NIST Technical Note 1724

Fire Exposures of Fire Fighter Self-Contained Breathing Apparatus Facepiece Lenses

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National Institute of Standards and Technology • U.S. Department of Commerce

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FIRE EXPOSURES OF FIRE FIGHTER SELF-CONTAINED BREATHING APPARATUS FACEPIECE LENSES

ABSTRACT

Fire fighters are exposed to highly variable environments including elevated temperatures and convective and radiant thermal flux, which can put a significant burden on personal protective equipment. Thermally degraded and melted self-contained breathing apparatus (SCBA) facepieces have been identified as a contributing factor in certain fire fighter fatalities and injuries in the United States. The SCBA facepiece lens is often considered the weakest component of a fire fighter's ensemble in high heat conditions, but the level of thermal performance of the facepiece lens is not well understood. These experiments, conducted by the National Institute of Standards and Technology (NIST), demonstrated a range of realistic thermal exposures and environmental conditions, which can result in thermal degradation and even catastrophic failure of facepieces. SCBA facepieces were exposed to thermal environments from propane-fueled calibration experiments and furnished townhouse fire experiments. The rooms and the facepieces were instrumented to measure temperatures of the environment and the facepieces. The fire experiments lasted 5 min to 10 min and produced ceiling temperatures of approximately 500 °C (932 °F) to 750 °C (1382 °F) in the room adjacent to the fire. A heat flux gauge was also installed next to the facepieces and measured peak heat fluxes from approximately 2 kW/m^2 to 55 kW/m^2. Eight facepieces were tested in six different experiments, with three facepiece lenses showing evidence of thermal degradation from the exposure. Maximum exterior lens temperatures were as high as 300 °C (572 °F) in these cases. The environments that caused the failures were identified in an attempt to characterize the thermal performance of SCBA facepieces. Constant airflow at 40 L/min was introduced into three of the facepieces to study if there is a cooling effect associated with breathing. The facepieces with airflow did have a slightly increased temperature difference between the interior and exterior lens surfaces as compared to facepiece lenses without airflow in the same experiment. Although much was learned about conditions associated with thermal degradation of SCBA facepiece lenses, more experiments are needed to understand the thermal degradation and more definitively predict the conditions that are likely to cause a facepiece lens failure. These experiments were conducted with the support of the Chicago Fire Department, the Department of Homeland Security, and the U.S. Fire Administration.

Keywords: fire environment; lens; performance metrics; radiant heat flux; lens; respirator; self-contained breathing apparatus; SCBA

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1. INTRODUCTION

Respiratory protection, in the form of a self-contained breathing apparatus (SCBA), is a critical component of a fire fighter's personal protective equipment because it protects the wearer from inhaling the life threatening atmosphere often present in and around the fire ground [1]. The SCBA lens forms a critical barrier that is designed to withstand physical and thermal impacts while maintaining integrity and visual acuity. Polycarbonate (PC) has been the material used for the lens of the modern SCBA for fire fighting applications due to its optical clarity, impact resistance, and thermal resistance. The SCBA lens typically has an abrasion-resistant coating to minimize scratching as well. The glass transition (softening) temperature of polycarbonate as reported in the literature is between 145 °C (293 °F) and 150 °C (302 °F) [2]. Melting temperatures can vary widely depending on the type of polycarbonate, between 215 °C (419 °F) and 338 °C (640 °F) [2-3].

The thermal environments that fire fighters are exposed to in structural fires are highly variable, and depend on many factors including fuel type and load (furniture, carpeting, etc.), interior finish, ventilation conditions, and structure layout and construction. Studies on fire fighter protective clothing [4-6] have described pre-flashover fire fighting environments with temperatures between 100 °C (212 °F) and 300 °C (572 °F) and maximum heat fluxes between 5 kW/m^2 and 12 kW/m^2. More dangerous fire fighting environments where protective clothing has been studied, are characterized by temperatures up to 700 °C (1292 °F) and heat fluxes of 20 kW/m^2 to 40 kW/m^2 [5-7]. However, conditions of flashover and post-flashover can reach 1000 °C (1832 °F) and 170 kW/m^2 [8]. Donnelly et al. [9] reviewed various reports and articles from the literature, which classified fire fighting environments into categories and specified the maximum time, temperature and heat flux associated with each class of exposure. The result was a recommendation of four thermal classes, which are displayed graphically in Figure 1. The maximum time for each class is listed within the shaded area showing the range of air temperatures and heat flux values for each thermal class. Thermal classes such as these can be used to establish performance requirements of protective equipment standards.

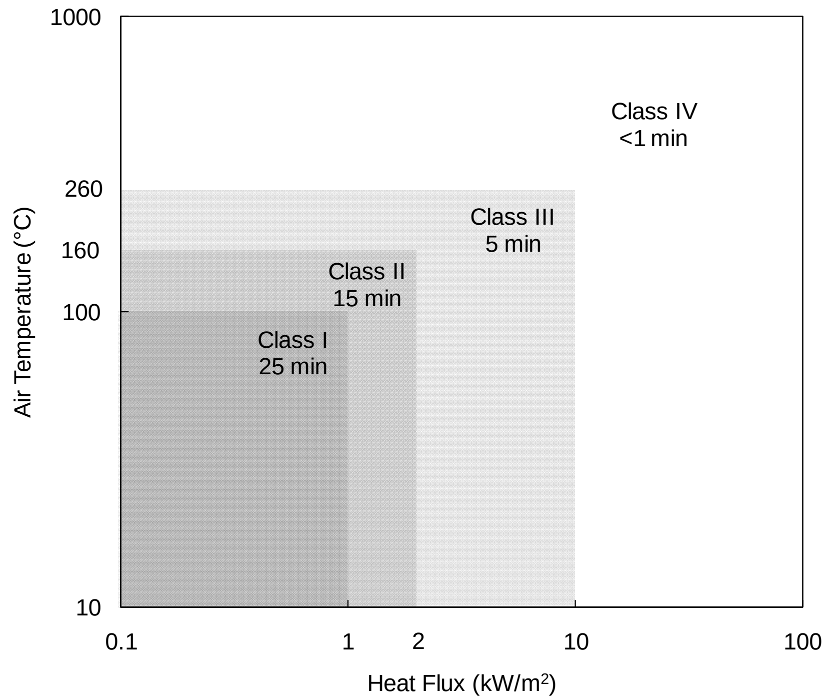

Figure 1 – Graphical representation of the recommendations for thermal classes of fire fighter environments, from Donnelly et al., 2006 [9], showing range of air temperature, heat flux and duration.

Currently in the US, the certification test that involves the most severe thermal exposure for an SCBA is the Heat and Flame Test, Section 8.11 of NFPA Standard 1981 – Open Circuit Self-Contained Breathing Apparatus (SCBA) For Emergency Services [10]. In this test, the SCBA is mounted on a test headform breathing at 40 L/min and placed in a convection oven at 95 °C (203 °F) for 15 minutes. This exposure would be classified as Class I in Figure 1. No more than 20 s later, the breathing rate is increased to 103 L/min, and the SCBA is exposed to direct flame contact for 10 s. The direct flame contact peak temperature is specified to be between 815 °C (1499 °F) and 1150 °C (2102 °F). Therefore, the second portion of the test fits into Class IV from Figure 1. Following the heat exposures, the headform is dropped from a height of 15.2 cm (6 in). The SCBA is tested for airflow performance and for visual acuity. Although this test involves elevated temperatures, it does not capture the conditions of temperature, heat flux and duration that a fire fighter may experience [4 – 9].

The need for improved SCBA and facepiece design to withstand a variety of extreme conditions, including high heat loads, was documented in a U.S. Fire Administration special report in 2001 [11]. In the decade since, several reports on fire fighter fatalities have indicated that inadequate thermal performance of the SCBA lens was a contributing cause to one or more fire fighter fatalities [12-18]. The SCBA facepieces displayed extensive damage to the point where the SCBA could no longer provide protection from the environment. The assumption was that the facepieces failed before the fatalities occurred, because the facepieces were still found on the victims, and thermal burns were found on the trachea of the victims. In addition, there have been numerous anecdotal accounts of crazing, bubbling, and softening of lenses, some of which have been reported as near misses [19-22]. The thermal exposure in these specific incidents is not known. There is a significant lack of information regarding the high temperature and high heat flux performance of SCBA. In addition, the specific types of thermal exposures or environmental conditions causing the failures have not been identified.

One study by Quintiere [23] on the radiative and convective heating of a polycarbonate face shield, which is typically fastened to a fire fighter's helmet, gives some indication of the thermal limits of the SCBA lens. Although the face shield considered was of polycarbonate material like an SCBA lens, a face shield is only intended to provide protection from debris and heat, and not to provide respiratory protection. The study involved a one dimensional theoretical heat transfer analysis, followed by a limited experimental validation using a natural gas-fired radiant panel. The "failure" criterion was considered to be the point when the face shield reached 140 °C, the "softening" or glass transition temperature of polycarbonate. The time to "failure" was analytically determined as a function of incident heat flux and ambient air temperature. Two experiments were performed for an incident heat flux of 1.3 kW/m^2 and 11.7 kW/m^2, and the face shield temperature was measured as a function of time. For 1.3 kW/m^2 at 300 s, the face shield temperature was 110 °C (230 °F). For 11.7 kW/m^2, the face shield reached 140 °C (284 °F) at 60 s into the experiment. The differences observed between the experimental results and the analytical predictions were attributed to inaccuracies in the heat flux measurement, and the effects of changing ambient air temperature and air flows. These experimental issues allowed only limited conclusions to be drawn about polycarbonate thermal capabilities. In addition, there are boundary condition differences to consider between an SCBA facepiece and a face shield. The face shield was surrounded by ambient air on both sides, but an SCBA facepiece lens has different air flows on both sides. The outside of a facepiece lens is at ambient temperature, but the inside is exposed to breathing air, and would be cooled by the flow of breathing air during firefighting.

A report by Held and Harder investigated SCBA models available in 1980 while exposed to a variety of temperature extremes [24]. SCBA facepieces were exposed to elevated temperatures of 38 °C (100 °F), 52 °C (125 °F), 65 °C (149 °F), 79 °C (174 °F), 93 °C (199 °F), and 250 °C (482 °F), a propane flame at 1050 °C (1922 °F) for 10 s, and a natural gas flame at 1000 °C (1832 °F) to 1500 °C (2732 °F) for 2 s and 4 s. During most of the tests, breathing was simulated with a breathing machine set at a breathing rate of 52 L/min. The internal facepiece pressure was measured throughout the tests. For temperatures up to 93 °C (199 °F), no thermal damage was observed, but some SCBA units, which were designed to maintain positive pressure, had negative pressures on inhalation at the elevated temperatures. When facepieces were exposed to 93 °C (199 °F) for 10 min followed by a light impact, some lenses separated from the retaining frame. During the exposure of 250 °C (482 °F) for 3 min, melting of plastic components and negative pressures were observed. The first flame test consisted of two exposures to 6 propane burners for 5 s each, after which flames remained on the plastic exhalation valve covers. The second flame exposure was designed to simulate a "flash-back" in a fire scene. The test consisted of a natural gas flame 1000 °C (1832 °F) to 1500 °C (2732 °F) exposure for 2 s and 4 s with a burner containing 8 jets spaced approximately 12.7 cm (5 in) apart. The breathing rate was 40 L/min. These experiments observed failures (melting and after-flaming) of plastic components of the facepiece such as straps, hoses, and the speaking diaphragm. Some bubbling of the lens was observed in some cases, although no lenses degraded to the point of failure. The authors recommended more radiant heat tests, which they suspected would cause the most damage to the straps. The resulting failures of many different components of the SCBA led to the adoption of the Heat and Flame Test in the NFPA 1981 document, which included a burner array exposure for 10 s [10] similar to the second flame exposure tested by Held and Harder. This standard test improved the design of the SCBA at that time and eliminated certain flammable and melting components.

The experiments in this report attempted to characterize the thermal performance of the SCBA facepiece lens in realistic fire environments. The facepiece exposures reported here were part of a set of fire experiments designed to study the effects of ventilation and suppression on fires in two-story townhouses in Bensenville, IL [25]. SCBA facepieces were placed in some of the townhouses during the experiments to measure the lens temperature rise in realistic fires, and assess associated damage to the facepiece lenses. The objective of these experiments was to obtain information on the temperature, heat flux, and duration of exposure associated with crazing, bubbling, and softening of the SCBA lens. Examples of the appearance of these degrees of thermal degradation to facepiece lenses are shown in Figure 2.

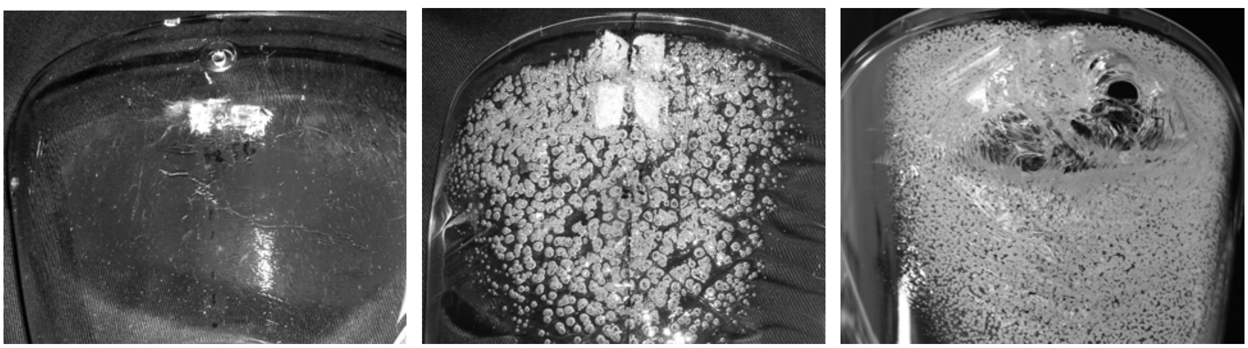

Figure 2 – Photos showing examples of crazing (left), bubbling (center), and deformation from softening and bubbling (right) of facepiece lenses.

2. UNCERTAINTY ANALYSIS

There are different components of uncertainty in the length, temperature, heat flux, and flow rate provided in this report. 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 [26]. 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 very close to 100 %. For some of these components, such as the zero and calibration elements, uncertainties are derived from instrument specifications. Uncertainty is reported in this study as the total expanded uncertainty, with a coverage factor of 2 and a confidence level of approximately 95 %.

Each length measurement was carefully taken. Length measurements such as room dimensions, instrumentation array locations and furniture placement were made with steel tape measures with a resolution of ± 0.5 mm (0.02 in). However, conditions affecting the measurement, such as levelness or tautness of the device, yield an estimated estimated uncertainty of ± 0.5 % for measurements in the 0.0 m (0.0 ft) to 3.0 m (9.8 ft) range. Some issues, such as “soft” edges on the upholstered furniture, or longer distances in excess of 3.0 m (9.8 ft) result in an estimated total expanded uncertainty of ± 1.0 %.

The times of various events, such as window and door openings, reported in the results were obtained carefully from either stopwatches or video footage of the experiments. Total expanded uncertainties in this measurement are estimated to be less than ± 5 s.

