THE RESPONSE OF GLASS WINDOWS TO EXPLOSION PRESSURES

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Normally, building designs do not specifically incorporate explosion relief, but the failure of glass windows during explosions usually provides some pressure relief. However, window failure normally results in a shower of high-velocity glass fragments which can constitute a serious hazard to personnel. This paper presents data from which the hazard can be assessed and suggests means by which it can be reduced.

INTRODUCTION

The provision of explosion reliefs or bursting discs on certain industrial, fuel-fired plant and on chemical plant processing flammable feedstocks has been accepted, widespread practice for many years. Generally these types of plant can be considered to present little hazard.

Protection for buildings, however, has received little attention although some types of industrial buildings (mainly associated with the food and plastics industries) are constructed so as to minimise structural damage in the event of an internal explosion. Non-industrial buildings are rarely, if ever, so designed, but most explosions in this type of building do not result in their complete destruction. This implies that some degree of fortuitous pressure relief has occurred Usually, this is provided by the failure of glass windows and in the majority of instances, window breakage is the only significant damage caused.

However, although glass windows can provide effective pressure relief, thereby minimising damage to buildings by internal explosions [Cubbage and Marshall (1), Astbury et al (2), Astbury et al (3) and Rasbash (4)], this is not their primary function since they are incorporated into a structure for a totally different reason, i. e. primarily the ingress of light. Hence, although possessing some of the characteristics required of an explosion relief, in acting as such, a glass window can itself produce a hazard; the shower of glass fragments, travelling at high velocities formed upon window failure. The distance of travel of these fragments can be considerable, further than the distance at which significant pressure effects occur. This is reflected in the fact that cuts caused by flying glass constitute one of the commonest injuries arising from an explosion.

Traditionally, Georgian-wired glass is used in situations where safety is a primary consideration. However, its proper application is more in the context of resistance to impact and, possibly, fire rather than to ameliorate the effects of an explosion.

Recently, shatter-resistant film has been promoted as one treatment for glass that will effectively reduce the effects of high-velocity glass fragments subsequent to window breakage by explosion pressures. The data presented in this paper makes possible an assessment of the hazard due to flying glass fragments produced after failure of both plain and Georgian-wired glass windows, both with and without shatter-resistant film applied. Suggestions are made as to how this hazard can be minimised, in particular, without reducing the effectiveness of windows as explosion reliefs.

The (apparently) conflicting requirements of effectiveness as an explosion relief for internal explosions and resistance to external blast wave pressures are also discussed. This latter property has received particular attention of late, not only in relation to commercial buildings but also to laboratories, office blocks and control rooms on or near large chemical process plants.

EXPERIMENTAL WORK

As part of a wider programme of research on the pressures generated in fuel-air explosions and the effect of explosions on structures, the failure pressures of various structural elements, including glass windows, have been determined. The data discussed in this paper have been obtained from two distinct series of experiments carried out in the one case in a concrete bunker and, in the other, in a full scale test building (1), (2) and (3) designed to simulate the top three storeys of a multi-storey block of flats. In the bunker experiments, the open end of the bunker was closed by steel cladding into which single window frames of different dimensions could be incorporated. Explosion pressures were generated by igniting stoichiometric air-gas mixtures contained in meteorological balloons which were suspended from a framework located within within the bunker. This technique has been described previously [Cubbage and Marshall (5)]. The pressures generated were measured by piezo-electric transducers located at various positions inside the bunker. From these experiments, the breaking pressures of a wide variety of glasses (plain, patterned, Georgian-wired) as a function of glass area and thickness have been obtained. The effect on the breaking pressure of treating a window with shatter-resistant film has also been determined. Additonal data (but limited in terms of the variation in the thickness and area of the glass pane) have come from the experiments conducted in the building, in which the windows constituted the main reliefs for any internal explosion that was engineered.

In both series of experiments, the glass panes were mounted in wooden frames, the glass being held in place by 12 mm x 18 mm beading, nailed into position. All the experiments were recorded on cine film, the film speed being adjusted between 32 and 1500 frames/s depending on the circumstances.

