

## Glass breakage in fires

by Dr. Vytenis Babrauskas, *Fire Science and Technology Inc.*

### Background

The size (more technically, the heat release rate) of fires is limited by the flow of oxygen available to it. In all except very rare circumstances, the flow of oxygen into a room comes largely from open doors and open windows, and to a slight extent from any mechanical ventilation systems and from building leakage. Once a fire gets going, however, windows previously closed may crack and break out. Or...they may not. The results will often be drastically different, depending on whether the windows break or not. Thus, it becomes of significant interest to be able to predict if, and when, glass may break out.

Here, an important distinction needs to be made. When a window pane of ordinary float glass is first heated, it tends to crack when the glass reaches a temperature of about 150 - 200°C. The first crack initiates from one of the edges. At that point, there is a crack running through the pane of glass, but there is no effect on the ventilation available to the fire. For the air flows to be affected, the glass must not only crack, but a large piece or pieces must fall out.

Understanding the conditions under which pieces actually fall out has been of considerable interest to many persons concerned with fire. Since the fire ventilation openings need to be known in order for fire models to be used, glass breakage has been of special interest to fire modelers. This has prompted a number of theoretical and simplified studies and a few empirical ones as well.

It must be realized that there are at least two distinct types of thermal exposure to glass that is involved in fires:

1. A window is inside a room in which a fire is taking place. The window is being subjected to immersion heating from one side. The local gas temperature and the radiating temperature are rather similar. There may be a gradient of temperature and heat flux from the top down to the bottom.
2. A window is exposed to an outside fire, typically a wildland or bush fire. In that case, there may be relatively little difference in exposure between the top and the bottom of the window. The heating is primarily by radiation. Local gas temperatures may be near-ambient, since flames are not directly washing against the window and there is a convective cooling flow along the surface.

### Theoretical and experimental studies of glass cracking in fires

Keski-Rahkonen [1] presented the first extensive theoretical analysis of glass cracking in fires. He identified that temperature differences between the exposed glass surface and the glass shielded by the edge mounting play the dominant role in controlling cracking. His theory predicted that a temperature difference of about 80°C between the heated glass temperature and the edge temperature is needed to initiate cracking. Pagni and Joshi [2] extended these ideas to include more heating physics and an expanded consideration of glass thermal properties. They predicted 58°C as the temperature difference for crack initiation. The difference was largely due to assuming different thermal and mechanical properties for glass. Skelly [3] conducted a series of experiments in an unusual small-scale fire test room. One peculiarity of his tests was that the windows were never exposed to a vertical temperature gradient. He reported some fall-out of glass sections, but did not provide any guidelines or tabulations to assist in determining conditions leading to glass breaking out.

Mowrer [11] presented the latest experimental study on the subject, heating both large-scale and small-scale specimens with a radiant panel to simulate a wildland, external exposure. The maximum heat fluxes,

which went up to  $16 \text{ kW m}^{-2}$ , were sufficient to cause cracking, but not breaking out of window panes. Cracking of single-strength glass was found to occur at 4 to  $5 \text{ kW m}^{-2}$ . Either black or bright insect screens raised by about 21% the heat flux needed to cause cracking. He also found that approximately 33% of the radiation incident on a single-strength pane of glass is transmitted through it. This information can be of use in estimating ignitions inside a building from external radiation.

The National Research Council of Canada (NRCC) has had a program for developing sprinkler protection for glazing. As part of that work, a few non-sprinklered tests have been run where glass 6 mm thick tempered glass was exposed to simulated room fire conditions, but without a sprinkler [9]. While such glass type would only be common in commercial buildings, the results are nonetheless of interest. Tempered glass behaves differently, in that it shatters upon initial cracking, but the initial cracking does not occur until the glass reaches rather high temperatures. An exposed-surface temperature of 290-380°C has been found to be needed, with the unexposed surface temperatures being about 100°C lower. Such glass temperatures are normally not reached until after room flashover has occurred. In a later study [10], NRCC examined glazing using radiant heat exposure. Under such conditions, "plain" glass of unspecified thickness was found to "break" when the exposed side reached 150-175°C, with the unexposed side being at 75-150°C.

