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An Experimental Determination of a Real Fire Performance of a Non-Load Bearing Glass Wall Assembly*

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Abstract. A glass wall assembly was exposed to an intense real-scale compartment fire. The wall assembly consisted of four glass sections, two of which were fitted with tempered double-pane glass and the other two sections were fitted with tempered single-pane glass. At each glass section, temperatures were measured at the exposed face and the unexposed face. Total heat flux gauges were used to measure both the temporal variation of the energy incident on the glass wall and the transmitted energy rate detected through two of the glass sections. Visual and infrared cameras were used to image the unexposed face of each wall assembly during the fire exposure. Results of glass breakage and subsequent glass fall out were compared to studies in the literature for glass sections exposed to compartment fires. The behavior of the glass wall assembly under a fire load is presented.

Key words: glass partition, glass breakage

Introduction

To mitigate fire spread in buildings, building codes dictate that compartments in buildings must be separated by fire rated barriers or partitions [1, 2]. Intact partitions prevent the spread of flame, keep the egress paths available, and increase the safe time in places of refuge. Typically, these partitions are constructed of gypsum panels attached to either steel or wood studs. The use of glass partitions as fire-rated barriers has begun due to advances in glazing technology.

The most important consideration for any fire partition in buildings is its ability to contain flames and smoke. Specifically, it is necessary to know such information in terms of real

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time. The challenge is that the absolute value for flame and smoke containment depends on the nature of the fire and the composition of the particular partition [3–6].

A great benefit to public safety would be the ability to have the fire resistance description of partitions on an absolute basis. Current fire resistance ratings for partitions obtained in furnaces do not coincide with actual safety times, but rather only provide *relative* guidance [1, 2]. The Fire Research Division at NIST has embarked on a course to provide a methodology for inclusion in performance-based design of buildings. This work has been focused on gypsum board partition construction, as this is the most common type of interior partition construction. The present paper extends this research to glazed partitions.

To this end, a non-load bearing glass wall was exposed to a real-scale compartment fire. The test was performed to provide information on the phenomenology of partition response and failure and also quantitative information to guide the model development.

Experimental Description

Figure 1(a) and 1(b) display schematics of the glass partition used for fire testing. The dimensions of the assembly were 2.42 m by 2.42 m. The frame was fitted with two different types of glass. Double-pane tempered glass (SAFTI Superlite II XL[1]) was installed in the two sections on the left (see Figure 1(a)). The double-pane glass consisted of two tempered glass panes, each with a thickness of 6.35 mm. Sandwiched in between the glass panes was a 6.35 mm layer of gel insulation. As a consequence, the double-pane glass had a total thickness of 19.05 mm. On the right hand side, single-pane tempered glass (SAFTI Superlite I) with a thickness of 6.35 mm was installed (see Figure 1(a)).