RESULTS

The experimental data obtained on breaking pressures, velocities of fragments and the maximum distance of travel of glass fragments are presented in Tables 1 to 3 and Figures 2 to 9.

Breaking Pressure and Mode of Failure

Data on breaking pressures for a variety of different glass types are presented in Table 3 and Figures 2 to 6; in general, they agree with previously published information [(2), Mainstone (6) and Institute TNO (7)]

Depending on the rate of rise of pressure and the magnitude of the pressure generated, glass panes can fail by either radial or circumferential fracture (Figure 1). At low rates of pressure rise, radial fracture is the normal failure mode, whereas glass panes subjected to high rates of rise of pressure (as typified by high magnitude blast waves) usually fail by circumferential fracture. This type of failure, occuring during the initial rapid rise in pressure, suggests that the inertia of a glass pane is sufficient to prevent the development of the normal system of stresses in the glass which would usually result in a radial fracture, i. e. when the rate of pressure rise is low [3M (UK) Ltd.(8), Reuter (9)].

Analysis of the cine film records indicated that, in general, failure of the glass panes resulted from radial fracture. Following removal of a pane from the frame, the untreated glass panes then broke up, either into several fairly large pieces as was observed with the Georgian-wired glass, or into a shower of small, high-velocity fragments in the case of plain glass panes. With panes treated with shatter-resistant film, however, the glass— although shattered— remained attached to the film and the window was projected outwards as a whole.

However, it was noticable that in a significant proportion of the experiments (particularly those at the higher pressures) the fracture pattern, although it could be classified as a radial fracture, was most complex and exhibited some features typical of circumferential fractures. This could be seen most easily on failure of the treated windows, of course, since the shattered glass remained attached to the film, but there is no reason to suppose that this complex fracture pattern did not occur with the untreated glass panes.

The appearance of this 'hybrid' fracture pattern suggests that, at the higher rates of rise of pressure, the behaviour of the glass panes under the transverse loadings produced by the air-gas explosions is similar to that of panes subjected to high intensity blast wave pressures deriving from the detonation of explosive charges (8) and(9).

Table 1: Summary of experimental data on plain glasses

Type	Size m x m	Measured pressure kN/m^2	Velocity of glass after removal, m/s	Impulse acted on glass to failure, kN. s/m^2
5 mm (40 oz) glass				
Treated	1.0 x 1.0	6.9-9.0	14.0-16.2	0.41-0.69
Treated	1.0 x 0.5	12.4-13.8	21.7-24.4	0.93
Treated	0.48 x 0.48	14.5-17.2	30.2-32.7 27.8-32.4	1.1-1.24
Treated (film on outside)	0.48 x 0.48	17.9-18.6	29.9-32.4	1.1-1.17
Treated	0.48 x 0.48	20.0-23.5	32.4, 34.2-36.6	1.65-1.86
Untreated	1.0 x 1.0	6.2-7.6	—	0.35-0.41
Untreated	1.0 x 0.5	8.3-11.7	32.4-39.0 39.0-48.8	0.55-0.69
Untreated	0.48 x 0.48	15.2-18.6	27.8, 32.4-39.0 39.0-43.3	1.1-1.24
Untreated	0.48 x 0.48	20.0-23.5	32.4-36.9, 35.4-39.0	2.34
32oz (4 mm) glass				
Treated	1.0 x 1.0	4.75	13.1-14.6	0.28
Untreated	1.0 x 1.0	4.85	36.6-43.3	0.42
3 mm (24oz) glass				
Treated	1.0 x 1.0	3.8-5.0	11.0-12.2	0.21-0.28
Treated	1.0 x 0.5	7.6-8.6	19.5-22.5	0.48-0.55
Treated	0.48 x 0.48	12.4-15.2	27.8-32.4	0.69-1.03
Untreated	1.0 x 1.0	3.45-5.25	—	0.21-0.28
Untreated	1.0 x 0.5	6.9-8.3	32.4-43.3	0.35-0.55
Untreated	0.48 x 0.48	12.4-15.2	30.5-48.8	0.69-1.1