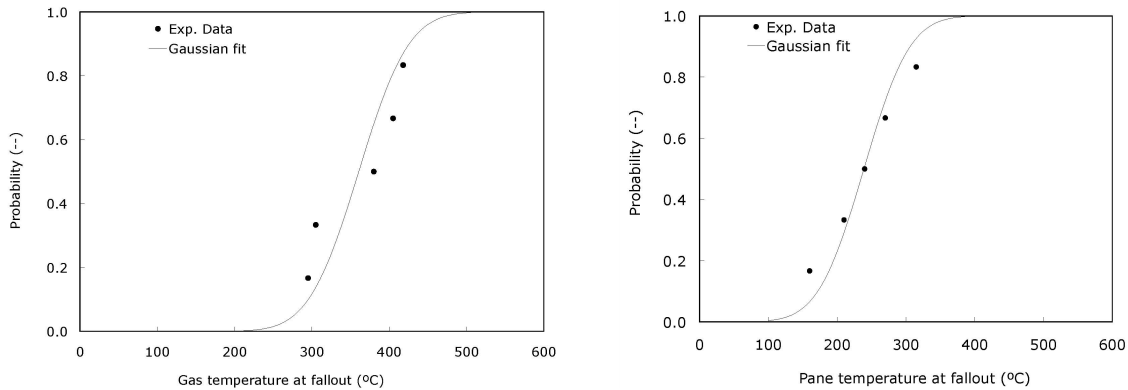
Shields [18] conducted a number of room fire tests using 6 mm thick float glass and showed that first cracking does not occur until the bulk glass temperature reaches around 110°C. This corresponds to a heat flux of around  $3 \text{ kW m}^{-2}$ .

## Experiments and guidance on glass breaking out in fires

The earliest guidance to be found in the literature on the question of when glass breaks out in fires comes from the Russian researcher Roytman [4] who notes that a room **gas** temperature of around 300°C is needed to lead to glass breakage. The research base for this conclusion is unclear, however.

Hassani, Shields, and Silcock [5] conducted a series of experiments in a half-scale fire test room using 0.9 x 1.6 m single-glazed windows where they created a natural top-to-bottom temperature gradient in the room and in the glass. At the time the first crack occurred in 4 or 6 mm thick glass panes, gas temperatures in the upper layer of 323 - 467°C were recorded. By the end of their 20 min tests, gas temperatures were at ca. 500°C. Yet in only 1 of 6 tests was there any fall-out of glass. Temperature differences between the glass exposed surface and the shielded portion ranged between 125°C to 146°C at the time of crack initiation. These temperatures were about twice that predicted from the no-vertical-gradient theories. The authors do not give the exact room fire temperature at which the glass fall-out began in the one test where this occurred, but this had to be higher than 431°C (crack initiation) and lower than ca. 450°C (end of test). One can put these data together, then, to conclude that at a room gas temperature of around 450°C the probability is 1/6 for glass to break out. Shields [18] later conducted further tests using a room with three windows glazed with 6 mm thick panes. Glass fell out when the exposed surface temperature reached 415 - 486°C on the average. But there was quite a lot of variability and individual values ranged from 278 to 615°C at failure. It required a heat flux of around  $35 \text{ kW m}^{-2}$  for fall-out to occur. In a follow-on test series [19] it was noted that the lowest temperature of the glass at fall-out was 447°C.

The only probabilistically-based results concerning glass exposed to a uniform hot temperature come from the Building Research Institute (BRI) of Japan [6]. In that study, researchers used a large-scale high-temperature door-leakage testing apparatus that resembles a large muffle furnace. Only single-glazed, 3 mm thick window glass was studied. For this type of glass, however, enough tests were run so that a probability graph could be plotted. These researchers' results are presented in terms of a probability of glass breaking out, as a function of temperature rise above ambient. The figures below shows the results.



*Japanese results on the breakage of 3-mm single pane glass*

The Gaussian fit that can correlate this data corresponds to a mean gas temperature of 360°C, with a standard deviation of 50°C, and a mean glass pane temperature of 240°C, with a standard deviation of 50°C.