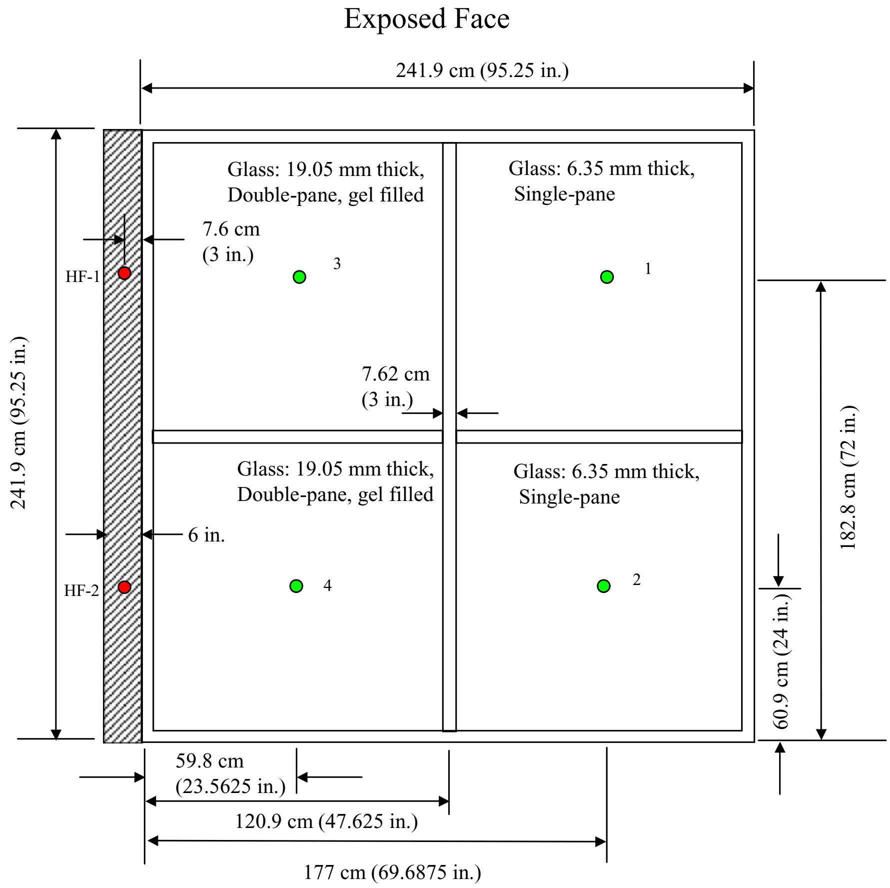
An important consideration in glazed wall assemblies is the framing. The entire assembly, including the glass, is given a fire rating. An insulated framing, (GPX), when glazed with the double-pane tempered glass (SAFTI superlite II XL), was designated as having a 45 minute fire rating under ASTM E119 [1]. It was decided to glaze the other half of the assembly with glass typically found in windows. The single-pane tempered glass (SAFTI Superlite I) was rated at 20 minutes based on ASTM E2010 [7]. The main purpose of using two different types of glass was to asses the relative performance of two different glazing technologies in the same experiment.

Temperatures were obtained using type K bare thermocouples (22 gauge) taped to the glass sections. Temperatures were obtained at the exposed and unexposed face and the locations of these thermocouples is displayed Figure 1(a)–(b). The thermocouples were offset 25.4 mm on the unexposed face to avoid blockage of radiation due to placement of the exposed face thermocouples.

Two Schmidt-Boelter water cooled total heat flux gauges (15 mm diameter) were used to measure the heat flux incident on the glass wall. The location of these gauges is shown in Figure 1(a)–(b). Ideally, it is desirable to have the gauges mounted flush to the surface of the glass sections, that way the gauges would be as close to the measurement location as possible. Unfortunately, it is not possible to drill into the glass sections to mount the gauges. An additional strategy may be to mount the gauges directly in front of the glass sections. This, however, is not desirable since the gauges would be shielding the glass sections from the radiation of the fire. Therefore, the gauges were located off to the side of the double-pane sections and mounted flush to the column (see Figure 1(a)). This method has been used extensively to obtain heat flux data for glazed sections [8–9].

Additionally, two Schmidt-Boelter water cooled total heat flux gauges (15 mm diameter) were placed behind the two double-pane glass sections (on the unexposed side). The gauges were placed at the same height (near the column) as the gauges located at the exposed face (see Figure 1(b)) and were located 15 mm from the glass surface. Such measurements were performed behind the double-pane glass assembly since it was expected that these two sections would survive longer in the fire than the single-pane glass sections and thus offer the ability to collect meaningful data for a longer duration.

To mitigate water condensation on the gauge surface, each gauge was water cooled to 75°C ± 5°C, which is well above the dew point. Since soot deposition on the gauge surface was not desired, the two gauges mounted on the exposed face were purged with N_2 for three



(a)

Figure 1. (a) Drawing of glass wall assembly showing the exposed face.(b) Drawing of the glass wall assembly showing the unexposed face.(c) Schematic of compartment used for the fire test.

