J. of Fire Prot. Engr., **3** (1), 1991, pp 25-34

# AN EXPERIMENTAL INVESTIGATION OF GLASS BREAKAGE IN COMPARTMENT FIRES

by

**Michael J. Skelly**
**Richard J. Roby**
**Mechanical Engineering Department**
**Virginia Polytechnic Institute and State University**
**Blacksburg, VA 24061-0238**

**and**

**Craig L. Beyler**
**Hughes Associates**
**2730 University Boulevard West**
**Wheaton, MD 20902**

## SUMMARY

An experimental investigation has been completed which examined the breaking of window glass by fire. The experiments were carried out in a compartment designed to achieve a two-layer fire environment characteristic of normal building fires. The experimental data was collected from two test groups: the first for windows with their edges insulated from the fire (edge-protected) as occurs in normal window installations and the second for windows uniformly heated by the fire (edge-unprotected).

The results of the edge-protected window tests indicated that the glass breakage was caused by a critical temperature difference between the central heated portion of the pane and the glass edge. The experimental work showed the critical value to be approximately 90°C. After the material properties of the glass were determined, the theoretical findings of Keski-Rahkonen were used to obtain a value of 70°C; the difference attributed to radiative heating of the glass surface thermocouple. The test results also demonstrated a distinctive loss of integrity by the windows. When breakage occurred, the cracks spread throughout the glass, joined together and caused catastrophic collapse of the pane.

The results from the edge-unprotected window tests were quite different. Relatively few cracks developed and almost no propagation across the glass was observed. Consequently, there was no window collapse in any of these cases. The breakage did initiate at a consistent glass temperature of 197°C, much higher than that observed for the edge-protected case.

## INTRODUCTION

The breaking of window glass during a fire is significant in that the new wall openings produced provide an inlet for fresh air and an exit for the hot fire gases. The increased ventilation changes the burning rate and the equivalence ratio for the system and consequently the amount and composition of the escaping combustion gases. These hot gases serve to spread fire throughout a structure, contributing to the staggering property losses suffered each year. Also, the gases themselves are a major cause of fire fatalities because the smoke and fumes released by the fire disable victims.

Several theoretical and experimental papers have addressed the mechanism of glass breakage in fires. The most comprehensive of these is the paper by Keski-Rahkonen[1]. This study used the heat conduction equation with linearized radiation boundary conditions to calculate the thermal field in an edge-protected window pane that was heated by fire. The temperature field was then used to determine the thermal stress field in the pane. These results indicated that the stresses were proportional to the difference between the average and local glass temperatures. Keski-Rahkonen generalized his stress results at the pane edge since this is where the maximum temperature difference occurs. His work indicates that the stress at the edge is very close to

$$\sigma_y = E\beta\,(T_c - T_e) \qquad [1]$$

where

$\sigma_y$ is the normal failure stress
$E$ is Young's Modulus
$\beta$ is the coefficient of linear thermal expansion
$T_c$ is the heated glass temperature
$T_e$ is the insulated edge temperature.

He obtained a rough value for the breakpoint temperature difference of soda glass, taking for maximum tensile stress, $\sigma_y$ = 50 MPa, linear thermal expansion coefficient $\beta = 8 \times 10^{-6}$°C$^{-1}$ and Young's Modulus E = 80 GPa, which yield $T_c - T_e$ = 80°C.

Emmons, in his paper reviewing the work done on glass breakage by fire[2], provides a simpler derivation of the above formula: the central part of a glass plate heated from temperature $T_e$ to $T_c$ will expand by $\varepsilon = \beta\,(T_c - T_e)$. However, the cool edge expansion is restricted by a normal stress, $\sigma_y$, which is equal to the expansion multiplied by Young's Modulus. The glass edge, where the original glass sheet was cut to fit the frame, contains irregularities which cause a crack to start at a tension lower than the normal breaking stress for the rest of the glass.

In the third of the theoretical papers[3], Pagni explains the edge-protected window breakage phenomenon with an analogy:

> A window breaks in a fire for the same reason that an ice cube cracks when placed in a liquid. Thermal expansion places the cooler portion in tension. The exposed window heats and expands placing its cooler shaded edge in tension until it cracks at a small defect, usually at the top inner edge.

The formulations that Pagni develops to estimate the glass temperature difference at breakage are the same as those in Emmons' work and are equivalent to the simplified version of Keski-Rahkonen's heat conduction equation. However, because Pagni uses slightly different material constants, he obtains a temperature difference at breakage of 58°C. Pagni also relates the results of a fracture mechanics computer simulation test of this theory. A two-dimensional unsteady version of this problem was run on a Cray computer with the resultant temperature difference obtained of 60°C with the same property values.