Double-glazed (or triple-glazed) windows can be expected to survive much longer in a fire without breaking out. The spectral radiant absorption characteristics of window glass are such that there is a very high transmission within a certain wavelength region that encompasses the visible and the near infrared parts of the spectrum. Outside of this region, glass is essentially opaque. Thus, in a double-glazed window, the radiation transmitted through the first pane is transmitted only in the spectral regions where the second pane also shows nearly no absorptivity. The consequence is that the second pane is not appreciably heated as the first pane is warming up. This behavior means that the second pane will probably never break out in a fire of short duration, or will break out much later in a long fire. Experimental results confirm this reasoning. Shields, Silcock and Hassani [13] exposed two sizes of double-glazed windows to room fires. The glass thickness was 6 mm. The room fire reached a peak of 750°C and no glazing fell out up to the peak. However, during the decay part of the fire, in one of 3 tests with the larger-size window (0.8 x 1.0 m) fall-out of the inner pane occurred at 21 min, when the temperature had dropped to 500°C. Glass did not ever fall out from the outer pane, nor did any fall-out occur in the smaller (0.8 x 0.5 m) window, nor did any fall-out occur in the other two tests. The same authors later [14] tested a room having a wall with twelve 1.5 x 1.5 m double-glazed windows. The test record is very brief, but it indicated that total failure of the first window occurred when the gas temperature was at 350°C; it is not clear what the temperatures were for the fall-out of the subsequent windows. In another test [21] involving double-glazed windows with 6 mm-thick panes, the authors found that a heat flux of around 70 - 110 kW m<sup>-2</sup> was needed to cause a substantial amount of both panes to fall out and a through-opening to thereby be created in a 0.85 x 1.9 m high window. A smaller, 0.85 x 0.85 m window, however, broke out its second pane a long time after the heat flux peak had been reached and the fire had substantially decayed.

The Loss Prevention Council of the UK [12] studied room fires which were providing fire exposure to a multi-story facade test rig. Double-glazed windows were examined, with each pane being 6 mm thick. Using 3 MW wood crib fires, it was found that temperatures of at least 600°C had to be sustained for 8 - 10 min before glass started falling out sufficiently so that fire venting would occur. When tests were repeated using a fully-furnished office room arrangement, however, glass broke out at 5 min after the start of fire. In that test, the temperature was also about 600°C at the time of failure, but occurred immediately as the temperature was reached. Thus, the findings lead to the conclusion that double-glazed windows using 6 mm thick glass will fail at ca. 600°C and that, if the fuel load is significant, the failure may be expected to occur essentially at the instant that 600°C is first reached.

For radiant exposure, Cohen and Wilson [7] reported on an interesting series of experiments simulating flame exposure from a wildland fire. They examined small (0.61 x 0.61 m) and large (0.91 x 1.5 m) panes, single- and double-glazed. They also repeated the tests with tempered glass and with double-glazed windows. For the small windows, at their lowest heat flux, 9.3 kW m<sup>-2</sup>, all windows cracked, but no glass

fell out. Even at the highest flux of  $17.7 \text{ kW m}^{-2}$  panes did not fall out. For the larger size panes, at fluxes of  $16.2$  to  $50.3 \text{ kW m}^{-2}$ , at least one out of 3 test specimens exhibited fall-out. Tempered glass, by contrast, showed no cracking at tests up to  $29.2 \text{ kW m}^{-2}$  in the larger size. The authors also did tests on double-glazed windows, which showed better performance. In experiments with large-size double-glazed windows (non-tempered), they found that fluxes between  $20$  and  $30 \text{ kW m}^{-2}$  were required to cause fall-out in both panes.

Harada et al. [17] tested 3 mm thick float glass (specimen size: 0.5 by 0.5 m) by subjecting them to various heat fluxes from a test furnace. Below  $8 \text{ kW m}^{-2}$ , no significant fallout occurred, but for a heat flux of  $9 \text{ kW m}^{-2}$ , in some cases 8 - 24% of the specimen area fell out. Edge constraint did not affect the results.

Additional data are available from the NRCC study [10], where heat-strengthened and tempered glass (unspecified thickness) was found not to break at an irradiance of  $43 \text{ kW m}^{-2}$ . The latter heat flux corresponded to  $350^\circ\text{C}$  on the exposed face and  $300^\circ\text{C}$  on the unexposed face. Thus, this appears to extend Cohen's data point of  $29.2 \text{ kW m}^{-2}$  for non-breakage to  $43 \text{ kW m}^{-2}$ , without actually determining the point at which breakage and fall-out do occur.