The component uncertainty in temperature of the thermocouple wire itself is ± 2.2 °C (36 °F) below 293 °C (559 °F) and ± 0.75 % at higher temperatures as determined by the manufacturer [27]. The variation of the temperature in the environment surrounding the thermocouple is known to be much greater than that of the wire uncertainty [28-29]. Thermocouples that were located closer to the floor were radiatively heated by the walls, gases and smoke in the hot upper layer. On the other hand, thermocouples toward the ceiling were radiatively cooled by the lower gas layer and floor. Small diameter thermocouples (AWG 30) were used to limit the impact of radiative heating and cooling of the thermocouple beads. Based on previous structure burn experiments, the total expanded uncertainty for temperature in these experiments is estimated to be ± 15 % [25].

In this study total heat flux measurements were made with water-cooled Schmidt-Boelter gauges. The manufacturer reports a ± 3 % calibration component uncertainty for these devices [30]. Results from an international study on total heat flux gauge calibration and response demonstrated that the expanded uncertainty of a Schmidt-Boelter gauge is typically ± 8 % [31]. Total expanded uncertainty for heat flux measurements is estimated to be ± 16 %.

The propane flowrate to the calibration burner was regulated by a mass flow controller with a manufacturer reported expanded uncertainty of ± 1 %. Constant airflow through the facepiece was established with an exterior pump. The air flowrate was measured by a variable area flowmeter with a manufacturer reported expanded uncertainty of ± 4 %. However, the variation of the pump contributed to fluctuations in the air flowrate estimated to be approximately ± 0.5 L/min. The total expanded uncertainty for the air flowrate is estimated to be ± 3 L/min.

3. EXPERIMENTAL SETUP

Five models of SCBA facepieces were exposed to realistic fire environments including high temperatures, and convective and radiative heat flux. All facepiece models have a 2 mm to 3 mm thick polycarbonate lens with relatively similar geometry. The experiments exposing one or two facepieces at a time, were conducted in furnished two-story townhouses. There were three different types of experiments, which exposed the facepieces to different levels of heat flux and temperature:

1. Calibration experiment with a propane burner with a heat release rate less than 150 kW in the center of the living room and the facepieces placed in the same room.
2. House fire experiment with ignition in a fully furnished living room leading to flashover. Facepieces were placed in the kitchen.
3. House fire experiment with ignition in fully furnished living room leading to flashover. Facepieces were placed on the front porch facing the front doorway.

The floorplan of the first floor of the townhouse including the kitchen and living room is shown in Figure 3. The dimensions of the rooms and doors are listed.

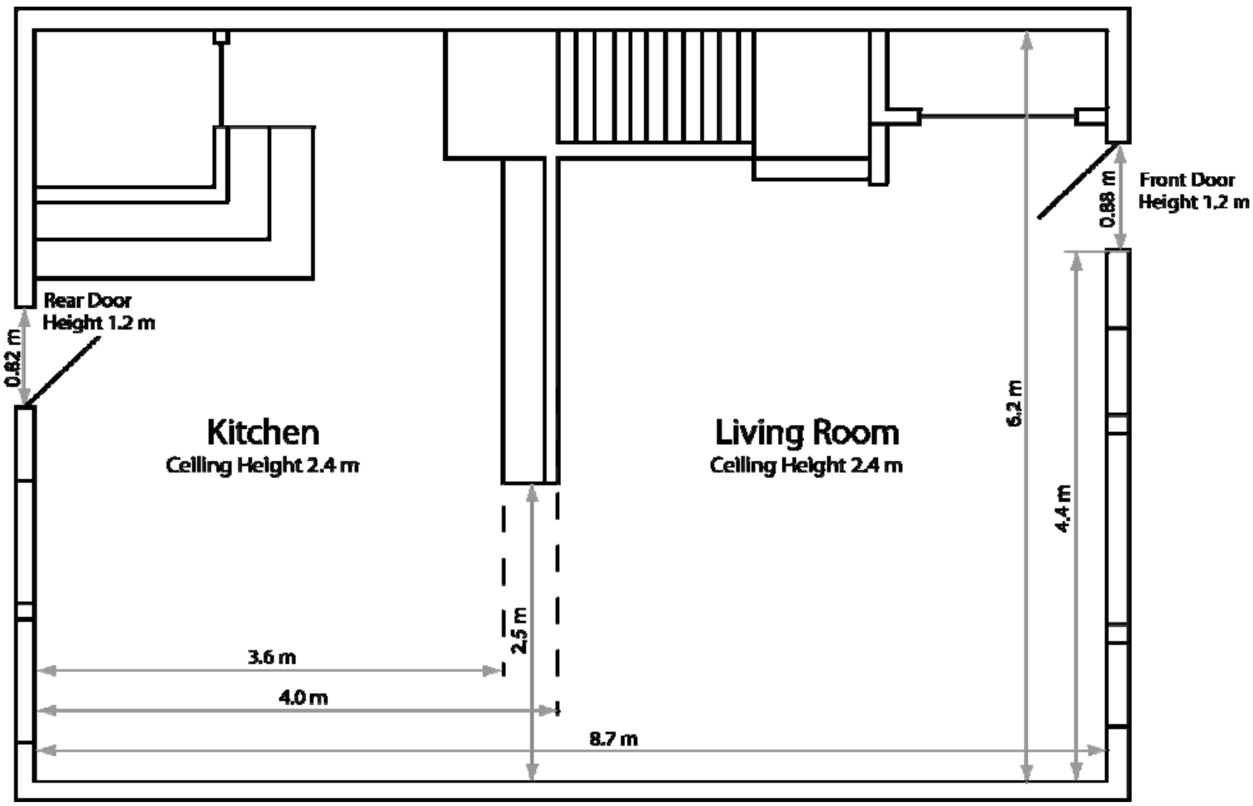

Figure 3 – Floorplan of the first level of the townhouses, showing room and door dimensions.

The temperature of the surrounding environment, the heat flux, and the duration of exposure are all important parameters for characterizing the severity of a thermal exposure. Temperatures were measured by a vertical array of 0.51 mm (0.02 in) nominal diameter bare bead, Type K thermocouples hung from the ceiling to the floor in the center of each room of the house for all the experiments. In each array, a thermocouple was located 0.305 m, 0.610 m, 0.914 m, 1.22 m, 1.52 m, 1.83 m, 2.13 m, and 2.41 m (1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 6 ft, 7 ft, and 7 ft 11 in) above the floor, to measure the temperature throughout the thermal layer of the room.

The approximate total heat flux seen by the facepiece lenses was measured by a 2.54 cm (1 in) diameter Schmidt-Boelter water cooled total heat flux gauge protected with ceramic fiber insulation and aluminum foil. The heat flux gauge was installed next to, and facing the same direction as the facepieces, 1 m above the ground as shown in Figure 4 (left). The upper range of the heat flux gauge was 200 kW/m^2. Temperature and heat flux data were sampled at a rate of 1 Hz and recorded with a computerized data acquisition system.

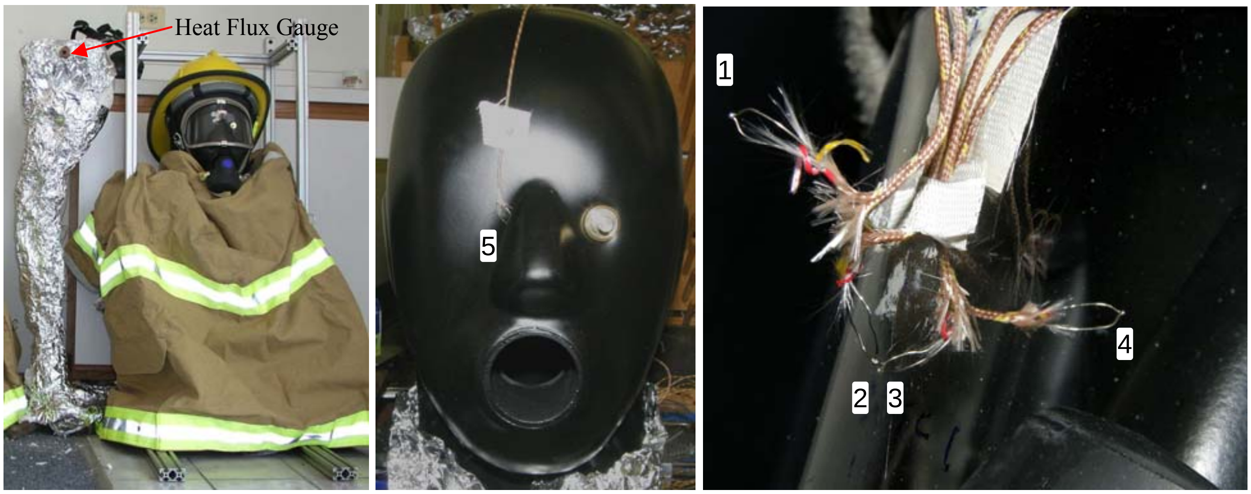

Figure 4 – (left) Picture of the test stand setup of headform, hood, helmet, SCBA facepiece, regulator, and turnout coat next to the heat flux gauge, (middle) the polyurethane headform with a thermocouple on the surface, and (right) a close-up view of the four thermocouples arranged on and around the lens.

3.1. SCBA Facepiece Setup

The facepieces were mounted on a polyurethane headform made by Biosystems PosiChek3, which is designed for SCBA air flow performance testing, shown in Figure 4 (middle). The headform was bolted to a board which was placed into the aluminum test stand. The base of the headform was located 0.77 m (31 in) above the floor. Fire fighter protective gear was used to protect the test stand and associated components. A nomex hood and helmet were placed on the headform to protect the polyurethane not covered by the facepiece, and a turnout coat was draped around the front of the stand, below the base of the headform. The test stand arrangement, including the headform, hood, helmet, SCBA facepiece, regulator, and turnout coat, is shown in Figure 4 (left).

Some of the experiments included airflow through the facepiece to examine the cooling effect of air flowing along the interior surfaces of the facepiece lens. A pump located outside of the building forced air at a constant flowrate through the headform neck and then mouth section and out the one way valves in the facepiece. The constant flowrate used was 40 L/min, equivalent to the average ventilation rate for the lower breathing rate specified in the NFPA 1981 airflow performance test [10]. Although the instantaneous flowrate through the facepiece is higher than 40 L/min at certain points in the breathing waveform, using the average flowrate demonstrated whether moving air has an effect on the temperatures of the facepiece lens.

Thermocouples were placed at five locations around the facepiece to measure air and surface temperatures. The thermocouples were secured to the lens and the headform with high temperature fiberglass tape placed over the wire. The thermocouple wire was formed and shaped in order for the bead to touch the appropriate surface or air space. A mark was made along the vertical centerline of the lens, 4.5 cm below the top edge of the exposed portion of the lens. This location was used for thermocouple placement for every facepiece. The air thermocouples were located approximately 1.0 cm ± 0.5 cm away from the lens surface. The locations are defined in Table 1.

Table 1 – Thermocouple locations around the facepiece.

TC	*Location*	*Description*
1	Outside air	In the air just in front of the lens.
2	Lens ext.	On the outside surface of the lens.
3	Lens int.	On the inside surface of the lens.
4	Inside air	In the air between the lens and head.
5	Headform	On the surface of the test head.

The first four thermocouples are shown in a close-up view of an SCBA lens in Figure 4 (right), and the fifth is shown on the headform in Figure 4 (middle).

3.2. Propane Fire Experiments Setup

Propane fire experiments were performed with two facepieces placed between the kitchen and living room and facing a propane burner in the living room, as shown in Figure 5 (locations I and II). In one of the calibration experiments, there was airflow through one of the facepieces. The propane used was at least 99 % pure. The approximate heat release rate of the burner was calculated from the propane flow rate assuming a chemical heat of combustion of 43.7 kJ/g [33]. The heat flux gauge was located between the facepieces also facing the burner, and a thermocouple array was placed in the center of the living room. The heat flux gauge and thermocouple array are labeled HF and TC respectively in Figure 5. The dimensions of the propane burner are also shown.

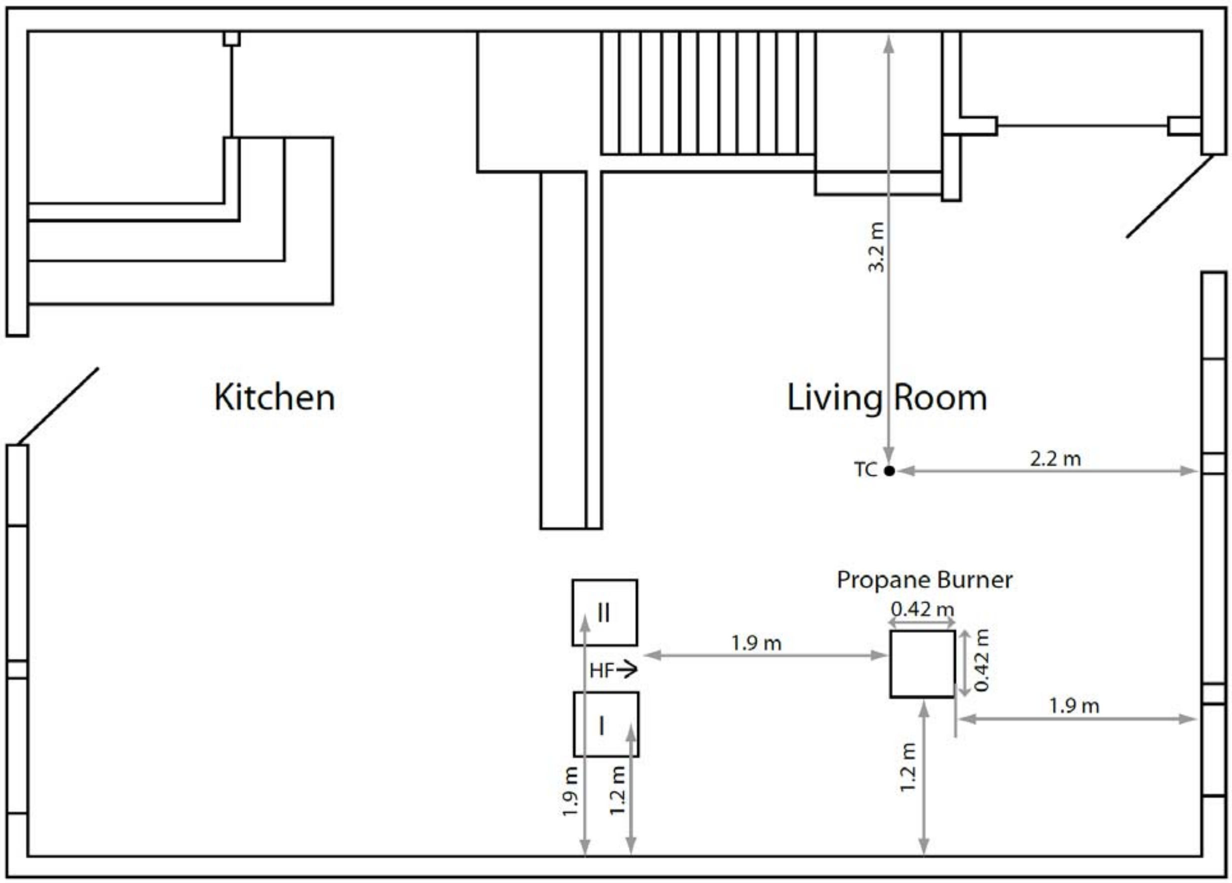

Figure 5 – Calibration experiment configuration of the first story of a townhouse, showing the living room locations of the propane burner, the two facepieces, and the heat flux gauge.