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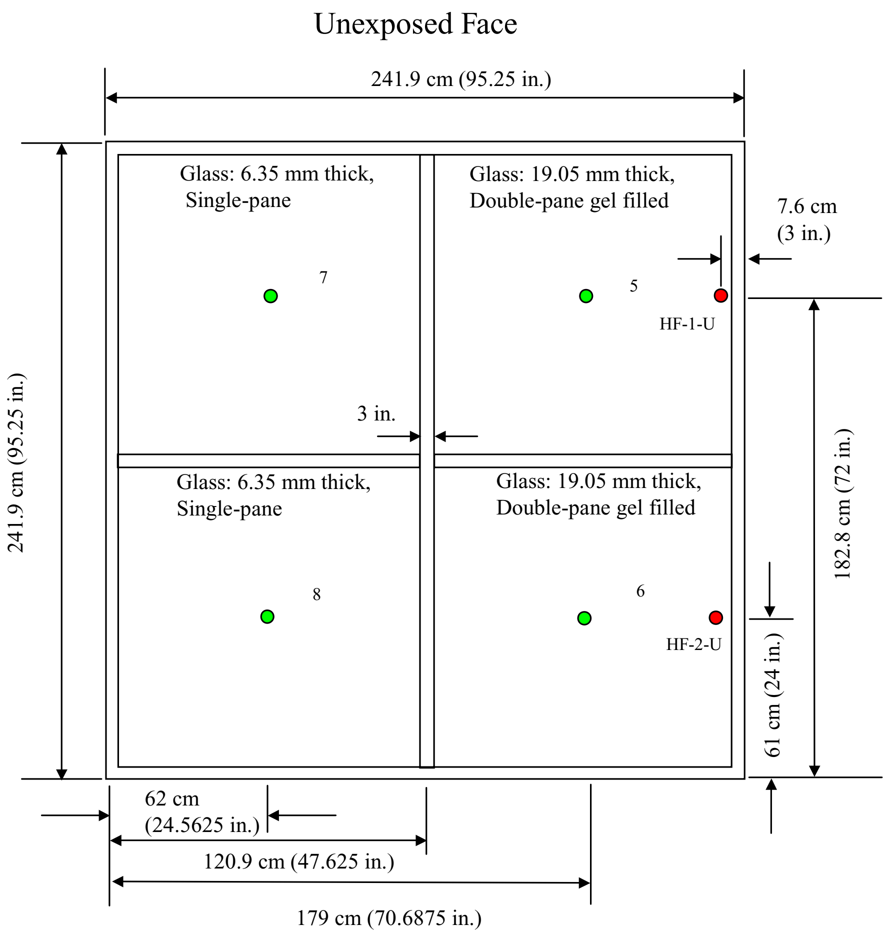


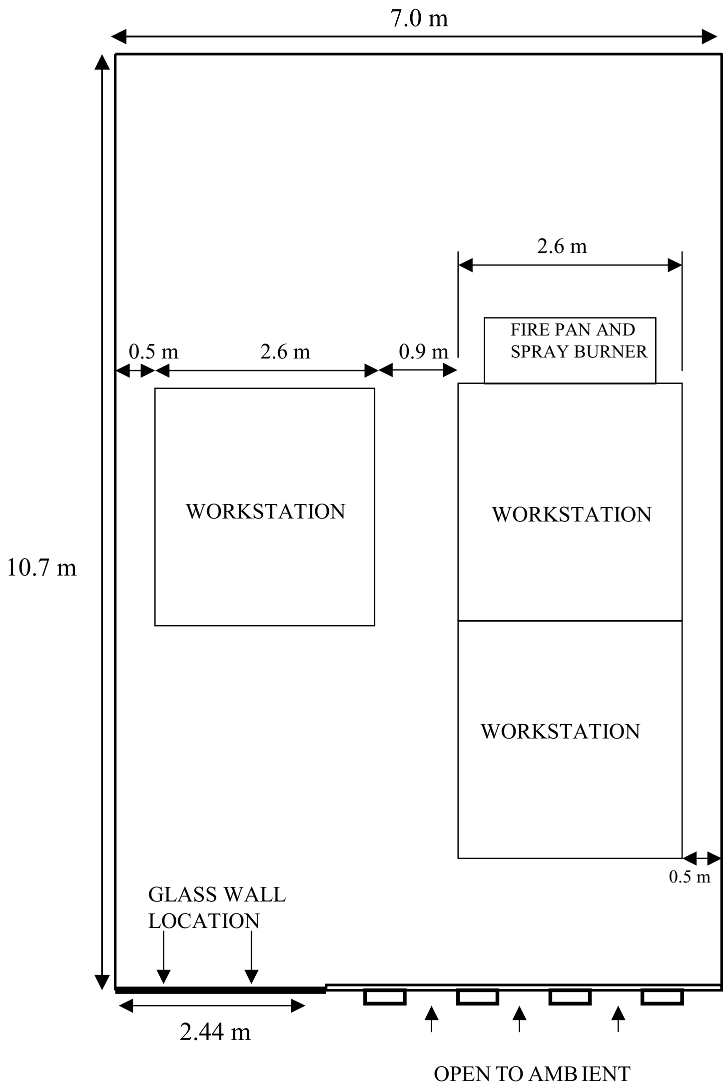
(b)