## Other types of glass

The published studies have dealt primarily with thin panes of annealed or tempered soda glass. Yet, there are many other types of glass to consider. Some very thick plate glass is used in many commercial buildings. Plate glass of 6 mm thickness was found to shatter after a significant time (7 min) of exposure to a radiant heat flux of  $23 \text{ kW m}^{-2}$  [15]; otherwise information is not available on its performance. Toughened (tempered) glass in 6 mm and 10 mm thicknesses was studied by Xie et al. [22]. They did not report fire temperatures nor glass surface temperatures, but only the temperature difference between the exposed and the edge (hidden) portion of the glass. Unlike common float glass, tempered glass falls out upon cracking and does not exhibit a cracked-but-still-in-place condition. The 6 mm glass required around a  $330 - 380^\circ\text{C}$  temperature difference to fail, while for the 10 mm thick glass it was  $470 - 590^\circ\text{C}$ .

There is not much published information about fire-resistive glass. This used to be traditionally wire glass, but nowadays various types of patented fire-resistive glasses also exist which are not wired glass. These are usually multi-layered structures, generally involving some polymeric inner layers. Fire-resistive glasses will normally be accompanied by a laboratory report of the endurance period. Such glasses can be assumed to have no ventilation flow until after their failure time. Manzello et al. [23] tested 6.3 mm thick single-pane tempered glass and 45-minute fire resistance rated glazing which comprised two glass layers with an intervening gel layer. The glass surface temperature at fallout for the single-pane glass was  $400^\circ\text{C}$ , with an incident heat flux of  $50 \text{ kW m}^{-2}$ . The fire-resistive assemblies never failed to the extent of opening up. Klassen et al [24] tested 7 types of specimens which were either thick laminated glass (two glass panes sandwiched with a polyvinyl butyral plastic layer), or triple-glazed panes, or both. None of the specimens were reported as having failed completely, in that a through-hole would be formed.

There does not appear to have been any glass fallout studies for automotive glazing.

Plastic glazing (e.g., polycarbonate) is often used in transportation vehicles and school buildings. A limited study [20] showed that about  $26 \text{ kW m}^{-2}$  was needed for such glazing to fail sufficiently that holes opened up.

## Effect of window frame type

Actual fall-out of glass from windows is also influenced by the window-frame material. Mowrer [11] found that vinyl-frame windows tended to show a failure of the frame (e.g., the whole assembly collapsing) before significant fall-out of glazing. Vinyl frame failures were observed when heat fluxes came up to the

range of 8 to 16 kW m<sup>-2</sup>. By contrast, McArthur [16] found that glass in aluminum-framed windows showed a tendency to survive longer than did glass in conventional wood-frame windows.

## Conclusions

A theory exists for predicting the occurrence of the first crack in glazing, but this is not directly relevant to fire ventilation. The above brief review of the literature shows that it is, in fact, very difficult to predict when glass will actually break enough to fall out in a real fire. The Russian recommendation of 300°C appears to be a reasonable lower bound for the gas temperature required for breakage. The BRI study can be taken to indicate that 3 mm window glass will break at a gas temperature of around 360°C. For thicker, 4-6 mm glass, the mean temperature of breakage would appear to be around 450°C, although the difference between the thinner and the thicker glass results seems rather larger than one would surmise. Double-glazed windows using 6 mm glass can be expected to break out at about 600°C. Tempered-glass is not likely to break out until after room flashover has been reached.

In terms of external fires, at a heat flux of 9 kW m<sup>-2</sup> some experimental results on ordinary glass showed the possibility of fallout, but the probability of fallout does not become high until about 35 kW m<sup>-2</sup> is reached. Double-glazed windows can resist approximately 25 kW m<sup>-2</sup> without fall-out. Tempered glass is able to resist fluxes of 43 kW m<sup>-2</sup>, at least under some conditions.

Factors such as window size, frame type, glass thickness, glass defects, and vertical temperature gradient may all be expected to have an effect on glass fall-out. Over-pressure due to gas explosions is an obvious glass failure mechanism. Yet, normal fires do show pressure variations and these could potentially affect the failure of glass panes. All of these factors deserve some more study to obtain useful, quantitative guidance.

The above review has dealt only with the role of glass breakage in fire ventilation. A number of other aspects of glass breakage are important to fire investigators; these have been well presented by Schudel [8].

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