repeatability [1] Random [1]	 ± 10 % - 2 % to + 2 % ± 5 % ± 3 %	- 12 % to + 12 %	- 23 % to + 23 %
Activation Temperature Zero Temperature Alarm/Light Activation Repeatability [1] Random [1]	 ± 2 % ± 12% -0 % to + 5 % ± 5 % ± 3 %	- 13% to + 14%	- 27 % to + 29 %
Instrument Location Zero Repeatability [1] Random [1]	 ± 1 % ± 5 % ± 2 %	± 5 %	± 11 %

Notes: 1. Random and repeatability evaluated as Type A, other components as Type B.

6.0 DISCUSSION

The evaluation efforts for the situational awareness device in the controlled, laboratory-scale experiments provided significant operational data. Systematic test methods involving conduction, convection, and radiation types of heat transfer were used to evaluate the performance of the thermal sensing units in one or a combination of the three heat transfer conditions.

6.1 Static Oven Experiments

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 °C. Although the thermostat knob was manipulated carefully in an effort to increment the oven temperature by 10 °C every three minutes, the rate of temperature increase was not uniform, and this contributed to the uncertainty in the warning indicator response/activation temperature. The Static Oven experiments provided data indicating that the thermal sensing device could withstand static, hot conditions at temperatures up to 140 °C.

The *repeatability* of the ‘blinking green’ indicator light across the six thermal sensing devices that was examined with respect to temperature was not uniform. The ‘blinking green’ indicator was noted to actuate throughout a large range of temperatures, from 56 °C to 83 °C. Thermal sensing 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 °C to 114 °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 °C to 123 °C, and TSU #4 did not present a ‘solid red’ indicator at all. Finally, the ‘blinking red’ indicator activated across all thermal sensing devices while the environment was cooling, during the experiments used to examine device repeatability. They did so across a wide range of temperatures between 102 °C to 135 °C. These results suggest that repeatability between thermal sensing devices may be spread over a large a range of temperatures.

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

6.2 Fire Equipment Evaluator Experiments

The second method of laboratory-scale examination 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 °C to 140 °C at a steady velocity of 1 m/s and a heat flux of 4 kW/m^2. It should be noted that thermal sensing device #1 failed to display *any* warning indicators during the FEE experiment, suggesting problems with the unit not functioning properly. The 'blinking green' indicator of the other five thermal sensing devices under identical experiment conditions (i.e., repeatability) was noted to actuate throughout a 15 °C range of temperatures, from 50 °C to 65 °C. The 'solid green' indicator was observed to actuate across a wide range of temperatures between 84 °C to 105 °C. The repeatability of the 'solid red' indicator was quite consistent (i.e., 107 °C to 108 °C) with the exception of TSU #2, with its actuation occurring at a temperature of 89 ° C. Finally, the 'blinking red' indicator was noted to activate across a wide range of temperatures, between 92 °C to 119 °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 °C to 66 °C. The 'solid green' indicator was reasonably consistent, ranging from 104 °Cto 107 °C. The reproducibility of the 'solid red' indicator was reasonably consistent, ranging from 110 °C to 114 °C across three trials, and finally, the 'blinking red' indicator was noted to activate between the temperatures of 120 °C to 131 °C when the environment began to cool. These results suggest reasonable reproducibility of a particular thermal sensing device under convective conditions.

6.3 Radiant Panel Experiments

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 and efficient mode of energy transfer and under fire conditions can represent a serious thermal source to which a fire fighter 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 (Donnelly et al., 2006). This energy level may cause burn injuries with prolonged exposure. 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 s 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 fire fighters and their protective gear are routinely exposed.

Even though the Radiant Panel experiments were not able to reach the temperatures of more than 100 °C to 110 °C at the heat flux of 1.6 kW/m^2 (and as described previously), the thermal sensing devices responded rapidly for radiant heat exposures at room temperature as the radiant panel was not an enclosed device. Within the heat flux of 1.6 kW/m^2 and with respect to repeatability, the 'blinking green' indicator of the thermal sensing devices varied between 39 °C to 61 °C. The 'solid green' indicators were observed to actuate between 40 °C to 87 °C, and the 'solid red' indicators actuated within the range of 37 °C to 88 °C. The 'blinking red' indicator was noted to display in the range of 40 °C to 96 °C when the environment began to cool. Thermal sensing devices #2 and #4 appeared to perform similarly for many indicator conditions;

however, thermal sensing 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 thermal sensing device in the Radiant Panel experiments that were conducted in a heat flux of 1.6 kW/m^2, the performance of TSU #5 was largely consistent between 55 ^{o}C to 61 ^{o}C for display of the 'blinking green' indicators. The 'solid green' indicator was noted to actuate between 72 ^{o}C to 87 ^{o}C, and the 'solid red' indicator actuated between 73 ^{o}C to 87 ^{o}C. Finally, the 'blinking red' indicator activated between the temperatures of 77 ^{o}C to 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 examined.