Figure 1. ***(Continued.)***

seconds, every two minutes (120 seconds), during the test. The purge signal was apparent and was removed from the temporal heat flux trace. Further details regarding total heat flux measurements are given elsewhere [10].

The unexposed face of the glass wall assembly was imaged using a standard (visual) video camera with a framing rate of 30 frames/s. In addition, an infrared camera was used to image the unexposed face, also at 30 frames/s. Both infrared and standard video cameras were recorded on mini-digital video (mini-DV) cassettes for subsequent image analysis. Prior to each test, photographs were taken at 2048 $\times$ 1024 pixel resolution of both the exposed and unexposed face using a digital camera fitted with a zoom lens. Another series of photographs was taken of the exposed and unexposed face upon completion of each test.

The size of the compartment for the fire experiments was 10.7 m long by 7.0 m wide by 3.4 m high. A schematic of the compartment is displayed in Figure 1(c). A 2.44 m by 2.44 m



(c)

Figure 1. ***(Continued.)***

opening was constructed on the lower 7.0 m side of the compartment to mount the glass wall assembly. The entire assembly was mounted flush to the ceiling of the compartment and all instrumentation was installed while the partition assembly was mounted. The compartment was lined with calcium silicate board.

The compartment was constructed to simulate a typical office space that would be found in tall buildings. Accordingly, the combustibles within the compartment consisted of three workstations for each of the fire exposures reported here. The fires were ignited using a spray burner (see Figure 1(c)). Gas-phase temperature profiles were obtained using thermocouple trees inside the compartment. The heat release rate (HRR) of the fire was measured using oxygen consumption calorimetry and observed to peak at 16.0 MW [11]. The total burn time for the fire was approximately 45 minutes. Further details of the compartment and the combustibles within the compartment are available elsewhere [11].

Results and Discussion

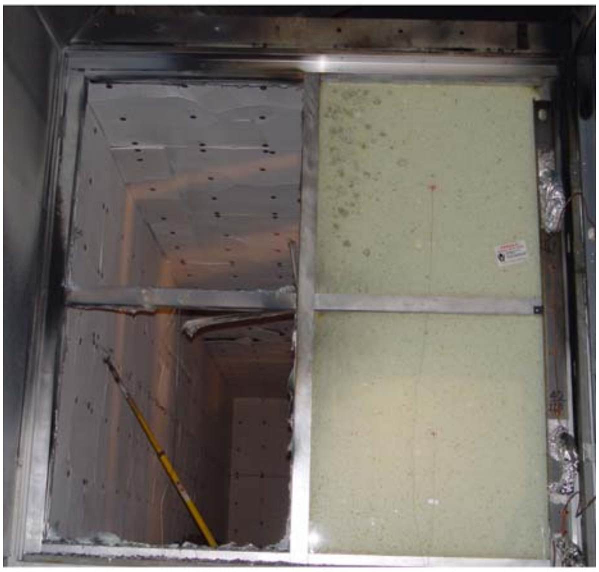
Figure 2(a)–(b) displays pictures the exposed face and unexposed face of the glass assembly upon completion of the fire test. Clearly, the two single-pane glass sections were destroyed during fire testing. As for the double-pane glass sections, the inside glass panes were destroyed but the glass panes on the unexposed side were completely intact (see Figure 2(b)). The gel insulation between the two panels frosted extensively.