The only experimental study done to date was by two Harvard University seniors P. K. Barth and H. T. Sung in 1977[4]. They heated glass plates (15 cm x 18 cm or 15 cm x 15 cm) using a radiant panel. Uniformly heated plates sometimes did not break at all, while when they did break, the break always started at the edge[3]. Some of the plates had definite surface scratches, but in no instance did the fractures follow these scratches, or originate there. The original crack often bifurcated (split into two diverging cracks) at a distance away from the edge (usually 1 cm or more). In the case of uniform heating, there was never more than one bifurcation.

In the edge-protected cases, the results were quite different. In these experiments, where the glass edge was shaded by a mask, the plates broke in every test. As with the uniform heating, all of the cracks originated at the edge (usually on the top or bottom). However, multiple bifurcations were the rule as the original fracture split within 1 cm of the edge and each of the new breaks soon split, resulting in five or more cracks. This type of break pattern was important because the cracks moved through the glass and joined together, causing the window to collapse.

This paper examines experientially the surface temperature conditions under which window glass will break during a room fire. Edge-protected and edge-exposed windows were installed in a compartment and tested during a fire to check the theory that the windows break at relatively low temperatures when a specific temperature difference between the center and edge surfaces is reached. Also, the manner in which the windows broke was studied.

## EXPERIMENTS

The experiments performed to investigate window breakage were made under conditions closely resembling those found in building fires. All tests were made within a compartment fire setting.

The compartment (see Figure 1), with dimensions of 150 cm x 120 cm x 100 cm, was framed using 0.6 cm angle with 0.6 cm thick, 10 cm wide iron slats welded onto the frame to provide support for fire insulating board. Thermal Ceramics brand Kaowool ceramic fiber board was the insulating material bolted to the frame to close off the walls and the ceiling. The 2.5 cm thick boards were bolted onto the iron slats inside the compartment. The ventilation path allowing the combustion gases to flow from the compartment was provided by cutting a rectangular window into the center insulating board in the front of the box. The height and area of the window were maintained constant throughout all of the tests. The area of the opening was 50 cm x 58 cm with the bottom of the vent 36.8 cm from the floor of the compartment and the top 20.0 cm from the compartment roof.

The plenum was also framed using the 0.6 cm angle iron but was sealed with 0.3 cm steel plate surrounding the frame up to the full plenum height of 58 cm. A 30 cm diameter hole was cut into the front plate to provide the ventilation path into the plenum. The plenum guide vanes were constructed of 0.16 cm steel plate. The design was such that the incoming air flowed around the sides of the lower plate up into the combustion zone guided toward the center of the compartment by the two side vanes.

The window breakage tests were conducted using standard 0.24 cm thick 28 cm x 50 cm soda-ash glass windows. The glass was cut by hand with a scribe; the edges were not ground in any way. The windows were mounted in a 36 cm x 56 cm aluminum window frame that was installed on the side of the compartment (Figure 1). The protected edge was maintained at 2.5 cm wide around the entire edge of the pane.

The fires were created in the compartment by burning liquid hexane. Four different sized aluminum trays were used as containers to hold the fuel: the 20 cm x 30 cm, 20 cm x 20 cm, 10 cm x 20 cm and 20 cm diameter pans were filled with the hexane to a depth of 3 cm to 5 cm and allowed to burn in the center of the compartment. There were a total of 17 experiments performed: 11 edge-protected and 6 edge-unprotected tests. In all tests, the entire pane of glass was fully immersed in the hot gas layer of the fire within the first 10 seconds.

The initial set of experiments tested the edge-protected window glass. Figure 2 shows the placement of the window pane in the frame for these tests. The insulation used was 1 cm wide cellular rubber weather stripping. The window was held in place against the weather stripping by metal washers. Figure 2 also indicates the position of

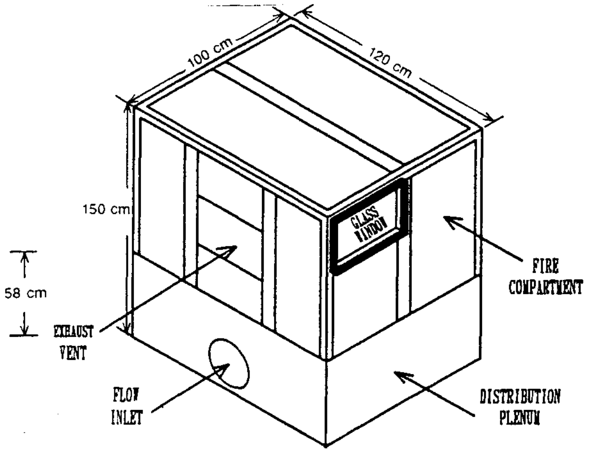


Figure 1. Schematic of the compartment used for window breakage tests.