The thermal sensing devices responded most rapidly to the heat flux level of 4.0 kW/m^2. Typically, the thermal sensing devices started displaying the 'blinking green' indicator within 3 minutes of Radiant Panel exposure. The Radiant Panel experiments at this flux exposure 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 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 to 74 ^{o}C. *The 'solid green' indicators were observed to actuate between 45 ^{o}C to 101 ^{o}C, and the 'solid red' indicator actuated between the temperatures of 47 ^{o} C to 107 ^{o}C. Finally, the 'blinking red' indicator was noted to actuate between the temperatures of 48 ^{o}C to 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 rate of heat flux.

The reproducible performance of the device within the heat flux of 4.0 kW/m^2 was largely consistent, with the 'blinking green' indicator actuating between 78 ^{o}C to 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 to 106 ^{o}C, 105 ^{o}C to 112 ^{o}C, and 107 ^{o}C to 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 examined, suggesting that the thermal sensing device maintained reasonable reproducibility at the 4.0 kW/m^2 exposure. This is quite different than the reproducibility at the lower flux of 1.6 kW/m^2 exposure.

7.0 CONCLUSIONS

A total of seven Static Oven experiments and seven FEE experiments were conducted. Two sets of seven experiments were conducted at two different heat flux using the Radiant Panel (i.e., fourteen total experiments). The experiments were conducted to examine performance of personal situational awareness tools/devices 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 thermal sensing device's performance in these varying heat conditions provided evidence to this effect. The range of temperatures catalogued 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 experiments employed, the thermal sensing device exhibited some inconsistencies in performance that give rise to questioning its reproducibility and/or repeatability under certain conditions.

A limited series of thermal exposure experiments in a static oven, a heated flow loop, and a radiant panel provide performance data for thermal sensing technology. Laboratory exposures such as those described in this report provide insight as to how energy or heat transferred via conduction, convection, and radiation can impact the performance of thermal sensing units. These thermal exposures were designed to simulate a fire fighter standing in a hot room (static oven), a fire fighter moving through smoke (heated flow loop), and a fire fighter exposed to a flaming heat source (radiant panel). In each scenario, the thermal sensing units survived the thermal conditions, tracked the gas temperatures, and provided the user with a visual display linked to the thermal conditions. The display of solid or blinking green and red LEDs provided the user with real time update as to the changing thermal conditions.

During thermal exposures, gas temperatures were monitored as well as sensing unit temperatures to characterize how the thermal sensing unit responded to changing thermal conditions. As one would expect, the gas temperatures demonstrate significant differences in thermal conditions from the static oven, heated flow loop, and the radiant panel. These thermal sensing units responded in a similar manner whether in the static oven, heated flow loop, or radiant panel. This suggests that this implementation of thermal sensing technology would provide the fire fighter with information about the thermal conditions whether the fire fighter was standing still, moving through smoke, or exposed to flaming conditions. The differences observed in the gas temperatures also demonstrate the need to examine the performance of all situational awareness technology in each of the scenarios. Standard testing protocols need to include conduction-, convection-, and radiation-dominated thermal conditions because fire fighters are exposed to all three scenarios. While these laboratory scale exposure allow the conditions to be carefully controlled, there will still be a need to conduct full-scale experiments in order to ensure the technology performs under real fire conditions.

Thermal sensing units can provide a fire fighter or emergency responder with information about their environment, but currently technology can only provide a snapshot of current conditions. The technology may include some past exposure as it displays information, but the technology can not predict future conditions. In this work, a thermal sensing unit can detect the change from previous thermal conditions, but it can’t predict whether a fire is decreasing or increasing in heat release rate. This implementation of thermal sensing technology displays a change in conditions, but does not provide information about how long the fire fighter has been exposed to these conditions or whether the fire fighter should evacuate. Obviously, thermal sensing units can only help the fire fighter be aware of their environment and their response or action to that information rests on their training and their ability to use the information.

Situational awareness technology can provide the fire service with more information that can be utilized by the fire fighter to understand the thermal conditions in which they are operating. With training, the fire fighter will be better able to use this data to work more safely and more effectively. It will be important that all situational awareness technology be able to survive and function in the range of conditions that fire fighters experience. Representative performance metrics and standard testing protocols would allow the fire service to understand better the performance characteristics of the thermal sensors. In addition, a standardized testing protocol would allow the manufacturers to match the performance of their devices with the requirements of the fire service.

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