The temporal evolution of glass fall out was obtained from the visual and infra-red video records. After ignition, all glass sections were observed to become coated with soot due to thermophoretic deposition of the hot soot onto the cold glass surfaces. The inside pane of the double-pane glass section (upper) was the first to fall out. Subsequent to this, the bottom section of the single-pane glass section cracked and fell out of the frame ($t = 185$ s after ignition). Within 27 seconds of the fall out of the bottom single-pane glass section, the other single-pane glass section cracked and fell out of the framing ($t = 212$ s after ignition). The final piece to fall out was the inside pane of the double-pane section (lower). The outside glass pane for double-pane glass sections remained in tact throughout the fire exposure and did not crack.

Both visual and infrared cameras were used to obtain information for the glass cracking and fall out process. The cameras were focused on the unexposed face of the glass wall. Figure 3 displays these processes for the bottom section of the single-pane glass section. From these images, the cracking and fall out process was rapid. Cracks developed across the glass and the panel fell out after 0.8 seconds of initial crack formation. The time scale of the fall out process was similar for the both single-pane sections.

The temperatures were measured at the exposed and unexposed face for the four glass sections and these distributions are displayed in Figures 4(a)–(b). Of all the reported results, the exposed face temperature measurements have the largest uncertainty due to the inherent difficulty of measuring surface temperatures within the fire environment. It has been shown that differences of greater than 100°C for exposed surfaces may be realized [12]. Accordingly, the relative combined uncertainty in these temperature increases at the exposed surface was $\pm 30\%$. For the unexposed surface temperatures, the relative combined uncertainty is estimated to be ± 10°C, as these measurements are taken on surfaces not directly exposed to the large heat fluxes. For the exposed face temperature locations (see Figure 4(a)), thermocouple location 3 indicated that this glass section was the first to fall out. This was in agreement with the direct visual observations from the video records. At thermocouple locations 1 and 2, the temperature traces suggested that both panels fell out at the same time. However, the glass section with thermocouple location 2 fell out 27 seconds before the panel where thermocouple 1 was mounted. When the bottom single-pane glass section fell out, a vent was created. The flow induced by this event resulted in the thermocouple 1 becoming disengaged from the glass surface. As a result, the fall out time indicated by the thermocouple trace is incorrect for thermocouple location 1. The trace

(a)



(b)

Figure 2. (a) Digital pictures of the exposed glass face immediately after the fire exposure. (b) Digital pictures of the unexposed glass face immediately after the fire exposure.