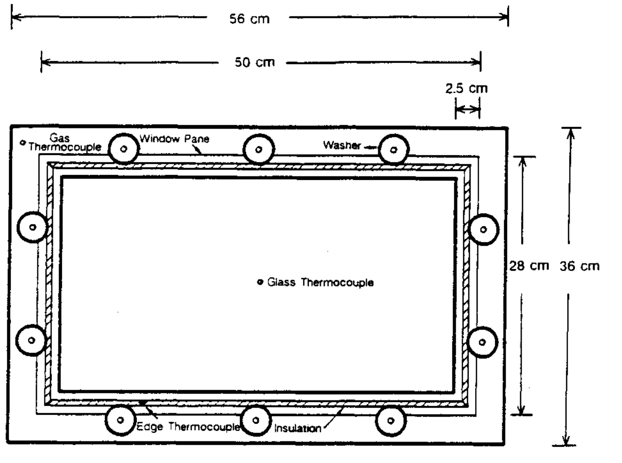


Figure 2. Schematic of window installation including thermocouple placement.

the thermocouples used to measure the temperatures. The glass temperature was measured using an Omega brand chromel-alumel "cement-on" thermocouple (K-type) attached to the inside center of the window. The glass edge temperature was also measured with a chromel-alumel thermocouple (K-type). The exposed junction was positioned between the window and the weather stripping. Omega electronic ice points were used as references for both thermocouples.

In the second set of experiments, edge-unprotected windows were tested. In these tests the windows were mounted on the opposite side of the window frame inside the compartment and held fixed by reversing the washers. In this way, the entire glass plate was exposed to the heat source. The glass temperature was again measured with a "cement-on" chromel-alumel thermocouple (K-type) attached at the same point as the edge-protected tests. There was no edge temperature to be measured in these tests; instead, the compartment gas temperature was measured. Figure 2 shows the point at which the thermocouple was inserted. The exposed junction was set at a position 10 cm deep into the compartment, where subsequent tests showed the gases to be well mixed. Again, electronic ice points were used as references for both thermocouples.

In all tests, digital voltmeters were used to record the thermocouple outputs. To obtain a complete record of all the data, each of the tests was videotaped. These tapes provide a record of the thermocouple outputs throughout the tests as well as a picture of the breakage patterns at the time of failure. The final tabulated and graphical results were obtained by viewing each test in real time, clocking the recording with a stopwatch and compiling data pairs of thermocouple voltages (later converted to temperatures) vs time. The qualitative breakage pattern results were obtained through viewing both real-time and stop-action footage of both the total glass failures and the crack initiations.

## RESULTS

The complete time histories for selected edge-protected and edge-unprotected tests are plotted together in Figures 3 and 4. Figure 3 shows the 20 cm x 30 cm pan fire data from Tests 3 and 14. The compartment gas temperature profile is plotted along with the edge-unprotected glass temperature record and the edge-protected test data of heated glass and edg temperature histories. The most conspicuous feature of the graph is the compartment gas temperature curve. This plot rises faster and higher than any of the glass temperature curves reaching a peak of 720°C. The final data point represents the temperature and time at which the fuel

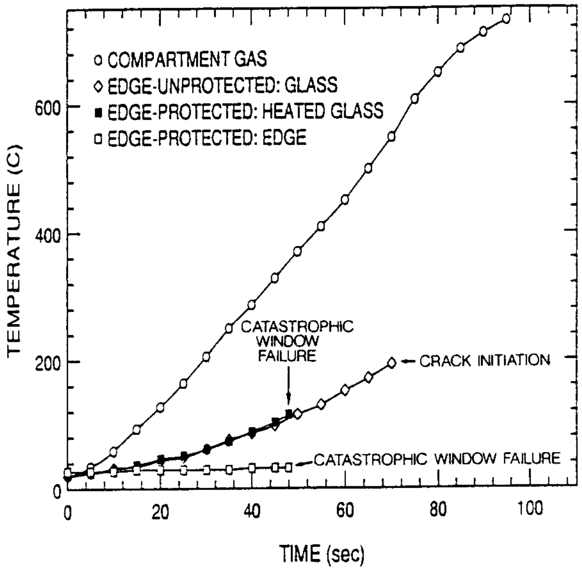


Figure 3. Time-temperature history of glass for 20 cm x 30 cm pan fire for both edge-protected (Test 3) and edge-unprotected (Test 14) installations.