3.3. Furnished House Fire Experiments Setup

The room of origin of the fire was the living room, which was furnished with typical living room furniture including sofas, chairs, tables, lamps, cabinets, etc. Like furniture pieces made by the same manufacturer that had similar build dates were obtained from the same source to ensure that the fuel load was the same for each experiment. The kitchen did not contain any furniture other than the permanently installed cabinets and appliances. The fires were ignited by an electric match located on a sofa in the living room. An electric match is a segment of nickel-chromium wire placed in an open book of paper matches. The wire is heated by applying a voltage resulting in the ignition of the matches and the surrounding furniture fabric. Additional details regarding the experimental setup and conditions can be found in a report of the test by Madrzykowski, et al. [25].

The facepieces were located in the kitchen for the first three fire experiments (locations I and II), as shown in Figure 6. The dimensions of the rooms on the first floor of the townhouse are shown again, as well as the locations of the facepieces, heat flux gauges (labeled HF), and thermocouple arrays (labeled TC). The facepieces were arranged to simulate the location of a fire fighter who is in a hot and smoky environment, but not necessarily in the room with the fire. Video from the experiments showed no flames in the kitchen. Therefore, the facepieces were probably exposed to mostly convective heat from the hot gases produced in the adjacent room, and a smaller contribution of radiant heat from the hot gas layer in the kitchen. The fires were allowed to develop to flashover in the living room, and were suppressed approximately five minutes after ignition. In the second experiment, airflow was pumped through one of the facepieces. In the first and third experiments, none of the facepieces had any air flow.

For the fourth fire experiment, one facepiece was located on the front porch facing the front doorway, shown in Figure 6 (location III). This experiment also incorporated airflow through the facepiece. This scenario would represent the location as a fire fighter is approaching the front door. For the first five minutes, the fire was allowed to develop with the door closed, blocking the fire from the facepiece. Then the door was opened, and the facepiece was exposed for about four minutes. Suppression of the fire began approximately ten minutes after ignition. Therefore, the duration of exposure was approximately the same as the other fire experiments, five minutes. Because the facepiece lens had a direct line of sight view of the fire for this scenario, this exposure emphasized radiant heat flux over convective heat flux.

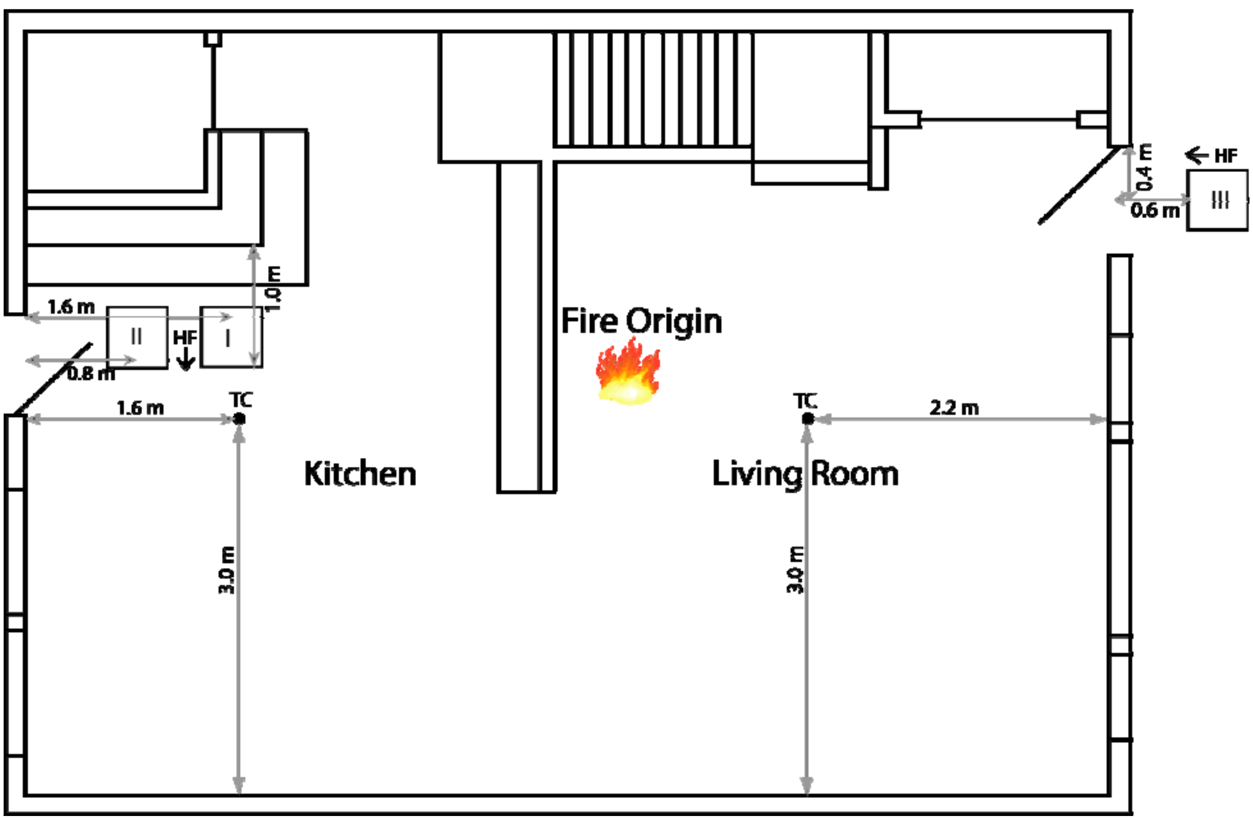

Figure 6 – Fire experiment configuration of the first story of a townhouse, showing the locations of the fire origin, the two facepieces (locations I and II) for the kitchen placement, the facepiece (location III) for the porch placement, and the heat flux gauges.

4. RESULTS

A total of eight facepieces were exposed to heat in two calibration experiments and four fire experiments. The types of experiments and facepieces used are listed in Table 2. Five different types of facepieces from different SCBA manufacturers were used in the experiments. Different facepiece models were designated by a letter, A-E, and each facepiece was given a number. For example the same facepieces, A2 and B2, were used in both calibration experiments.

Table 2 – List of calibration and fire experiments performed and the facepiece samples tested.

Experiment Number – Street Address	*Facepiece Sample*	*Facepiece Airflow*	*Location*
Calibration Experiment #1 – Sunset 8	A2	--	Living room, location I (Fig. 4), 1.9 m from burner
	B2	--	Living room, location II (Fig. 4), 1.9 m from burner
Calibration Experiment #2 – Sunset 8	A2	--	Living room, location I (Fig. 4), 1.9 m from burner
	B2	40 L/min	Living room, location II (Fig. 4), 1.9 m from burner
Fire Experiment #1 – Hamilton 125	B1	--	Kitchen, location I (Fig. 5), 1.6 m from rear door
	A1	--	Kitchen, location II (Fig. 5), 0.8 m from rear door
Fire Experiment #2 – Sunset 8	C1	--	Kitchen, location I (Fig. 5), 1.6 m from rear door
	C2	40 L/min	Kitchen, location II (Fig. 5), 0.8 m from rear door
Fire Experiment #3 – Sunset 18	D1	--	Kitchen, location I (Fig. 5), 1.6 m from rear door
	E1	--	Kitchen, location II (Fig. 5), 0.8 m from rear door
Fire Experiment #4 – Sunset 34	B2	40 L/min	Front porch, location III (Fig. 5), 0.6 m from front door

4.1. Propane Fire Experiments

The first calibration experiment began with an approximate heat release rate (HRR) of 100 kW. At 345 s after ignition, the flow of propane was increased corresponding to an approximate HRR of 130 kW. At 600 s, the fuel was shut off. All doors and windows were closed for the experiment except the front door, which was open for the first 20 s and then closed for the remainder of the experiment. There was no airflow through either of the facepieces. The room environment is characterized in Figure 7, which shows the temperatures measured by the thermocouple array in the center of the living room. The peak temperature at the ceiling was around 120 °C (248 °F) for both experiments. The incident heat flux near the facepieces is plotted in Figure 8. Both experiments included two facepieces, A2 at location I and B2 at location II in Figure 5. Figures 9 and 10 show the facepiece temperatures from the thermocouples located on A2 and B2 in the first calibration experiment. Although data was recorded every second, the data have been time averaged and plotted every 10 s for clarity.

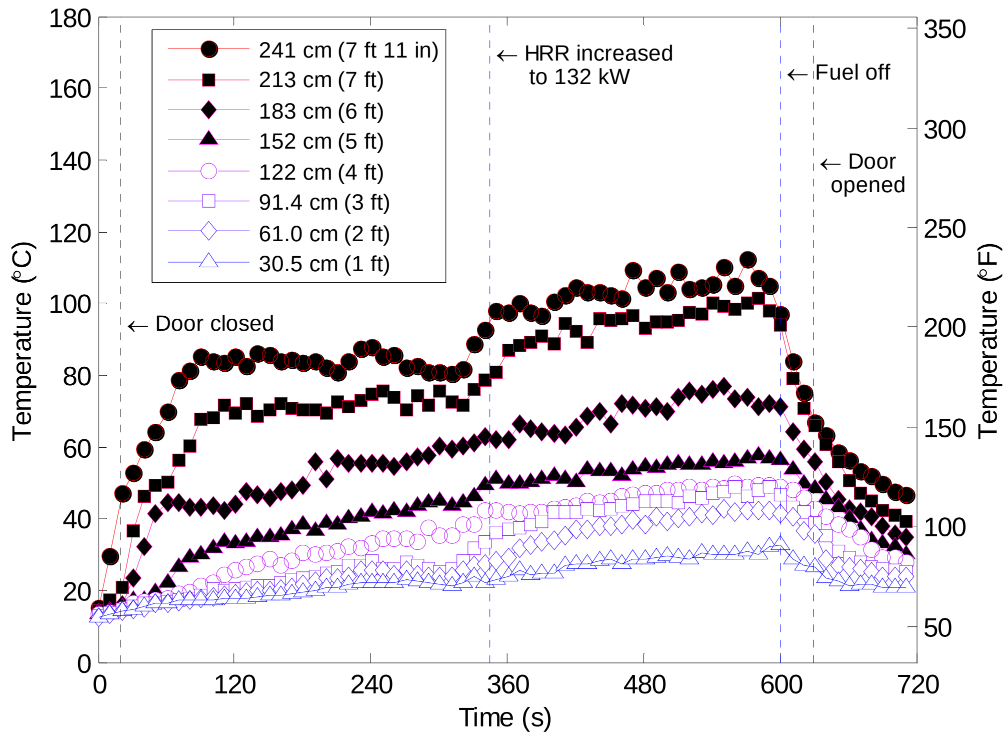

Figure 7 – Living room air temperatures from the thermocouple array (distances measured from the floor) during calibration experiment #1.

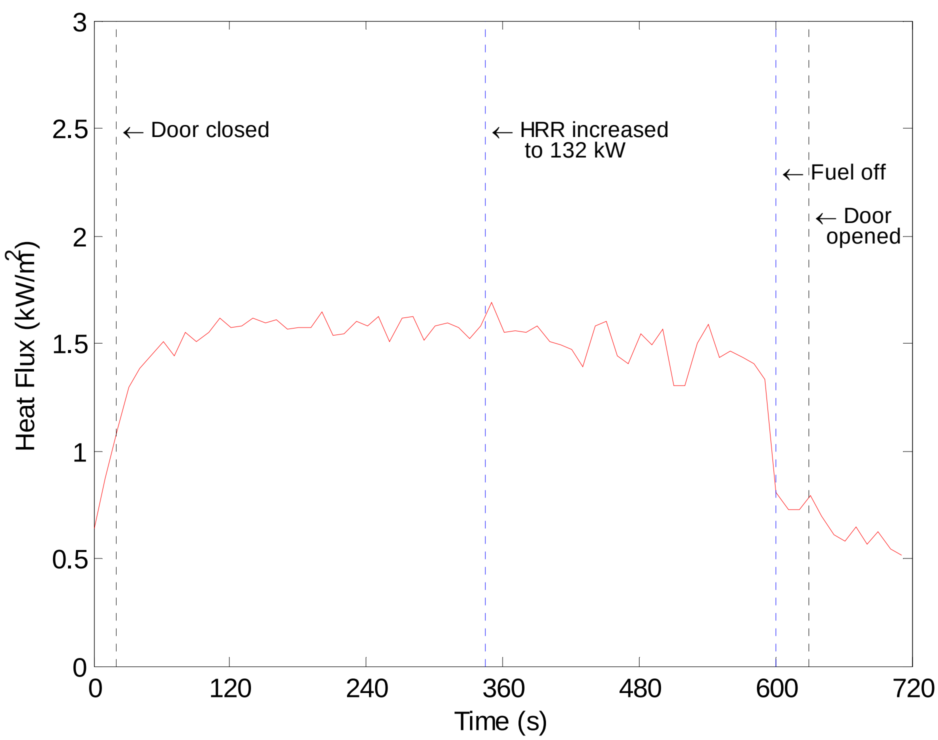

Figure 8 – Incident heat flux measured between the facepieces and oriented horizontally (Figure 5) during calibration experiment #1.

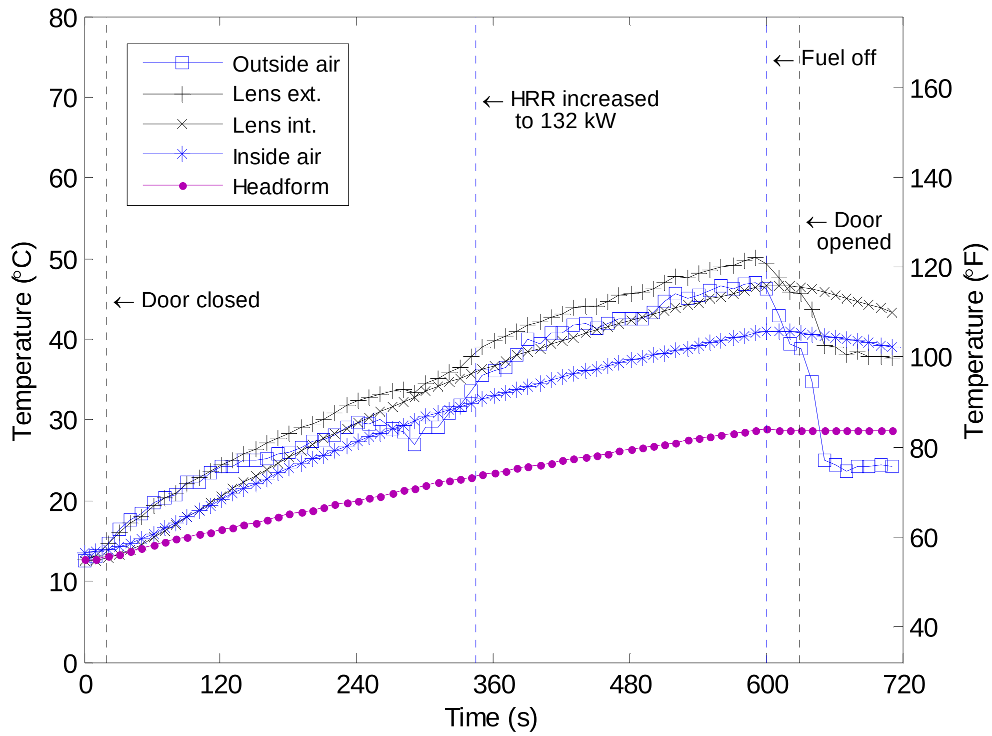

Figure 9 – Facepiece A2, placed in location I from Figure 5, temperatures during calibration experiment #1.