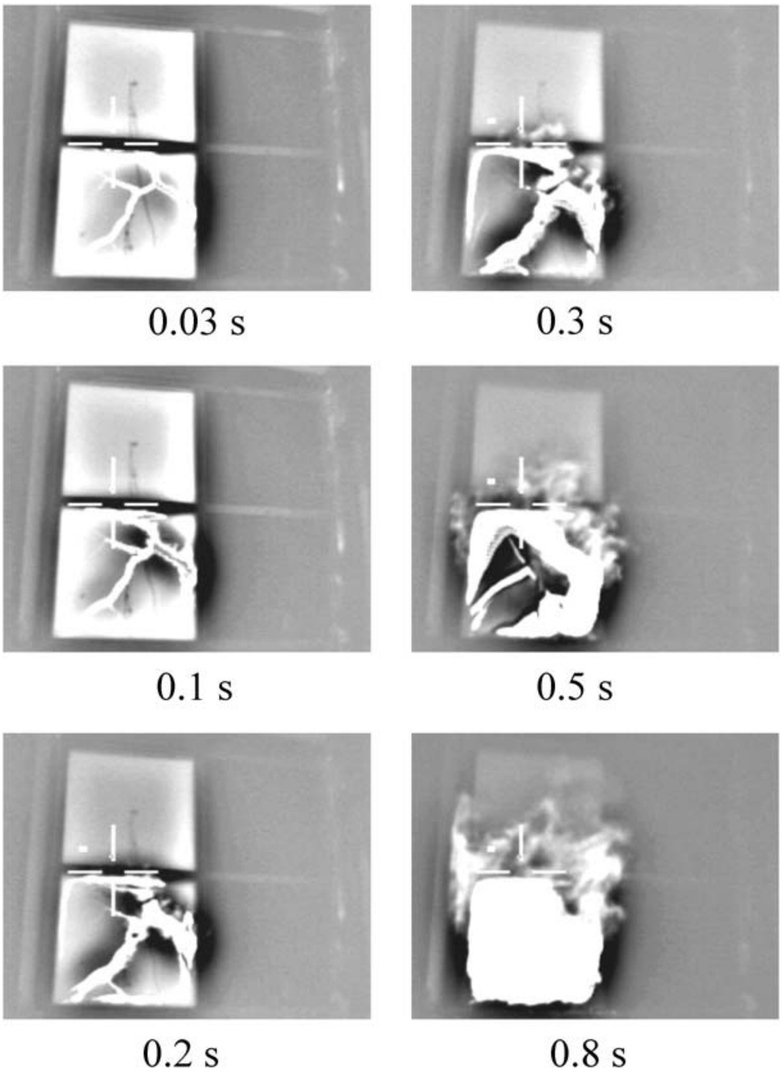


Figure 3. (a) Temporal evolution of the glass fall out as seen with the infra-red camera. The camera is focused on the unexposed face.

obtained for thermocouple location 4 shows that the inside panel of the double-pane glass section on the bottom fell out last. This agreed with the fall out time measured from the video records.

The unexposed face temperature measurements are displayed in Figure 4(b). Thermocouple location 8 corresponds to the backside temperature for thermocouple location 2. Since this section fell out, the time of fall out matched thermocouple location 2. Thermocouple location 7 resulted in a large increase in temperature when fall out was observed for thermocouple location 8. As mentioned, the upper single pane section remained in place

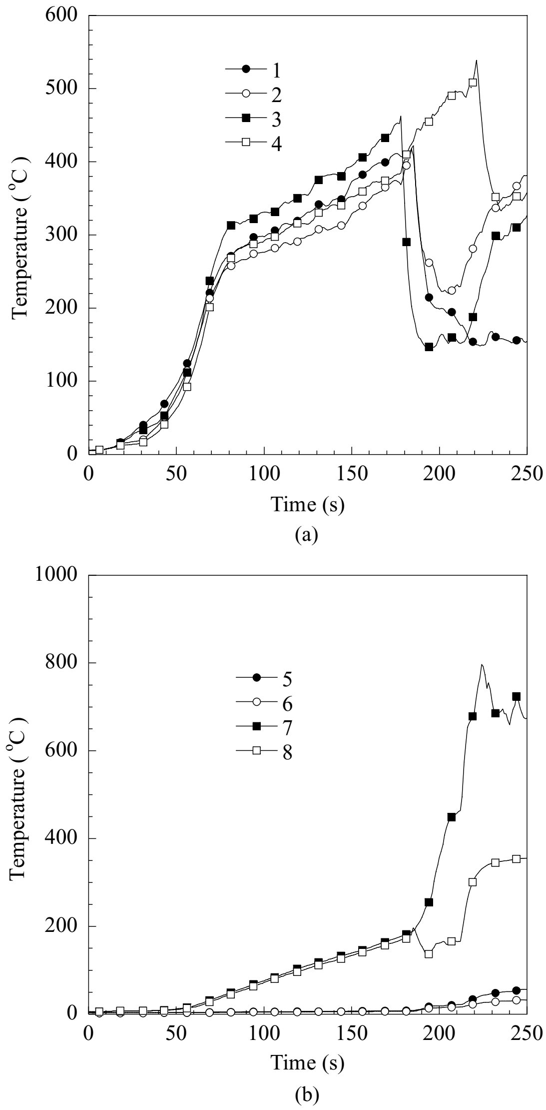


Figure 4. (a) Temporal evolution of temperatures measured on the exposed glass face as a function of location, and (b) Temporal evolution of temperatures measured on the unexposed glass face as a function of location.

after the bottom single pane section fell out. As soon as the bottom single pane section was gone, hot gases rushed out of the compartment and upwards due to buoyancy over thermocouple 7. Therefore, the temperature measured at thermocouple location 7 is merely the prevailing gas temperature after the lower single-pane glass section fell out. The exposed face temperature at fall out was 400°C–500°C for all glass sections. For unexposed