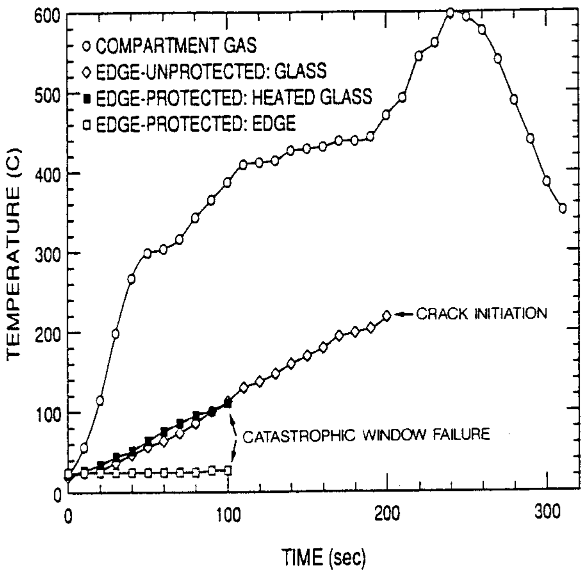


Figure 4. Time-temperature history of glass for 20 cm x 20 cm pan fire for both edge-protected (Test 4) and edge-unprotected (Test 15) installations.

was exhausted. The continuously rising curve indicates that the fire diminished very little in intensity before extinction. Below this, the identical shapes of the two heated glass temperature curves show that there were very similar fire conditions in these two tests. The edge-unprotected curve extends further and only ends where the crack initiation occurs. At this point, the compartment is still heating up, as the rising compartment gas curve indicates. The edge-protected curve ends at the 49 second mark where the catastrophic window failure occurred. The lowest curve, the plot of the edge temperature for Test 3, shows that almost no heating of the edge took place.

Figure 4 shows the 20 cm x 20 cm pan fire data from Tests 4 and 15. The same variables are plotted as in Figure 3. In this case, the compartment gas temperature curve rises more slowly and for a longer time than for the 20 cm x 30 cm gas temperature curve. Also, after reaching a peak temperature of 600°C, the gas curve falls for 80 seconds before the fire goes out. This size pan fire bums with less intensity and diminishes over a longer period of time than the 20 cm x 30 cm size. The coincidence of the two heated glass temperature curves is similar to that shown in Figure 3. Until the point of glass breakage of the edge-protected pane, the two time-temperature curves are nearly identical. However, while the edge-protected heated glass curve undergoes failure at 100 seconds, the edge-unprotected plot continues for another 100 seconds until the crack initiation occurs. These values are more than twice as high as the corresponding times in the 20 cm x 30 cm tests of Figure 3. Again, the lowest curve is the plot of the edge-protected data. As in the last figure, the nearly constant temperature curve shows that virtually no edge heating has taken place.

Figure 5 differs from the previous two graphs in that the data from two edge-protected window tests are now plotted together as opposed to that from one edge-protected and one edge-unprotected. The data for these curves is from Tests 9 and 11, both performed with a 10 cm x 20 cm pan fire. Test 11 represents the only edge-protected test where there was no glass breakage. Both time scales are similar, extending out past 300 seconds. The glass temperature curves are of similar shape and follow together closely. The values for Test 9 are 5-10°C lower before the failure occurs, but the glass temperature plot for Test 11 continues on for about 120 seconds more, rising to a maximum temperature of about 120°C before falling slightly before the fire is extinguished. The two edge temperature curves are even more similar, overlapping for most of their common length and showing a temperature rise of 15°C. When failure occurs in Test 9, the breakpoint temperature difference is quite low at approximately 60°C. This is the lowest of all tests. When the fire is extinguished in Test 11, the temperature difference is 70°C. However, the maximum difference is 80°C and occurs about 60 seconds before this point.

Table 1 summarizes the results from all the edge-protected window tests. There were a total of eleven tests performed using four different pan sizes. In ten of the cases there was a catastrophic window failure. In Test 11, with the 20 cm x 10 cm pan fire, no cracking was observed. Each of the other ten tests resulted in multiple bifurcations which joined together causing partial window collapse. For each of the tests, the pan fire size, the temperatures at glass breakage and the time to breakage are listed in the table. The table averages are provided for the center temperature, edge temperature and the breakpoint temperature difference. The standard deviations are listed in parentheses.