Type	Size, m x m	Measured pressure, kN/m^2	Velocity of glass after removal, m/s	Impulse acted on glass to failure, $kN. s/m^2$	No. of large fragments produced
Roughcast					
Untreated	1.0 x 1.0	8.5-9.3	16.1-19.5	0.69-0.76	8
Untreated	1.0 x 1.0	12.0	22.2-24.4	0.62	5-7
Untreated	1.0 x 0.5	12.9-15.2	27.8-32.4, 26.8	0.9-1.04	9-11
Untreated	1.0 x 0.5	16.6	26.5-28.4	1.1	10
Untreated	0.48 x 0.48	18.6-21.4	-	0.96-1.03	8-10
Untreated	0.48 x 0.48	19.3-20.7	-	1.1	4-7
Untreated	0.48 x 0.48	28.3	-	1.59	shattered
Polished					
Untreated	1.0 x 1.0	5.5-6.9	10.7-12.2	0.17-0.26	5
Untreated	1.0 x 1.0	5.3-5.5	10.7-11.6	0.17-0.29	2, 2-3
Untreated	1.0 x 1.0	9.85-10.0	16.1-19.8	0.41	9-12
Untreated	1.0 x 1.0	12.7	22.2-26.5	0.83	1
Untreated	1.0 x 0.5	7.0	15.8-20	0.46	2
Untreated	1.0 x 0.5	5.5	-	0.44	2
Untreated	1.0 x 0.5	11.7	-	0.47	-
Untreated	1.0 x 0.5	9.5-10.6	17.0-22.6	0.30	4-5
Untreated	1.0 x 0.5	16.4	29.4	0.21	10
Untreated	1.0 x 0.5	13.8-15.9	-	0.97-1.1	5-8
Untreated	1.0 x 0.5	18.6-22.1	32.6-36.6	1.31-1.52	9-11
Untreated	0.48 x 0.48	13.4	35.0-38.4	0.77	4-6
Untreated	0.48 x 0.48	13.8	27.4-30.5	0.85	6-8
Untreated	0.48 x 0.48	17.1-19.6	32.0-38.4	0.70	6-8
Untreated	0.48 x 0.48	11.5-12.7	25.6	0.60	3
Untreated	0.48 x 0.48	14.4-14.9	32.4	0.73	5-6
Untreated	0.48 x 0.48	17.2-23.7	32.6-48.8	0.41-1.72	5-7, 8-10
Untreated	0.48 x 0.48	22.1-24.9	-	1.45-1.59	4-6
Treated	1.0 x 1.0	4.4-5.2	9.1-10.7	0.15	1
Treated	1.0 x 0.5	11.3-13.1	14.9-19.8	0.37-0.76	1
Treated	0.48 x 0.48	12.6-14.1	16.1-21.4	0.76-1.72	1
Treated	0.48 x 0.48	17.2-22.1	21.4-30.5	0.7-1.71	2

Table 2 : Summary of experimental data on Georgian-wired glasses

Type	Size, m x m	Breaking pressure, kN/m^2	
		Untreated	Treated
5 mm plain	1.0 x 1.0	6.2-7.6	6.9-9.0
	1.0 x 0.5	8.3-11.7	12.4-13.8
	0.48 x 0.48	15.2-20.7	15.2-20.0
3 mm plain	1.0 x 1.0	3.5-5.2	3.8-5.0
	1.0 x 0.5	6.9-8.3	7.6-8.6
	0.48 x 0.48	10.3-12.4	10.3-12.4
32oz (4 mm) plain	1.0 x 1.0	4.8	4.8
Georgian-wired (Roughcast)	1.0 x 1.0	9.0	-
	1.0 x 0.5	12.4-13.8	-
	0.48 x 0.48	19.3-26.2	-
Georgian-wired (Polished)	1.0 x 1.0	5.5-9.0	4.7-5.2
	1.0 x 0.5	11.7-13.8	10.4-11.7
	0.48 x 0.48	17.2-26.2	17.2-22.1