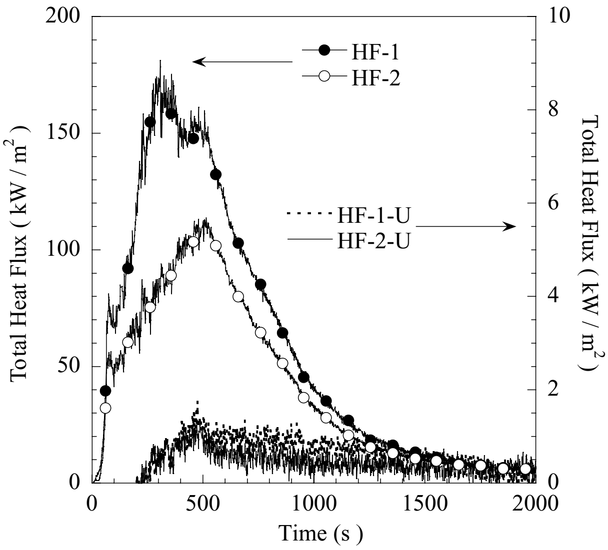


Figure 5. Temporal evolution of the total heat flux measurements, both at the exposed and unexposed face.

temperature measurements on the double-pane glass sections (thermocouple locations 5 and 6) the temperatures never climbed above 80°C and 120°C for thermocouple location 6 and 5, respectively.

Figure 5 displays the measured total heat flux measurements. The combined uncertainty in the total heat flux measurements was ± 10% [10]. Measurements obtained at the exposed and unexposed face are shown. During the time of glass fall out, the total heat flux at the exposed face was between 50–70 kW/m^2 at locations HF-1 and HF-2, respectively. At the unexposed face of the double-pane gel filled glass sections, the measured total heat flux was only on the order of 1 kW/m^2 to 2 kW/m^2.

Considerable effort has been devoted to understanding how glazing responds to a thermal insult, such as a fire [8, 9, 13–21]. Most, if not all of these investigations have focused on glass typically found in window assemblies. To the authors knowledge, an in depth study is not available in the open literature for gel-filled glass panes subjected to fire. Fire-rated glass walls include gel-filled glass to obtain the insulation criterion mandated by ASTM E119 [1].

In light of this, results of glass breakage and subsequent glass fall out can be compared to studies in the literature for the single-pane glass sections. Joshi and Pagni [21] have developed a simplified mathematical model, BREAK1, which can be used to estimate the time for a window to break that is exposed to a compartment fire. This model does not describe glass fallout, only the time required for a glass panel to crack. Details of the model are provided elsewhere [21], however it is important to note that several parameters are required as input to the model. BREAK1 [21] was used to compare the time for the 6.35 mm single-pane tempered glass to break. The input parameters used for the 6.35 mm single-pane tempered glass in the present experiment are: glass thermal conductivity = 0.97 W/mK, glass thermal diffusivity $= 0.46 \times 10^{-6}$ m^2/s, glass absorption length $= 0.1 \times 10^{-2}$ m, glass breaking stress $= 0.12 \times 10^9$ Pa, glass Young's Modulus $= 0.7 \times 10^{11}$ Pa, glass thermal coefficient of linear expansion $= 0.85 \times 10^{-5}$/°C, glass thickness $= 0.0063$ m, shaded thickness $= 0.0508$ m, and half-width of glass section $= 0.58$ m. In addition, BREAK1 [21] required the following additional input parameters: the heat transfer coefficient, unexposed side $=$ 5.0 W/m^{2}K, ambient temperature of glass, unexposed side $= 300$ K, emissivity of the glass $= 0.85$, emissivity of ambient $= 0.8$, and heat transfer coefficient on hot layer side $=$ 20 W/m^{2}K. Finally, the heat flux data (see Figure 5) was used as boundary conditions for the model.

The model predicted that the lower single-pane glass section would break at a time of 134 s after ignition. The experimentally observed time for the first crack to form was 185 s. BREAK1 predicted that the temperature of the lower single-pane glass panel at breakage was 311°C and 224°C on the exposed face and unexposed face, respectively. The experimentally observed temperatures at the exposed face and unexposed face were 400°C and 200°C, respectively. The model under-predicted the time for the single-pane glass section to break.