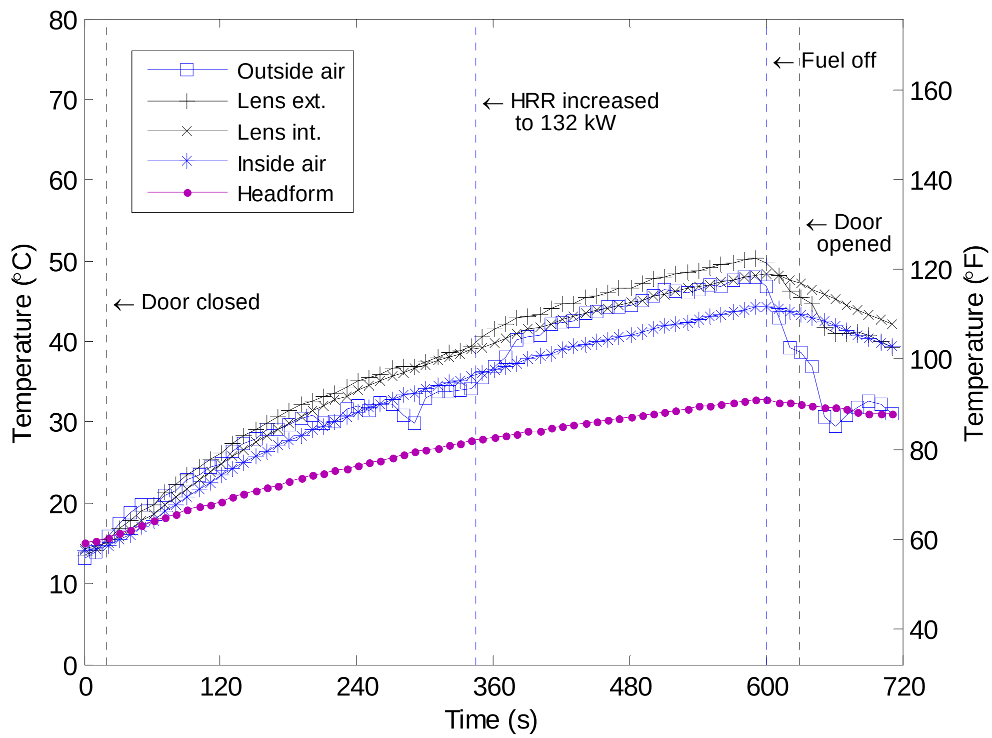

Figure 10 – Facepiece B2, placed in location II from Figure 5, temperatures during calibration experiment #1.

In the second calibration experiment, the initial heat release rate was approximately 100 kW, increasing to 130 kW from 345 s until 660 s after ignition. The front door was open at the beginning of the experiment until 312 s after ignition, when it was closed. The front door was reopened from 540 s after ignition until the end of the experiment. Figures 11-12 show the temperatures in the center of the living room measured by a thermocouple array and the incident heat flux to the facepieces. B2 had 40 L/min of air flowing through the facepiece. A pump pulled air from outside the room through the neck and mouth of the head to the facepiece, where the air exited through one way valves. There was no airflow through A2 in order to observe the effect of airflow through the facepiece on lens temperatures. Figures 13-14 show the temperatures from the thermocouples located around A2 and B2 (with 40 L/min) in the second calibration experiment.

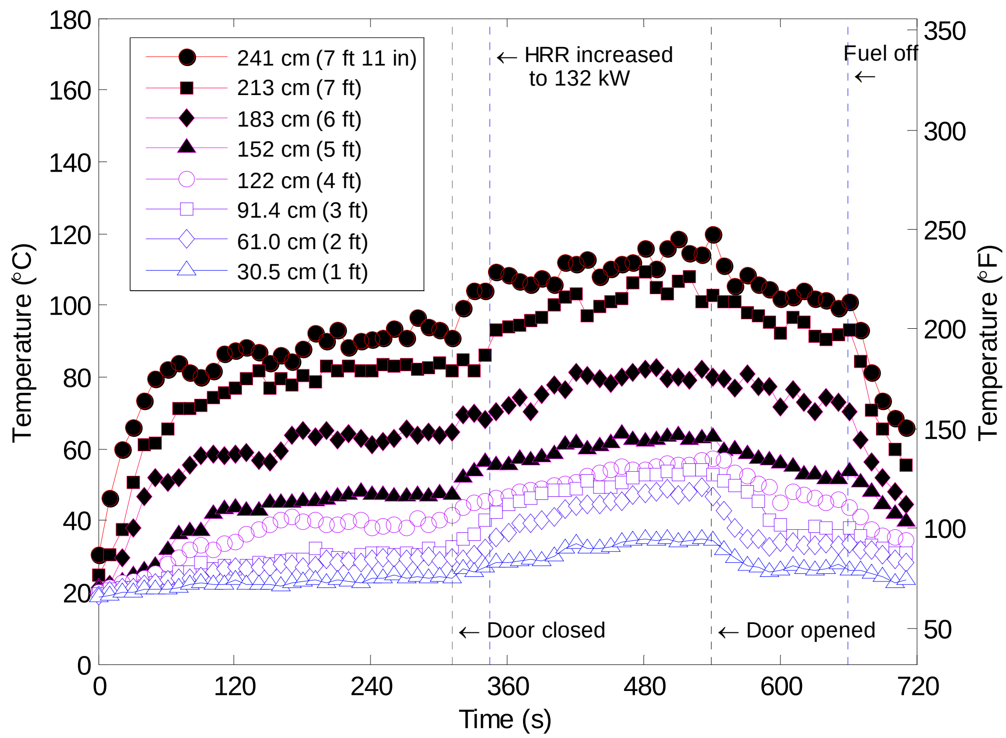

Figure 11 – Living room air temperatures from the thermocouple array (distances measured from the floor) during calibration experiment #2.

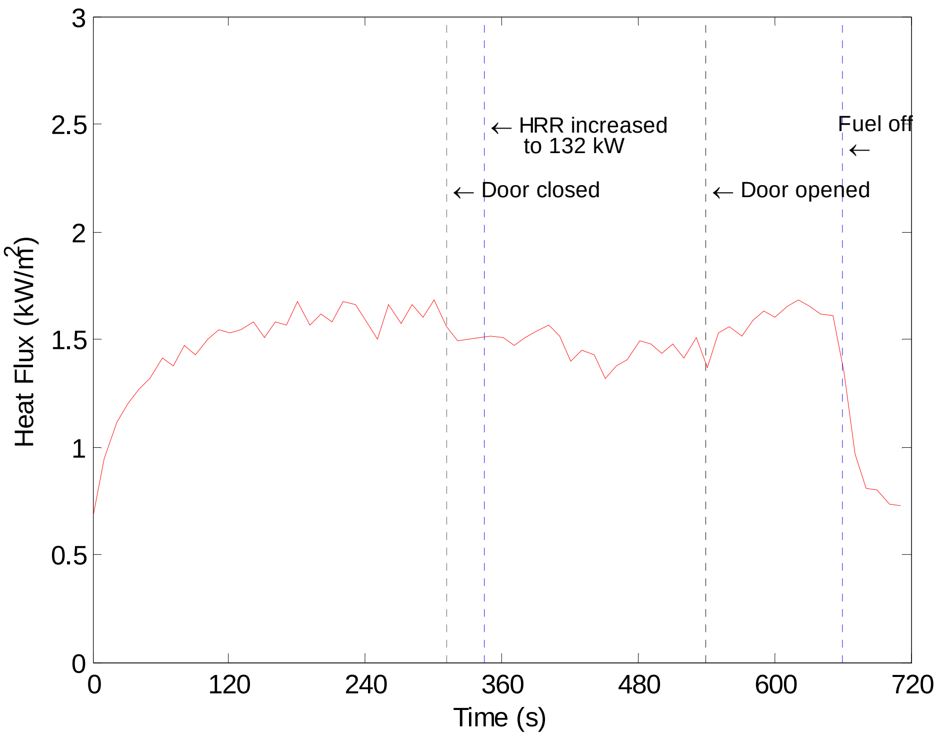

Figure 12 – Incident heat flux measured between the facepieces and oriented horizontally (Figure 5) during calibration experiment #2.

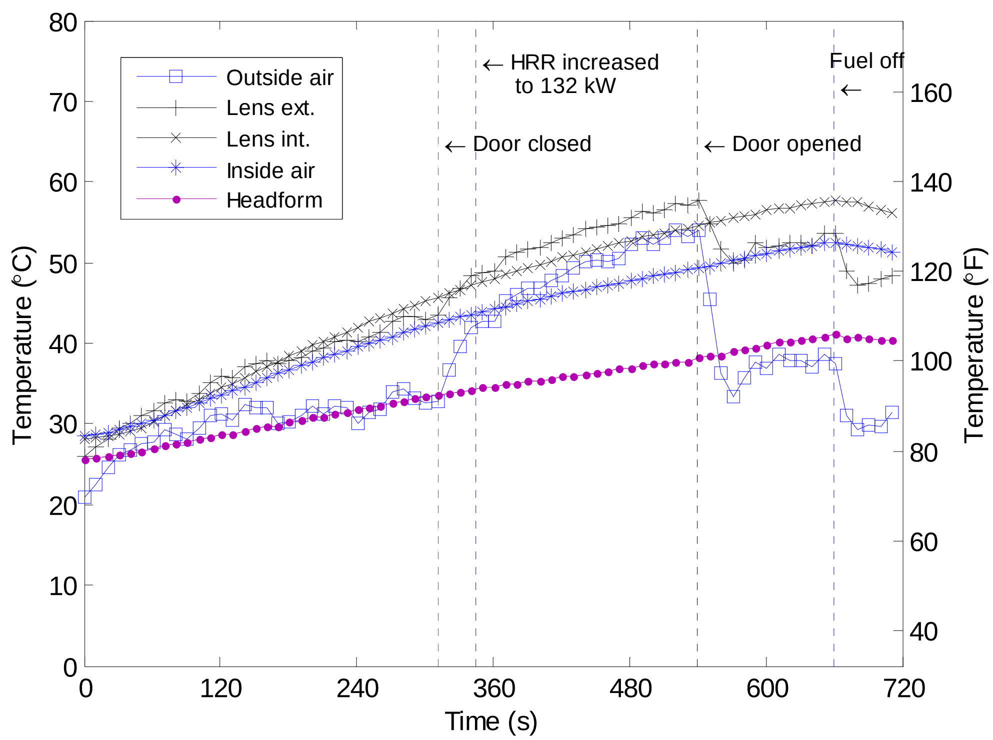

Figure 13 – Facepiece A2, placed in location I from Figure 5, temperatures during calibration experiment. #2

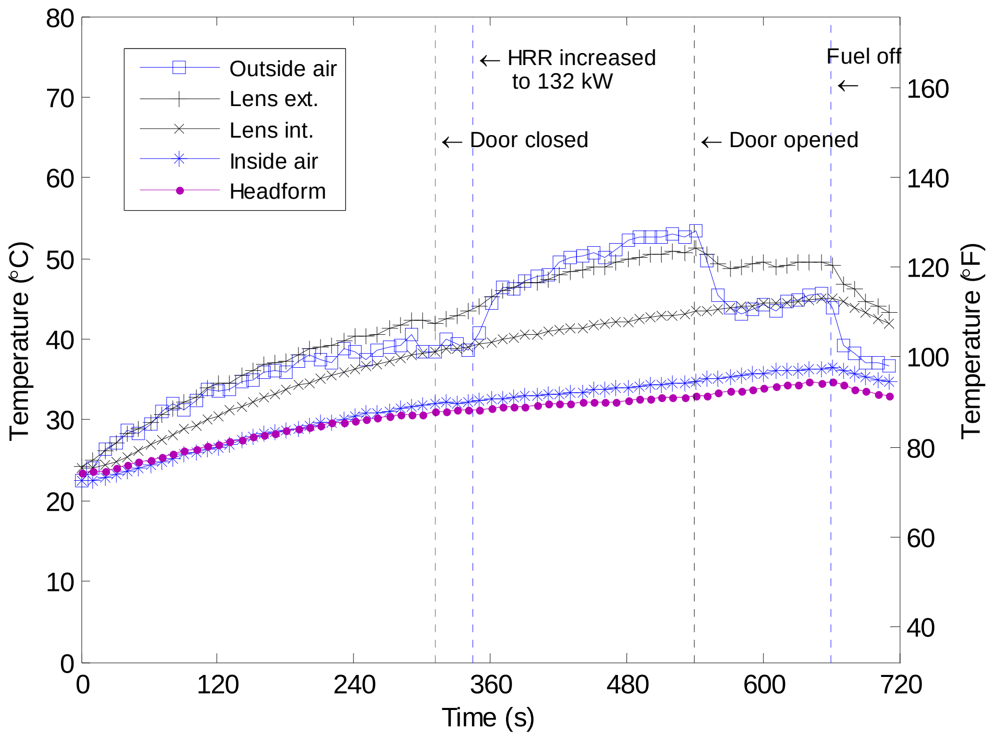

Figure 14 – Facepiece B2 with 40L/min airflow inside facepiece, placed in location II from Figure 5, temperatures during calibration experiment #2.

The temperature measured by the air thermocouples outside the facepieces during calibration experiment 1 (Figures 9 and 10) and calibration experiment 2 (Figures 13 and 14) were similar to the temperatures measured by the respective room thermocouple arrays at about the same height of 90 cm (Figures 7 and 11). The peak temperatures measured by these thermocouples were similar, at approximately 50 °C (122 °F). The heat flux measured in both calibration experiments was less than 2 kW/m^2. Although these conditions correspond to the thermal Class I or Class II from Figure 1, and are not representative of extreme environments, facepiece lens temperatures did rise to between 50 °C (122 °F) and 60 °C (140 °F). Due to the slow heating, the interior and exterior temperatures of the facepiece lenses in Figures 9, 10 and 13 are almost the same. In contrast, as shown in Figure 14, the additional cooling provided by the 40 L/min airflow in B2 resulted in the "Lens int." and "Inside air" temperatures remaining over 5 °C (41 °F) and 15 °C (59 °F) respectively less than the "Lens ext." temperature.