All windows used for the tests shown in Table 1

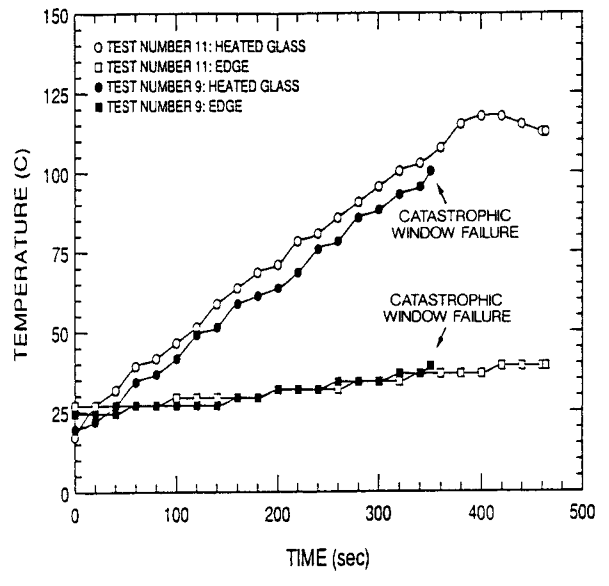


Figure 5. Time-temperature history of glass for 10 cm x 20 cm pan fire for two edge-protected installations (Test 9, with glass breakage and Test 11, with no glass breakage).

**Table 1. Window Test Results: Edge-Protected**

| Test No. | Fire Size (cm) | Temperature at Glass Breakage Edge, $T_e$ (°C) | Center, $T_c$ (°C) | $T_c - T_e$ (°C) | Time of Crack Initiation (sec) |
|---|---|---|---|---|---|
| 1 | 20 x 30 | 22 | 117 | 95 | 55 |
| 2 | 20 x 30 | 27 | 159 | 132 | 56 |
| 3 | 20 x 30 | 32 | 116 | 84 | 48 |
| 4 | 20 x 20 | 27 | 110 | 83 | 100 |
| 5 | 20 x 20 | 35 | 135 | 100 | 112 |
| 6 | 20 x 20 | 35 | 115 | 80 | 109 |
| 7 | 20 round | 29 | 110 | 81 | 127 |
| 8 | 20 round | 35 | 132 | 97 | 132 |
| 9 | 10 x 20 | 40 | 101 | 61 | 350 |
| 10 | 10 x 20 | 50 | 137 | 87 | 330 |
| 11 | 10 x 20 | 37* | 118* | 81 | No Cracks |
| AVG. (SD) | | 33(8) | 123(16) | 90(18) | |

* At Maximum Temperature Difference

were initially at 20°C. The average measured temperature difference between the center and edge temperature is 90°C with a standard deviation of 18°C. There is no systematic trend between this temperature difference and the pool fire size or time to breakage. However, there is a systematic trend in the edge temperature at breakage. The average edge temperature at breakage is 33°C, and this temperature systematically increases with breakage time (see Table 1). This indicates that for accurate predictions of breakage time, the heating of the edge must be predicted. Although conservative predictions of breakage time can be made by ignoring this edge heating, it may be significant in slowly growing fire situations.

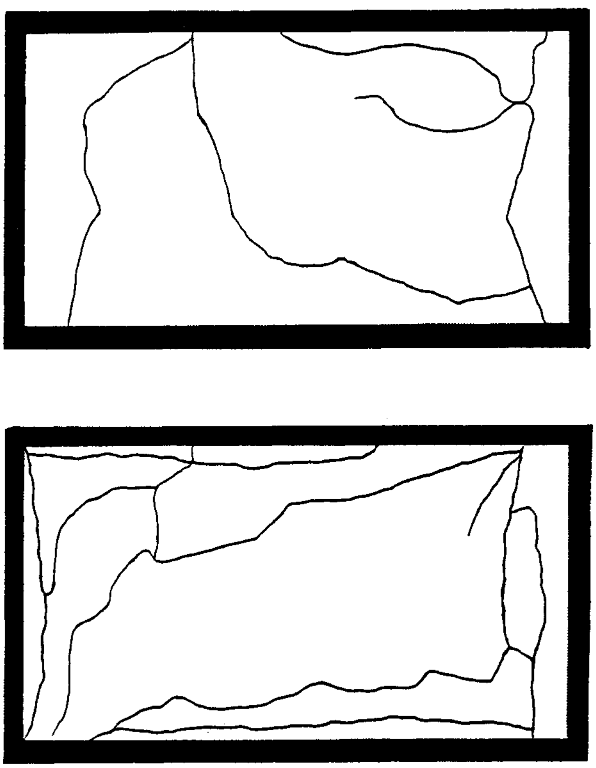

Figure 6. Diagram of the window breakage pattern for two edge-protected tests (top: Test 2; Bottom: Test 7).