The problem of glass fallout in compartment fires has not received the degree of attention as the problem of glass breakage. The work of Shields et al. [8, 9] is most appropriate for comparison to the single-pane glass sections, since these investigators exposed the glazing to real-scale compartment fires and used 6 mm tempered glass, similar to the glass used for the single-pane glass sections reported here. They reported that the average exposed glass surface temperatures at major glass fall out was 447°C. Total heat flux measurements were measured in columns near the glass panels and the average total heat flux incident on the glass panels was reported to be 35 kW/m^2 when major glass fall out occurred. No uncertainty was reported in these measurements.

Comparing these results with the present measurements, the exposed glass surface temperature for fall out of the bottom single-pane glass panel was 400°C. The total heat flux incident at this section of the glass wall was 50 kW/m^2. These values are similar to literature values [8, 9]. Shields et al. [8, 9] stressed that vent formation due to glass fall out occurs at much higher glass temperatures than previously accepted values in the literature. Present measurements further support this position. Similar to literature values, the single-pane glass sections were observed to break before the time of the peak heat release rate of the fire. It must be noted, however, that in the present experiments glass breakage and glass fallout for the single-pane sections occurred at essentially the same time after ignition (see Figure 3).

In terms of fire safety, it is important to understand how much energy is transmitted through the glass as a consequence of the fire exposure [13, 15]. As mentioned, two total heat flux gauges were placed behind the double-pane glass. The measured unexposed glass temperatures were used to calculate glass emission (due to surface re-emission by the glass) [15]. The hemispherical emissivity used in these calculations was 0.85, a value typically assigned to window glass [15]. The results of these calculations are shown in Figure 6 and are plotted along side the heat flux measurements. The calculations suggest that the majority of the heat flux measured was due to emission from the glass. Consequently, the amount of radiation transmitted through the two gel filled double-pane glass sections was minimal.

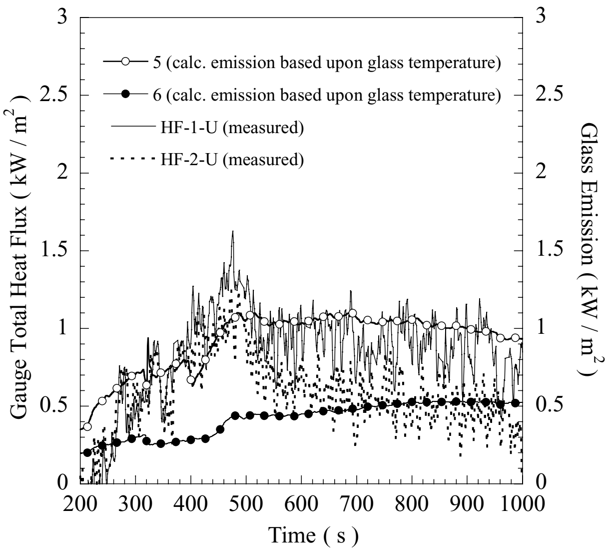


Figure 6. Temporal evolution of the calculated emission based upon glass temperature. The temporal evolution of the measured total heat flux at the unexposed glass surface is shown as well.

Conclusions

The exposed glass surface temperature for fall out of the bottom single-pane tempered glass panel was 400°C and the total heat flux incident at this section of the glass wall was 50 kW/m^2. These values are similar to literature values [8, 9]. Shields et al. [8, 9] stressed that vent formation due to glass fall out occurs at much higher glass temperatures than previously accepted values in the literature; current measurements further support this position. Presently, the times for glass breakage and glass fallout were essentially the same. The model, BREAK1 [21], under-predicted the time for the single-pane tempered glass section to break (134 s predicted, observed 185 s). The amount of radiation transmitted through the two gel filled double-pane glass sections was minimal; the measured total heat flux was only on the order of 1 kW/m^2 to 2 kW/m^2. To the authors' knowledge, this is the first study in the open literature to subject gel-filled glass panes to real fire exposures.

Acknowledgments

The authors acknowledge the staff of the Large Fire Laboratory (Mr. A. Maranghides, supervisor) at NIST for assistance in the experiments. Dr. T. J. Ohlemiller of BRFL-NIST is acknowledged for his guidance in performing total heat flux measurements.

Note

1. Certain commercial equipment are identified in this paper in order to accurately describe the experimental procedure. This in no way implies recommendation by NIST.

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