4.2. Fire Experiments

Figures 15 through 31 show the results of the four fire experiments. Although data were recorded every second after ignition, data have been time averaged and plotted every 10 s for clarity. Two facepieces were located in the kitchen for the first three fire experiments (locations I and II in Figure 6), and one facepiece was located on the porch for the fourth fire experiment (location III in Figure 6). The room environment is characterized by the temperatures from the thermocouple array closest to the facepieces, shown in Figures 15, 20, 24, and 28. Experiments #1, #2, and #3 lasted about 5 minutes, and data are shown for a total of 10 minutes following ignition. Experiment #4 lasted about 10 minutes, but the front door wasn't open until 5 minutes into the experiment. Therefore the facepiece lens was only exposed for the second 5 minutes of the experiment. The peak temperature at the ceiling was between 500 °C (932 °F) and 700 °C (1292 °F) for all the experiments. It is important to note that the facepiece lens thermocouples may not have remained in contact with the lens surface throughout the experiment.

4.2.1. Furnished Fire Experiment #1

Figure 15 shows the temperature data from the thermocouple array in the first fire experiment. The front door was open for this experiment. Ventilation events, when windows opened, and suppression events, when water was applied, are marked in the plots. More detailed explanations of the ventilation and suppression events can be found in a future report [25]. Temperatures at facepiece height, 90 cm from the floor, were very high and exceeded 300 °C (572 °F) for more than two minutes. Figure 16 shows the incident heat flux measured between B1 and A1, while Figures 17 and 18 show the facepiece temperatures for B1 and A1, respectively. The facepiece lenses were exposed to 10 kW/m^2 to 20 kW/m^2 for about three minutes. There was no airflow through either of these facepieces. The exterior surface temperature of the facepieces reached or exceeded the melting temperature range of polycarbonate, 215 °C (419 °F) to 340 °C (644 °F). The appearance of the facepieces after the experiment was consistent with melting of the lens material. The facepiece lenses deformed, and there was extensive bubbling in the polycarbonate, which would cause impaired visual acuity, as shown in Figure 19. Both of these facepiece lenses exhibited bubbling, but the appearance of the bubbles was not the same. It is worth noting that both facepiece lenses were covered in black soot following removal from the townhouse, and these pictures were taken after the soot was removed with water. The impact of the black soot on the absorption coefficient of the leans was not characterized. If the soot increased the absorption coefficient and this resulted in additional radiative energy being absorbed by the lens/soot, this could reduce the time to lens failure in a radiative environment.

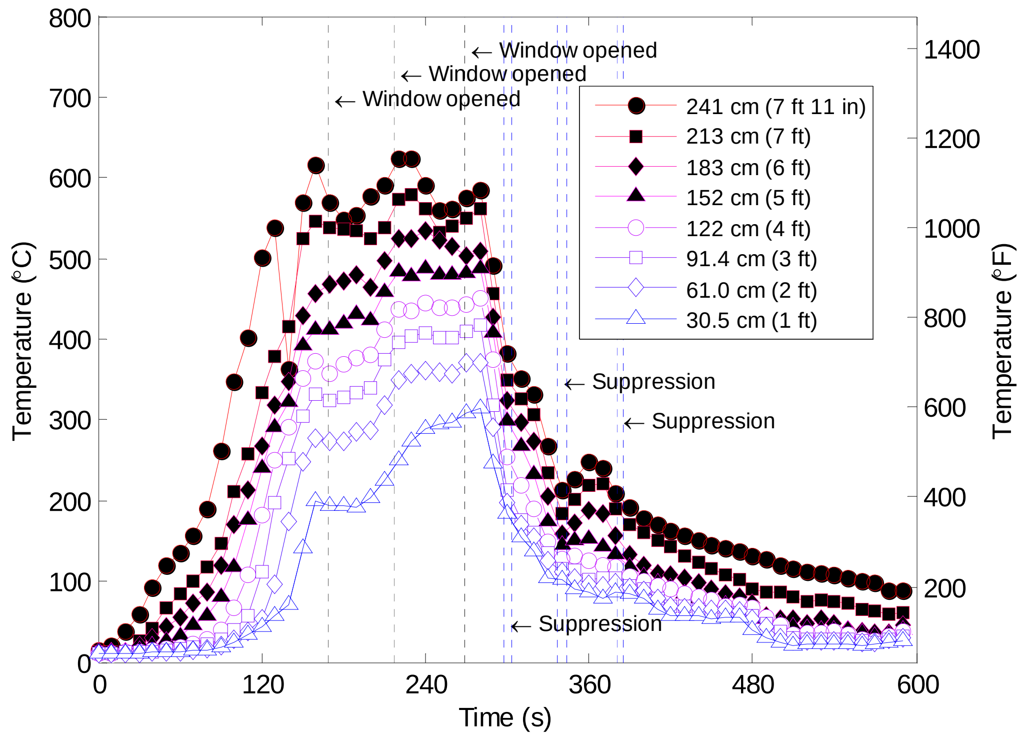

Figure 15 – Kitchen air temperatures from the thermocouple array (distances measured from the floor) during fire experiment #1.

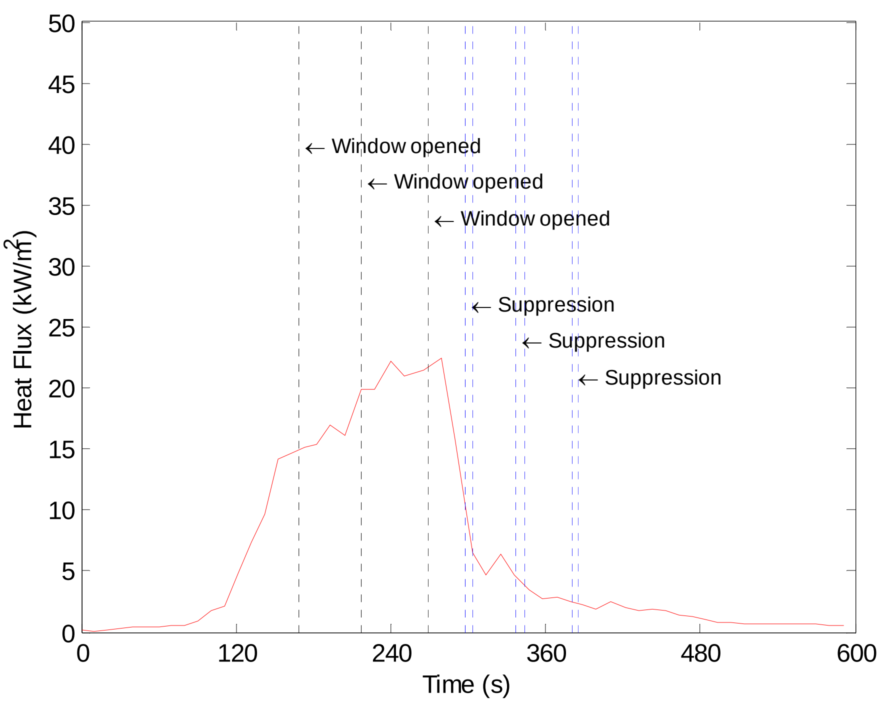

Figure 16 – Incident heat flux measured between the facepieces and oriented horizontally (Figure 6) during fire experiment #1.

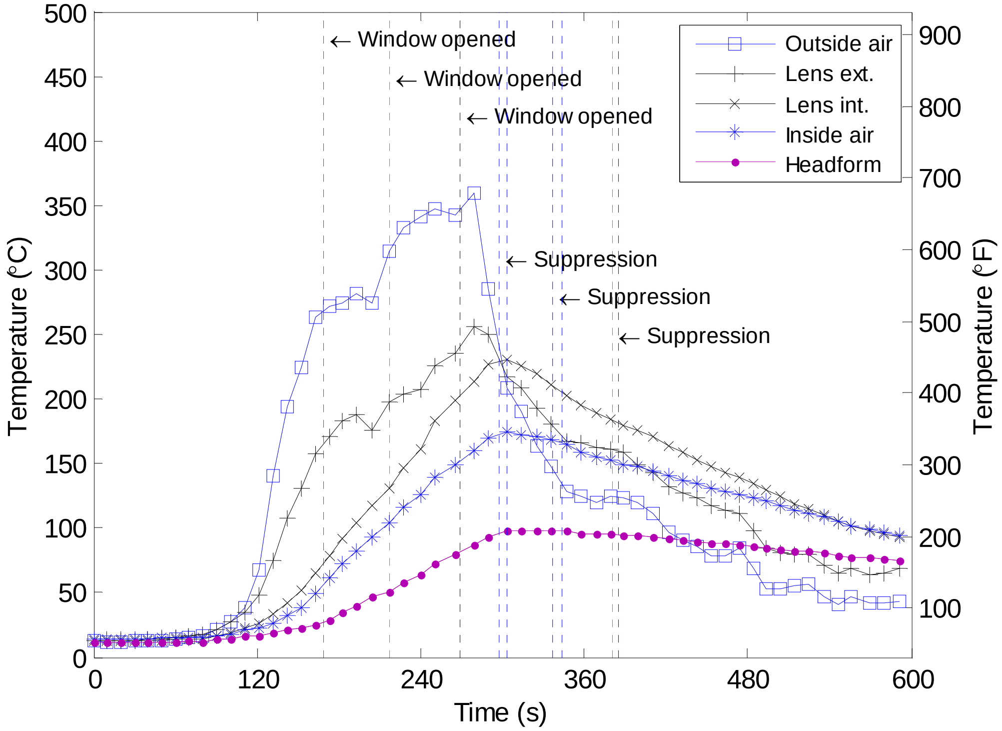

Figure 17 – Facepiece B1, placed in location I from Figure 6, temperatures during fire experiment #1.

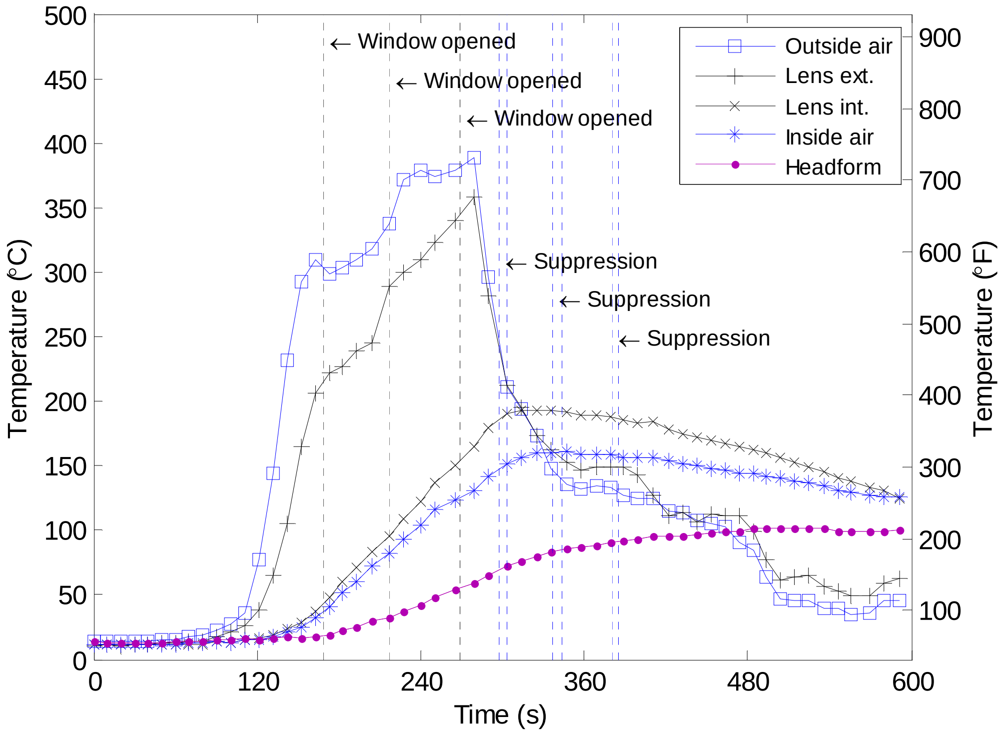

Figure 18 – Facepiece A1, placed in location II from Figure 6, temperatures during fire experiment #1.

 

Figure 19 – Photos of B1 (left) and A1 (right) in fire experiment #1, showing lens degradation after the exposure.

It appears that either the exterior or interior surface thermocouples, or both, came off the surfaces of A1, in Figure 18. The exterior surface temperature was much higher in A1 than in B1, and the interior surface temperature in A1 was much lower than in B1. Even if the thermocouples came off the surface just slightly, the surface temperatures would become closer to the adjacent air temperature, as seen in Figure 18. It is known that both facepiece lenses are made of polycarbonate, and have the same thermal conductivity, and both are approximately the same thickness. Therefore, the temperature difference between the surfaces for the same exposure should be similar.

4.2.2. Fire Experiment #2

Figure 20 shows the temperature data from the thermocouple array in the experiment #2. The front door was open for this experiment. The time of suppression is noted in the plots. Thermocouples at facepiece height, 90 cm from the floor, measured above 200 °C (392 °F) for a minute and a half. Figure 21 shows the incident heat flux measured between C1 and C2, while Figures 22 and 23 show the facepiece temperatures for C1 and C2 respectively. The facepiece lenses were exposed to 5 kW/m^2 to 10 kW/m^2 for about two minutes. C1 had no airflow, but C2 had 40 L/min of airflow through the facepiece to compare the effect for the same exposure. This exposure was milder than the first fire experiment, and the exterior surface temperature of the facepiece lens did not even reach the glass transition temperature, 150 °C (302 °F). There was no observable thermal degradation to the lens and no change to the lens appearance except for the deposition of soot. The airflow did not have a significant effect on the temperatures, but the maximum temperature difference between the exterior and interior facepiece surfaces was slightly greater for the facepiece with airflow.

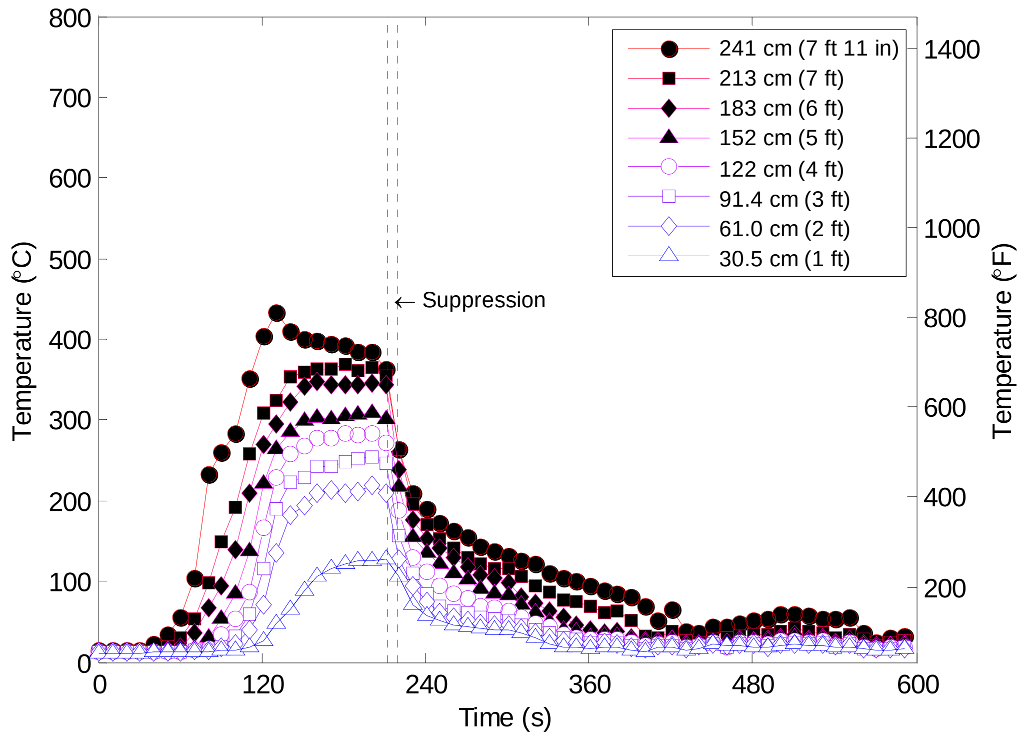

Figure 20 – Kitchen air temperatures from the thermocouple array (distances measured from the floor) during fire experiment #2.