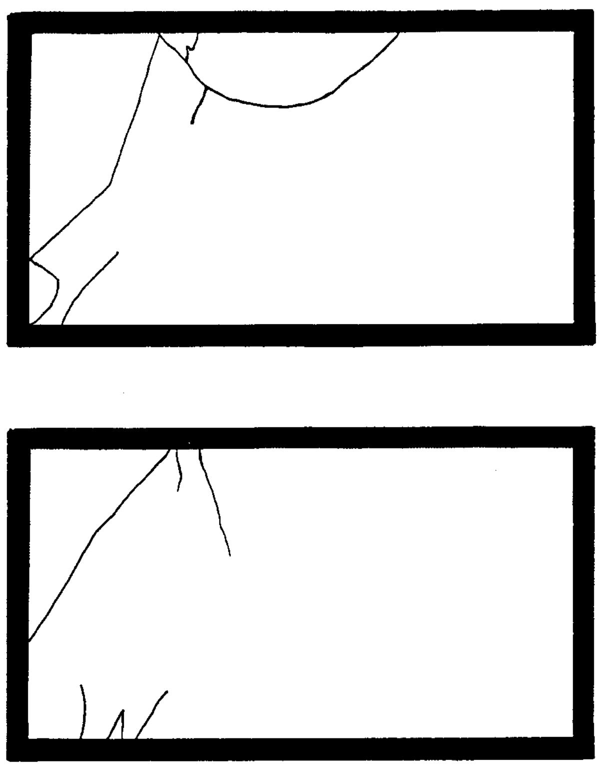

Figure 7. Diagram of the window breakage pattern for edge-unprotected tests (top: Test 14; Bottom: Test 15).

Table 2 summarizes the results from the edge-unprotected window glass tests. There were three tests performed with the 20 cm x 30 cm pan fires and three with the 20 cm x 20 cm pan fires. In all of the tests, there were cracks developed in the glass plates, however, there were no catastrophic failures as in the edge-protected tests. For each test, the time to crack initiation, and the temperatures at that time are listed in the table. The table average for the glass temperature is 197°C ± 15. There is no average for the compartment gas temperature because the values differ between the two pan sizes.

Figure 6 shows representative breakage patterns from the ten edge-protected window tests where cracking occurred. In all of the tests, the cracks initiated at the edges of the glass and they propagated rapidly, such that all breakage was complete in less than one second. The figures show that there were many single and multiple bifurcations, with the cracks spreading throughout the pane and joining together. In all ten of the tests, there was at least partial window collapse. In the majority of the cases, more than half of the window was removed from the frame.

Breakage patterns for typical edge-unprotected window tests are presented in Figure 7. For the edge-unprotected tests, crack propagation across the pane lasted from less than one second to more than one minute. The two patterns in Figure 7 (test 14 on top and test 15 below) represent the maximum and minimum amount of cracking that occurred in the tests. Tests 16 and 17 produced patterns very similar to those shown from Test 14 in regard to the absence of multiple bifurcations and in the isolation of the individual cracks. There are some bifurcations present in the upper pattern in Figure 7, however, the resulting cracks do not continue to split. Also, in Tests 12, 14 and 15, small portions of the window were removed because of the cracking. In none of the three cases did the newly created openings exceed 3 cm2 in area. Even in the case of Test 13 where the glass split completely in half, the window remained intact. And, just as in the edge-protected tests, all the cracks initiated at the edges of the glass. Although some of the cracks started in the vicinity of the washers used to hold the glass in place, most did not.

In the research reviewed earlier, Equation 1, developed independently by Keski-Rahkonen, Emmons and Pagni[1-3], was applied by all three investigators to determine the theoretical breakpoint temperature difference across a pane of glass. That work required the use of material properties for the glass and in all three cases, the values used were taken from reference books listing the properties for an average sample of soda-ash glass. For this paper, the material properties were determined for glass samples cut from the same large sheet of glass as the glass panes that were used in the tests.

The first material property obtained was the coefficient of linear thermal expansion, $\beta$. The coefficient was determined from tests made with a Netzsch Dilatometer. Two samples were measured and each had the same coefficient value of $9.5 \times 10^{-6}$ %/°C. This is 17% greater than the literature reference value of $8 \times 10^{-6}$ %/°C used by Keski-Rahkonen and Emmons[5].

The glass modulus of elasticity, E, and tensile

**Table 2. Window Test Results: Edge-Unprotected**

| Test No. | Fire Size (cm) | Temperature at Cracking Center, $T_c$ (°C) | Gas, $T_g$ (°C) | Time of Crack Initiation (sec) |
|---|---|---|---|---|
| 12 | 20 x 30 | 184 | 632 | 75 |
| 13 | 20 x 30 | 215 | 630 | 65 |
| 14 | 20 x 30 | 195 | 550 | 70 |
| 15 | 20 x 20 | 218 | 470 | 200 |
| 16 | 20 x 20 | 186 | 404 | 190 |
| 17 | 20 x 20 | 186 | 426 | 200 |
| AVG.(SD) | | 197(15) | | |

strength, $\sigma_y$, were both measured on a universal testing machine. Tensile loads were applied to "dog-bone" shaped samples of the glass until the breaking point was reached. These samples, which were 3 cm wide at the ends and necked down to 1.5 cm in the middle, were cut from a glass sheet. No attempt was made to further prepare the edges. The modulus was determined from the stress-strain diagram that was produced for each sample. The modulus is the slope of the elastic portion of the curve. The strain was monitored using a strain gage fixed to the sample and the load applied to the glass was measured and recorded by the machine. The results from the tests were used to calculate an average modulus of 70 GPa ±10 %/°C This is 13% less than the literature reference value of 80 GPa[5].

The ultimate strength of the glass, $\sigma_y$, was calculated as the breakpoint load divided by the cross-sectional area of the sample where the break occurred. Because of the difficulty in cutting them, the dog-bone shaped samples were produced with more edge imperfections than the panes of glass. For this reason, the highest tensile strength of any test, 47 MPa, was taken as the truest measure of the window strength. This is 6% less than the reference value of 50 MPa[5].

Using these properties in the stress equation from above:

$$\sigma_y = E\beta\,(T_c - T_e) \qquad (2)$$

yields $T_c - T_e$ = 70°C. This temperature difference is 13% lower than the 80°C value determined by Keski-Rahkonen and Emmons, and it is 17% greater than the 60°C value calculated by Pagni.

## Discussion

The edge-protected window data indicate several important relationships. Specifically, window breakage was seen to be a function of the temperature difference between the exposed center of the glass and its protected edge. With the exception of Tests 2 and 9, the temperature differentials were concentrated around the table average of 90°C. As for the 132°C difference of Test 2 and the 61°C difference of Test 9, these represent serious deviations. However, they do not indicate that the benchmark value of 90°C for breakage should be moved in any particular direction as they are almost evenly spaced on either side of this average. This trend of the glass breakage occurring when a consistent temperature difference is reached, is exactly what is predicted by Keski-Rahkonen, Emmons, and Pagni[1-3].

More evidence for regarding the temperature difference as the mechanism of glass breakage can be found by considering the lone test in which the window remained intact (Test 11) along with Test 10, which followed immediately after and used the same window pane. The fact that the window broke at a temperature difference of 87°C after remaining intact at a temperature difference of 81°C in a previous test, run under the same conditions, strongly indicates that the particular temperature difference caused the breakage.

However, the experimental average of 90°C is 30% greater than the expected value of 70°C, formulated using the stress equation. The 61°C temperature difference from Test 2, is 13% lower, which is the closest individual value to and the only one below the expected figure. The other nine values are from 14% to 89% greater. In order to consider the stress equation a valid means of predicting the breakpoint temperature difference, these large discrepancies must be explained.

The thermocouples used to measure the heated glass temperatures were embedded between two paper thin, glass reinforced, high temperature polymer laminates. They were then glued to the inside center of the window. The covering was not sufficient to eliminate the radiation heat transfer from the fire. Because of the positioning of the edge thermocouple, radiative heating did not affect these measurements. This means that, since the heated glass temperature is actually smaller than what was measured, the true breakpoint temperature differences are also smaller than the tabulated values. The radiative heating effects were, therefore, one reason for the difference between the experimental values and the theoretical breakpoint temperature difference calculated for this paper.

A similar pattem of the windows cracking as a function of the glass temperature can be detected in the numerical data from the edge-unprotected window tests. Although the times to breakage and the compartment gas temperatures vary with pan fire size, the glass temperatures at crack initiation do not show this pattern. For these experiments, the standard temperature was 197°C with individual values spaced evenly on both sides of this number. This temperature is probably a function of a number of other variables including the window size and the compartment itself, but there does seem to be a direct relationship between the time to crack initiation and the temperature at crack initiation. There is, however, no theoretical or experimental research describing the temperature conditions under which this might take place.