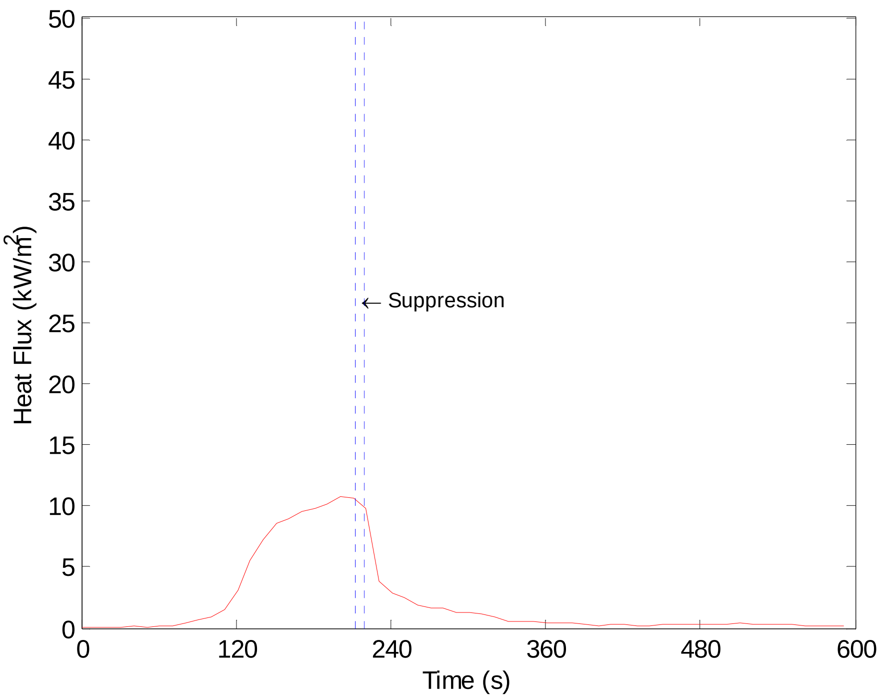

Figure 21 – Incident heat flux measured between the facepieces and oriented horizontally (Figure 6) during fire experiment #2.

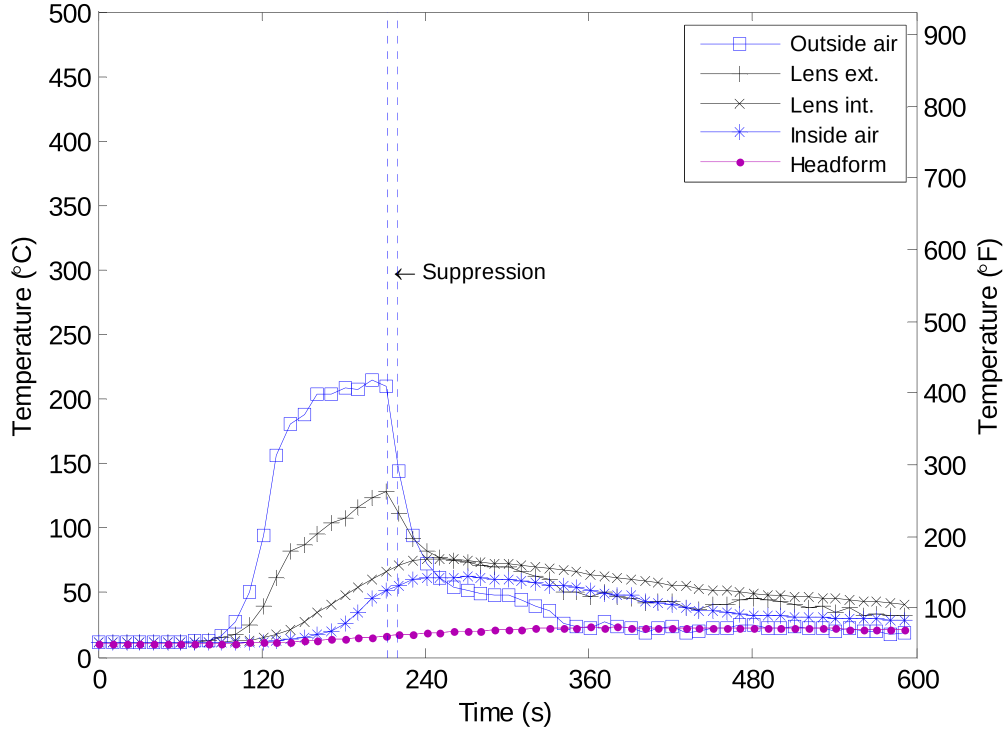

Figure 22 – Facepiece C1, placed in location I from Figure 6, temperatures during fire experiment #2.

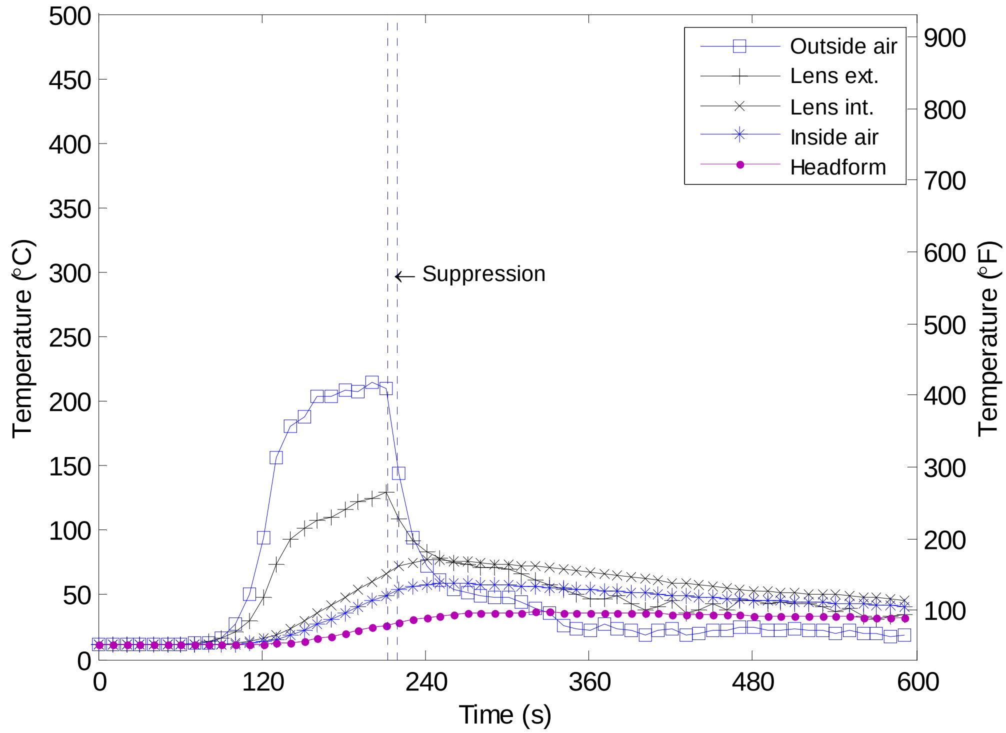

Figure 23 – Facepiece C2 with 40 L/min airflow inside facepiece, placed in location II from Figure 6, temperatures during fire experiment #2.

4.2.3. House Fire Experiment #3

Figure 24 shows the temperature data from the thermocouple array in fire experiment #3. Both the door and window were opened around 180 s, allowing some heat to escape, and the temperatures dropped. Suppression occurred between 240 s and 300 s after ignition. The temperature profiles peaked twice during this experiment, due to the opening of the door and window in the middle of the experiment. The temperature at the 90 cm height peaked just below 350 °C (662 °F) the first time and 300 °C (572 °F) the second time, but did not remain at these temperatures for any significant amount of time. In Figures 25 and 26, the heat flux and exterior facepiece temperatures follow a similar profile with two peaks, both below 15 kW/m^2 and 200 °C (392 °F) respectively. However, similar to the second fire experiment, this exposure was not severe enough to cause any visible damage to either D1 or E1. Neither of the facepieces in experiment #3 had any airflow through them. It appears that the interior surface thermocouple on E1 came off the surface, and was instead measuring the inside air temperature, as suggested by the plots of interior surface temperature and inside air temperature data on top of each other in Figure 27.

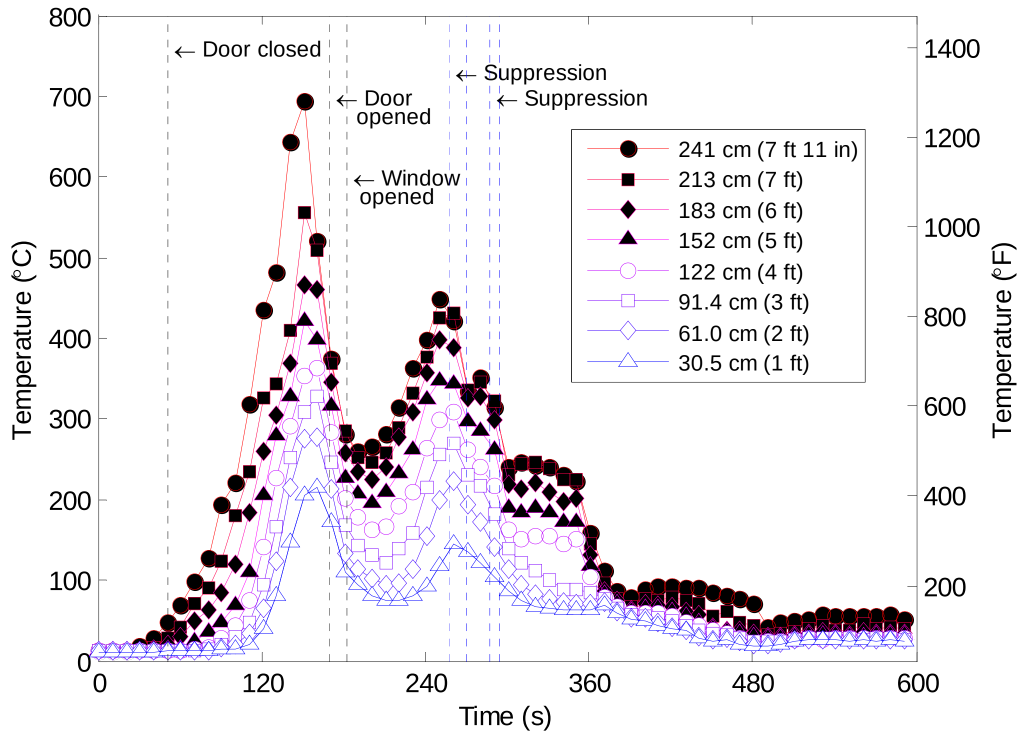

Figure 24 – Kitchen air temperatures from the thermocouple array (distances measured from the floor) during fire experiment #3.

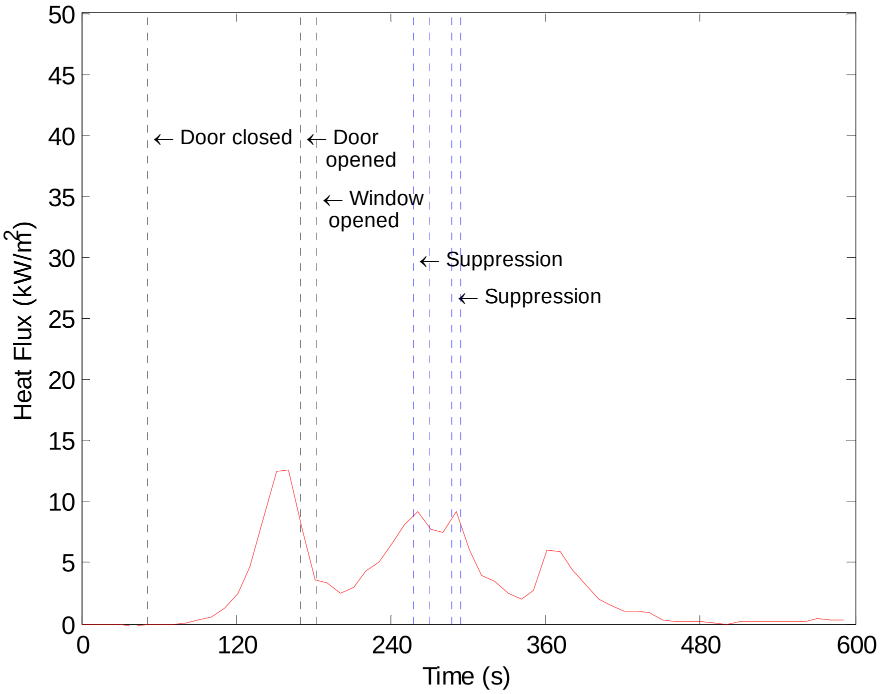

Figure 25 – Incident heat flux measured between the facepieces and oriented horizontally (Figure 6) during fire experiment #3.