The breakage patterns produced in both the edge-protected and edge-unprotected window tests represent an important qualitative trend in the data. Although there was breakage in all but one of the experiments (Test 11), there were important differences between the breakage patterns for the two types of tests. In the edge-protected tests there were multiple bifurcations with partial window collapse in all ten cases. In contrast, the edge-unprotected windows, while cracking in all six cases, held together and remained firmly in the frame. And, although there were multiple cracks in several of the edge-unprotected tests, these rarely extended more than 7-10 cm beyond their point of initiation.

The ten edge-protected tests show the multiple bifurcations that the Harvard experimental work[4] and Emmons' theoretical work[2] predict. And in each case, the tests confirm Emmons' observation that this situation is most conducive to window collapse. The edge-unprotected results are similar to those from the Harvard work in that there was no window collapse, and the bifurcations that occurred did not multiply. Also, the fact that the edge-unprotected cracks did not, in general, travel extensively throughout the glass can be inferred from the crack growth derivations of Emmons.

## CONCLUSIONS

Ten of the edge-protected tests resulted in breakage at an average temperature difference of 90°C. The consistency of this value supports the theory of the temperature difference as the cause of breakage. The fact that the window pane from the eleventh test did not break until a retest under the same conditions produced a higher temperature difference also strongly supports this theory. Using the material properties specific to the glass tested in these experiments, a theoretical breakpoint temperature difference of 70°C was determined using the stress equation. The experimental average for the breakpoint difference taken from the test data was 90°C. This value is 30% higher than that predicted from the measured material properties of the glass. However, these differences are attributed to radiative heating of the thermocouple on the center of the window. This type of heating causes the measured heated glass temperature (and thus the temperature difference) to be greater than the actual value. In light of these results, the proposed breakage mechanism and the stress equation should be considered valid.

Also in the earlier literature review, the work by Emmons[2] and the Harvard students[4] was discussed. The work dealt with the types of breakage patterns that result from either protecting the edges of the window or exposing them to the fire. The main work on the subject suggested that the edge-protected windows will develop more cracks and that these cracks will be more extensive, with multiple bifurcations and thus, a greater likelihood for window collapse due to cracks joining together. This theory, supported by a previous experimental study, has been confirmed by this study.

The tests were filmed, and all breakage patterns were recorded on tape. The results were very clear. The edge-protected windows collapsed in all 10 cases where there was breakage. There was considerable cracking and numerous bifurcations with the collapses resulting from the cracks joining together. Also, the cracks behaved as theorized in bifurcating at a short distance from the original crack and moving off at sharp angles. On the other hand, in the six edge-exposed tests the largest piece of glass removed from any window was 3 $cm^2$. There were relatively few single bifurcations and no multiple bifurcations. And nearly all of the cracks halted their progress within 7-10 cm of their point of initiation. Based on these results, the theory on the differences between window breakage patterns does agree with the experimental results.

There is broad acceptance of computer modelling as the way of the future in fire engineering. Previously, these models have been very limited in regard to incorporating new vent flows as a result of window breakage. However, based upon the findings here, it is safe to conclude that these new vent flows can be integrated into these models using the 70 °C breakpoint difference value from this work as a benchmark figure. However, if very accuarate results of time to breakage are required, the effect of edge heating, particularly in slowly growing fires, should be included.



## *Acknowledgements*

*This work was supported by the Center for Fire Research of the National Institute of Standards and Technology under Grant No. 60NAWB8D0829.*


## REFERENCES


1. Keski-Rahkonen, Olavi, "Breaking of Window Glass Close to Fire", *Fire and Materials*, **12**, pp. 61-69,1988.
2. Emmons, H.W., "Window Glass Breakage by Fire," Home Fire Project Technical Report No. 77, Harvard University, 1988.
3. Pagni, P.J., "Fire Physics-Promises, Problems, and Problems," *Fire Safety Science-Proceedings of the Second International Symposium*, pp. 49-66, 1988-
4. Barth, P.K. and Sung, H., "Glass Fracture under Intense Heating," Senior course project, Harvard University, 1977.
5. Baumeister, T., Avallone, E.A., and Baumeister, T., III, eds-, *Marks' Standard Handbook for Mechanical Engineers*, 8th ed., McGraw-Hill, New York, NY, 1978.