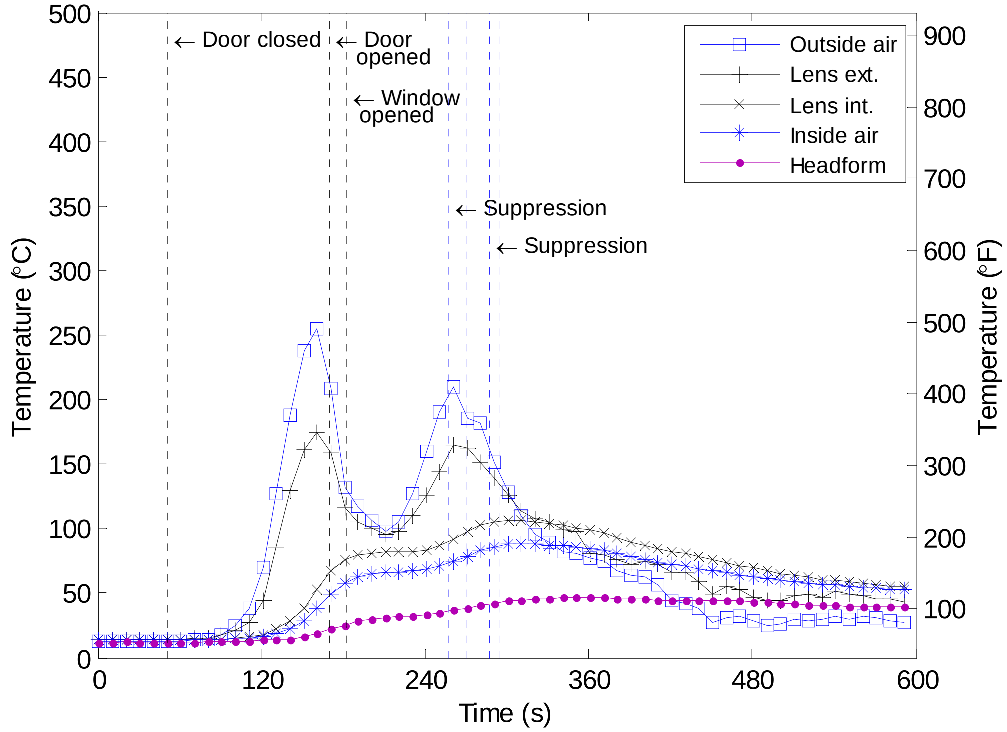

Figure 26 – Facepiece D1, placed in location I from Figure 6, temperatures during fire experiment #3.

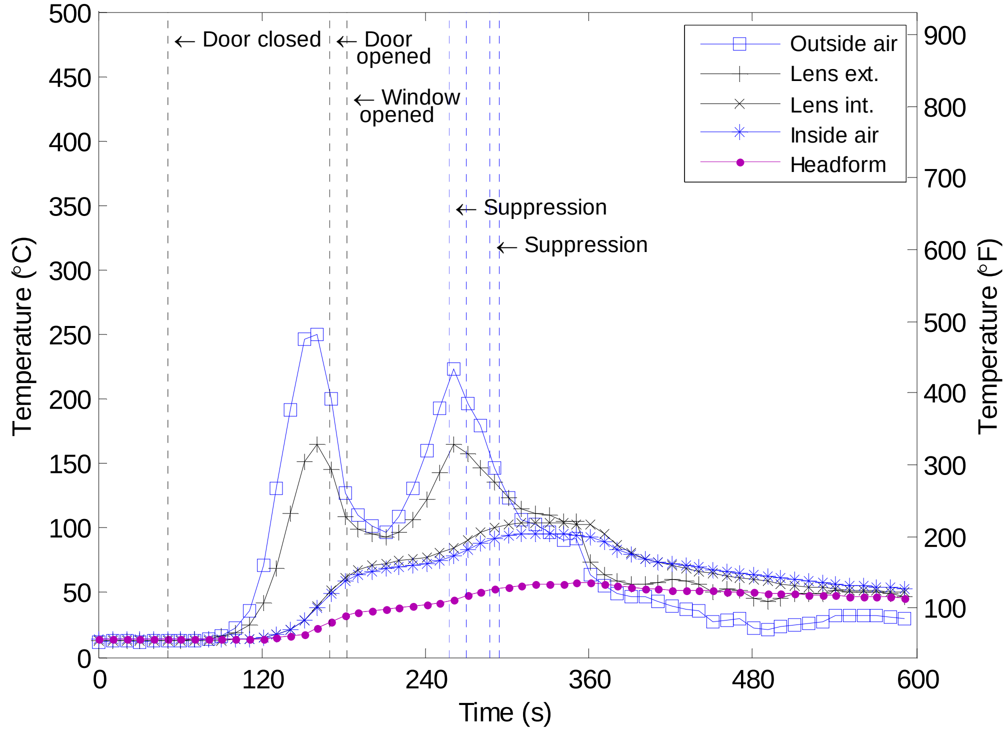

Figure 27 – Facepiece E1, placed in location II from Figure 6, temperatures during fire experiment #3.

4.2.4. Fire Experiment #4

Figure 28 shows the temperature data from the thermocouple array in fire experiment #4. The front door was closed until about 300 s after ignition to create under-ventilated conditions. When the door was opened, the temperatures rose because the pyrolysis products from the underventilated fire were suddenly mixed with the oxygen in the fresh air and able to burn inside and outside the doorway. After the door was opened, the fire burned for about four more minutes. Then the facepiece was removed from the porch and fire fighters began to extinguish the fire. The kitchen temperature profiles peaked twice during this experiment, with the drop in temperature in the middle of the experiment due to the under-ventilated condition before the door was opened. Since B2 was located outside the house on the porch, it was not exposed to heat until the door was opened, as shown in Figures 29 and 30. In addition, the outside air temperature around the facepiece was always cooler than the facepiece lens surface temperature. This is consistent with radiative heating being the dominant mode of heat transfer to the facepiece lens. In the other experiments, the facepiece lenses were exposed to both convective and radiative heating. Despite it being outside the house in a cool environment, the heat flux gauge measured between 40 kW/m^2 and 50 kW/m^2 for about a minute, making this the most severe thermal exposure. Although the heat flux was high, the flames from the doorway did not touch the facepiece lens. B2 had 40 L/min of air flowing through the headform, and after the radiant flux softened the lens, the pressure from the airflow actually pushed the softened polycarbonate lens outward, before rupturing the thinned lens at some point during the exposure. From the photograph in Figure 31, the bubbling and deformation to the facepiece lens still on the headform can be seen. No deposited soot needed to be removed from this facepiece lens, because the smoke from the fire was free to escape directly upwards from the doorway. The temperature reported by the thermocouple on the exterior surface of the facepiece lens peaked around 280 °C (536 °F), but the interior surface temperature continued to rise to almost 400 °C (752 °F). This occurred because the lens developed a severe hole, and the "Lens ext." thermocouple came off the surface began to report approximately the same temperature as the outside air thermocouple. The facepiece material melted around the "Lens int." thermocouple, and therefore it continued to measure the temperature rise of the material. It is important to note that B2 was one of the facepieces that was used in the calibration experiments, although it had not been exposed to excessive heating and displayed no apparent thermal degradation after the calibration experiments.

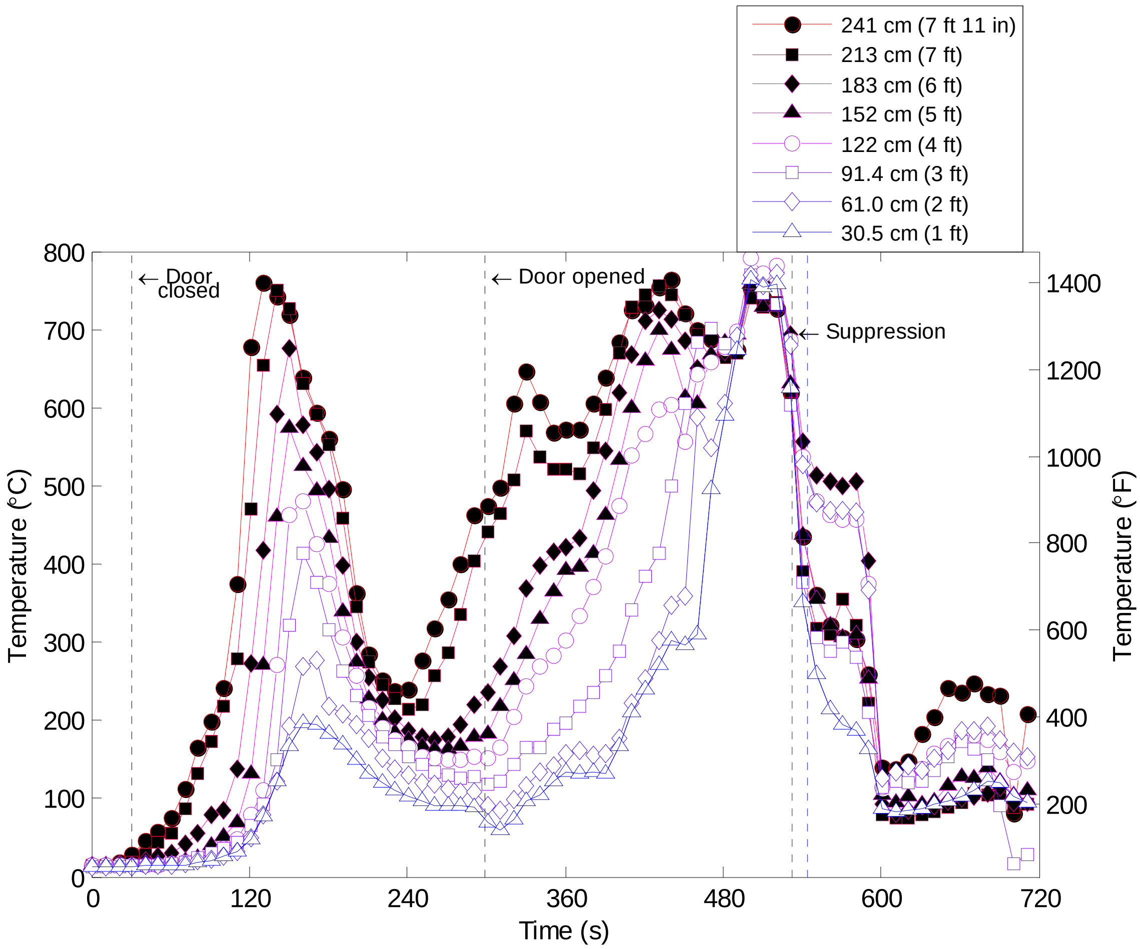

Figure 28 – Living room air temperatures from the thermocouple array (distances measured from the floor) during fire experiment #4.

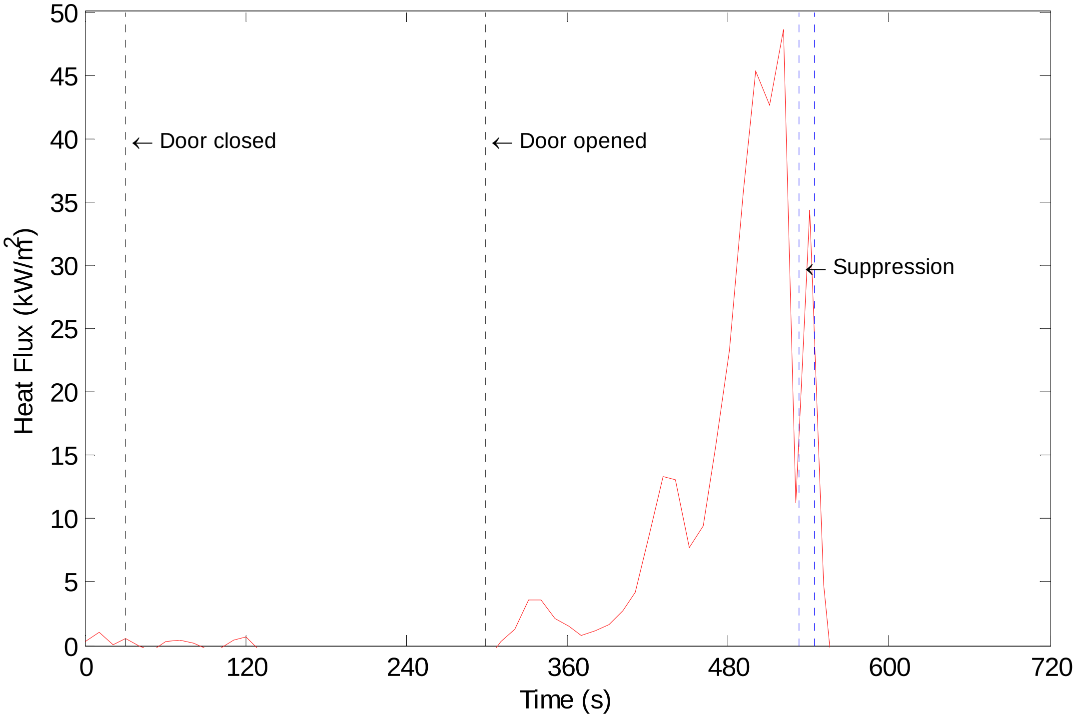

Figure 29 – Incident heat flux measured next to the facepiece and oriented horizontally (Figure 6) during fire experiment #4.

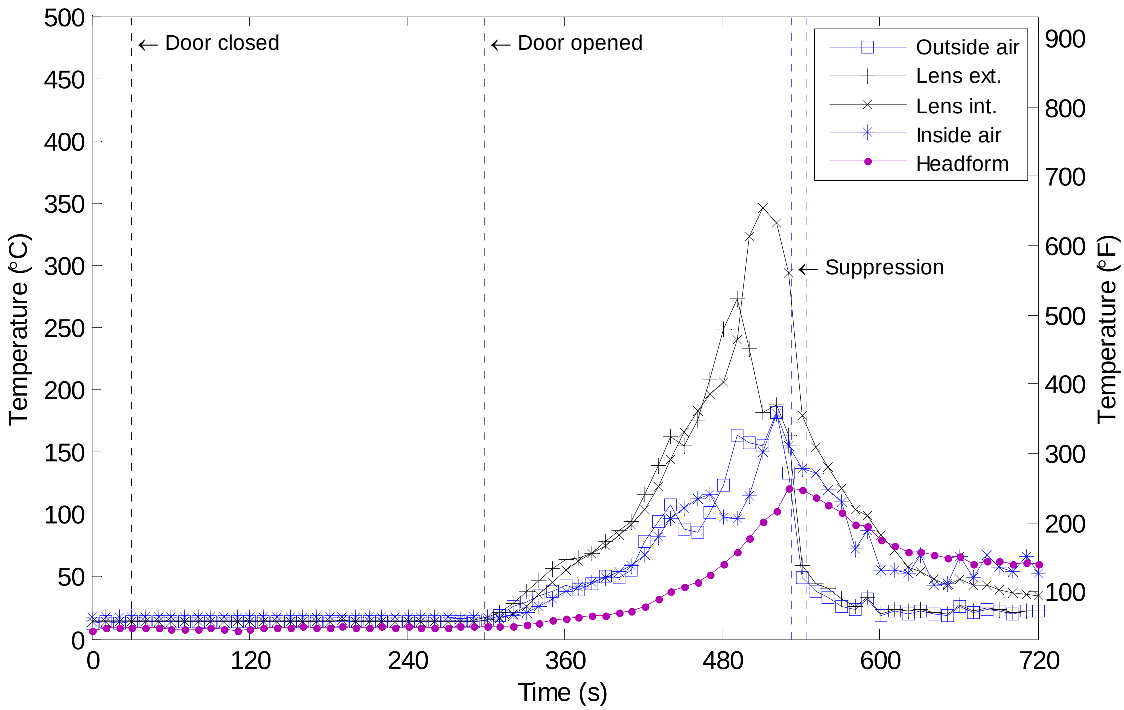

Figure 30 – Facepiece B2, placed in location III from Figure 6, temperatures during fire experiment #4.

Figure 31 – Photo of B2 from the fire experiment #4, showing the lens degradation after exposure, but still in place on the headform.

5. DISCUSSION

In the structure fires, SCBA facepieces were exposed to environments with heat fluxes as high as 20 kW/m^2 to 50 kW/m^2 and ceiling temperatures as high as 500 °C (932 °F) to 750 °C (1382 °F). The facepiece lenses showed severe degradation in these conditions of temperature and heat flux. From the facepiece temperature plots, it can be seen that the exterior lens surface temperature rise corresponded to the heat flux and room air temperature profiles. However, in exposures dominated by radiative heat transfer, the outside air temperature was lower than the facepiece lens exterior temperature, and the heat flux measurement characterized the exposure better than the exterior air temperature. Therefore, both temperature and heat flux should be measured to accurately capture an exposure.

Once the polycarbonate reaches its glass transition temperature, it begins to lose all integrity and becomes vulnerable to physical impact. Eventually, as seen in the first fire experiments, the lens can begin to deform under its own weight and potentially develop holes. As seen during the fourth fire experiment, breathing may also cause deformation due to the positive pressure that is maintained inside the facepiece by design. Damage to the integrity of the lens has dire consequences for a fire fighter in an (IDLH) environment leaving the user susceptible to toxic gas exposure, asphyxiation, and thermal burns to the respiratory tract.

All four of the furniture fire experiments began with identical layouts and similar fuel loads, but the ventilation conditions varied, contributing to differences in the development and severity of the fires. Therefore, the exposure and resulting conditions of the facepiece lenses were not the same following the experiments. This wide range of results given similar initial conditions speaks to the uncertainty of the fire environment. Since the magnitude and profiles of heat flux and room temperature varied between experiments, the heat flux was integrated over time, to compare the exposures from different experiments. The integrated heat flux represents the total amount of energy per unit area to which the facepiece lenses were exposed. Table 3 lists relevant information for each experiment, including the maximum heat flux, the thermal classification (from Figure 1), the integrated heat flux or total energy flux, the maximum exterior surface temperature, and the maximum temperature difference between facepiece lens interior and exterior surfaces.

Table 3 – Summary of relevant data for each calibration and fire experiment.

Experiment	*Facepiece Sample*	*Max heat flux, ± 16 % (kW/m²)*	*Thermal Class - Figure 1*	*Integrated heat flux, ± 16 % (MJ/m²)*	*Max temp. Lens ext. Surface, ± 15 % (°C)*	*Max temp. diff. btw. Lens ext. and int. surfaces, ± 15 % (°C)*	*Thermal Degradation of Lens*
Calibration Experiment #1	A2	2.1	II	1.0	50	4.4	No
	B2				51	2.6	No
Calibration Experiment #2	A2	2.0	II	1.0	58	3.6	No
	B2-40 L/min				52	8.4	No
Fire Experiment #1	B1	25	IV	3.3	265	102	Yes
	A1				367*	203*	Yes
Fire Experiment #2	C1	13	IV	1.3	130	66	No
	C2-40 L/min				132	75	No
Fire Experiment #3	D1	14	IV	1.7	181	136	No
	E1				173	132	No
Fire Experiment #4	B2-40 L/min airflow	54	IV	3.1	284*	53*	Yes

* Indicates that a thermocouple came off the surface, and affected this value.

The facepieces that had the 40 L/min airflow had a greater temperature difference between the exterior and interior surfaces than the facepieces without airflow in the same experiments. For calibration experiment #2, the maximum temperature difference was 8.4 °C (48 °F) in B2 and 3.6 °C (39 °F) in A2. For fire experiment #2, the maximum temperature difference was 75 °C (167 °F) in C2 and 66 °C (151 °F) in C1. This difference may have been due to the cooling effect of the airflow inside the facepiece.

The maximum temperature on the exterior surface of the facepiece lens gives an indication of the extent of damage of the facepiece lens. This maximum temperature is plotted as a function of the maximum heat flux measured in the experiment in Figure 32. The filled symbols represent the facepiece lenses that had no indication of thermal degradation, and the open symbols represent the three facepiece lenses that displayed thermal degradation. The temperatures plotted are the maximum values, which may exceed the temperatures of the lens when the degradation first appeared. Identification of the threshold temperatures would have required real time video of the experiments, which was not possible in the smoke-filled environment. The cutoff point in lens exterior temperature for thermal degradation was between 200 °C (392 °F) and 250 °C (482 °F), which is consistent with the lower end of the polycarbonate melting temperature range. The highest data point, at 367 °C (693 °F) corresponds to A1, and may be artificially high because the exterior surface thermocouple came off the surface.

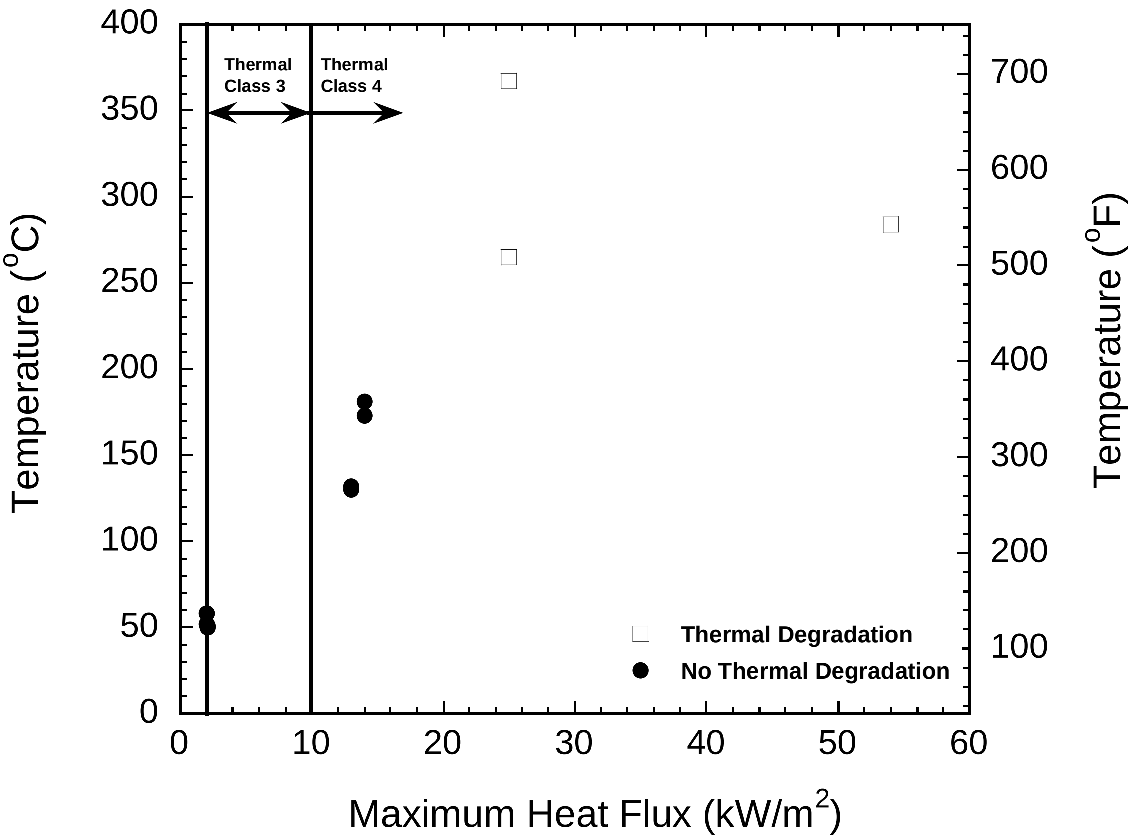

Figure 32 – Relationship between maximum facepiece exterior surface temperature and maximum incident heat flux for all experiments. Facepiece lenses with no indication of thermal degradation are shown as closed circles, and facepiece lenses with thermal degradation are shown as open squares.

An order of magnitude one-dimensional analysis of the energy balance for the facepiece lens can be approximated by the components of heat transfer represented in Figure 33. In the experiments, the heat flux gauge measured the incident heat flux on the lens, including both convection and radiation components. A simple analysis results in only a small contribution from the other heat gain and heat loss terms. The reflectance of polycarbonate is approximately 5 % of incident radiation for the lower range of infrared wavelengths [34,35]. However, the facepiece was covered in soot during some of the experiments, which may have reduced the reflectance considerably more. Most of the non-reflected radiant flux and all of the incident convective flux are absorbed by the lens. The absorption of non-reflected radiant energy for wavelengths greater than 2 µm, is greater than 95 % for a polycarbonate slab with a thickness of 2 mm to 3 mm [36]. There is some heat loss from the lens to the cooler facepiece air and headform through convective cooling and reradiation from the lens. However, this combined loss is estimated to be at most 15 % of the incident heat flux. Some incident radiation to the headform could be reflected back to the facepiece, but this reflection is estimated to be negligible because the components of radiation to the headform are small. Because of the small contributions from these other components, the incident heat flux is the most significant term in the energy balance of the lens. Therefore, the lens temperature is taken as approximately a function of the incident exposure in these experiments.

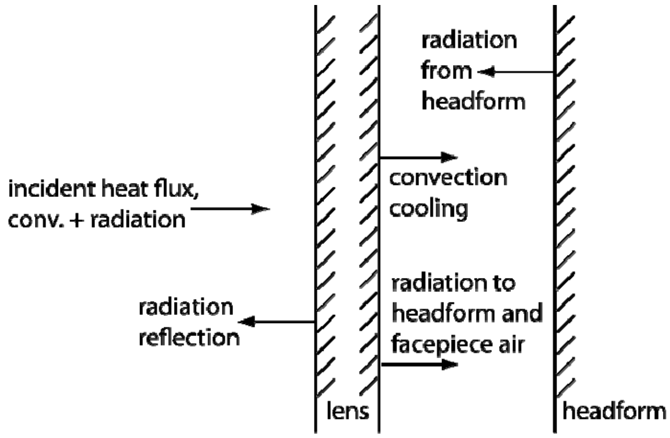

Figure 33 – Diagram of a one-dimensional approximation of significant heat transfer terms involving the lens.

Since the duration of the thermal exposure varied during each experiment and between different experiments, integrating the heat flux captured the total exposure better than the peak heat flux measured. For the most part, the maximum temperature measured on the exterior surface of the facepiece lens occurred just before the fire was extinguished (as the heat flux then began to decrease). In Figure 34 the maximum temperature on the exterior surface of the facepiece lens is plotted as a function of the integrated heat flux, which represents the total energy flux over the experiment. Despite the variability in the experiments, the correlation between the maximum temperature and the integrated heat flux is consistent. Thermal degradation was observed in facepieces that exceeded 3.1 MJ/m^2. Figure 34 supports the conclusion of the analysis that the temperature of the polycarbonate lens was roughly a function of the total incident energy exposure, for these specific fire experiments. In other situations, the integrated incident heat flux may not have as much importance, for example, when the lens does not absorb a large fraction of the incident energy, or when the comparative size of the cooling terms are larger.

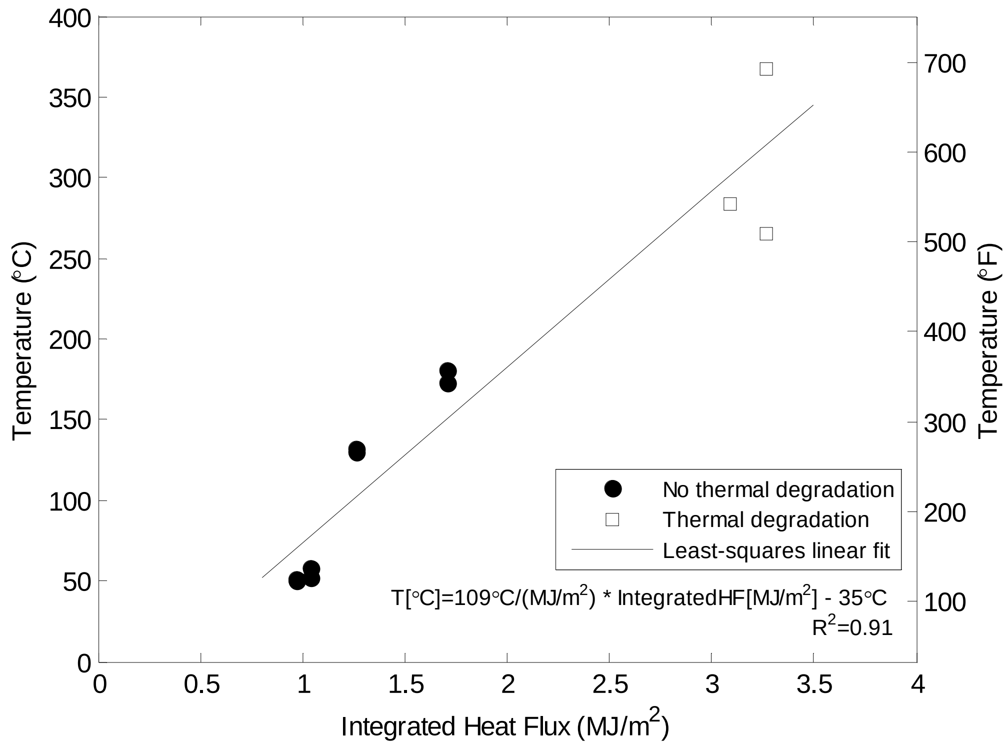

Figure 34 – Relationship between maximum facepiece lens exterior surface temperature and integrated incident heat flux for all experiments. Facepiece lenses with no indication of thermal degradation are shown as closed circles, and facepiece lenses with thermal degradation are shown as open squares.

6. CONCLUSIONS AND FUTURE WORK

Fire experiments performed in furnished townhouses demonstrated the effects of a range of realistic fire fighting environments on SCBA facepiece lenses. The fire environment and exposure conditions were measured and quantified, and the lens performance was assessed through the lens temperature rise and visual inspection. There was no observable difference in performance between different facepiece models, although the geometry and construction of the facepiece and SCBA components may affect the results. Thermal degradation of SCBA facepiece lenses was observed in all cases when the facepiece lens temperature exceeded the lower end of the melting temperature range for polycarbonate, and the integrated heat flux exceeded 3.1 MJ/m^2. These lenses exhibited bubbling and loss of visual acuity, as well as severe deformation, and in one case, a hole. Conditions that caused the degradation involved peak levels of heat flux above 20 kW/m^2, but not necessarily high ambient air temperatures. The effect of airflow through the facepiece was considered in some cases, and a slight cooling effect was observed in the temperature difference between the interior and exterior surfaces of the facepiece.

The next step is to identify the exposure limit just before thermal degradation occurs. Data on the limits of the equipment would be valuable information for the fire service to help prevent further injuries and fatalities related to SCBA equipment failure. These fire experiments revealed information on the approximate heat flux and temperature environment that will cause a facepiece lens to degrade, but future experiments will utilize a gas fired radiant panel exposure, which can provide a controlled and repeatable way to generate a uniform heat flux. The heat flux from a radiant panel can be controlled and varied from low heat flux, with intensity just above the flux of sunlight, to a high heat flux representing conditions at the onset of flashover. In future experiments more information on the progression of the degradation can be gathered by recording video of the facepiece lens during the exposure. In addition, the breathing effect can be further studied using a breathing machine to simulate both inhalation and exhalation.

7. ACKNOWLEDGEMENTS

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