Table 3: Summary of breaking pressures of glass panes

The effect of the dimensions of rigid panels such as glass panes and brick walls on their failure pressures are described by scaling laws. As generally applied to panels which fail in flexural tension rather than by peripheral shear, the scaling laws show that the breaking pressure of a panel is a function of the square of its dimensions. The data presented in Figures 2 to 5 indicate that, in conformity with this, the breaking pressure of a glass pane of a given thickness is inversely proportional to its area.

However, figure 6 demonstrates that, for a glass pane of given area, the breaking pressure is proportional to its thickness, and not the square of this dimension, as would be appropriate if the scaling law is applied. A possible explanation may be the appearance of the 'hybrid' fracture mode of failure in a significant proportion of the experiments. Similar tests on brick panels (which failed in flexural tension) indicated that in this instance the scaling laws did apply (2), i.e. the breaking pressure of a panel was found to be inversely proportional to its area and directly proportional to the square of its thickness.

A further indication that most of the data obtained can be correlated on the basis of the linear, not square, dimension of thickness is afforded by Figures 2 to 4, which refer to experiments conducted in the bunker on single pane windows. The line through the experimental data for 5 mm glass presented in Figure 3 is a 'best fit'; the lines in Figures 2 and 4 were obtained from the data in Figure 3 on the basis that the breaking pressure is proportional to the thickness of the glass and not according to the scaling law. The good agreement is obvious. The poor correlation for 4 mm (32oz) glass panes, (Figure 5) calls for explanation. Under identical conditions, there is reasonable agreement, as demonstrated in Figure 6, which refers to data obtained from bunker experiments. However, nearly all the data presented in Figure 5 were obtained from experiments in the test building in which the glass panes formed part of larger windows which constituted the explosion vents for the different rooms. Furthermore, in these experiments, the air-gas mixture ignited was not usually confined as a stoichiometric mixture in a meteorological balloon, as in the bunker experiments, but was present in the form of a high level layer of varying concentration in one or more of the rooms. These differences in experimental conditions resulted in greater flexing prior to failure of individual glass panes in the building experiments than those conducted in the bunker, as a consequence of the lower rigidity of the multi-pane window frames in the building. In addition, because of the differences in confinement and composition of the air-gas mixtures in the two series of experiments, rates of pressure rise in the building experiments were lower. In these circumstances, it is to be expected that the individual glass panes would have slightly different (and almost certainly lower) measured breaking pressures to those obtained from the bunker experiments.

It is apparent from Table 3 that the application of shatter-resistant film has no significant effect on the breaking pressures of a glass pane, indicating that the effectiveness of a window as an explosion relief will not be reduced by the application of shatter-resistant film. The data also suggest that there are no significant differences in the breaking pressures of the two types of Georgian-wired glass over the range of window areas investigated.

Fragment Velocity and Distance of Travel of Fragments

From the cine film records of the experiments, it was possible to determine the average velocity after failure of glass panes treated with shatter-resistant film over the first 6 m of travel. For the 6.5 mm Georgian-wired glass panes the number of large fragments produced on failure could also be ascertained. Although it proved difficult to follow the trajectories of the smaller fragments produced on failure of untreated, plain glass windows, measurements indicated that the initial velocities of plain glass fragments were higher than for both treated and 6.5 mm Georgian-wired glass fragments. These findings are in accordance with the previously published data (9).

Figures 7 and 8 show, respectively, the average velocities after failure of glass fragments as a function of the measured explosion pressure and the window area. The distance of travel of glass fragments as a function of the pressure to which a window pane is subjected is illustrated in Figure 9. It is apparent from Figures 7 and 8 that the velocity of a glass fragment depends on a number of factors such as its area, its weight and the breaking pressure of the window. However, these factors are not totally independent. From Figure 7, it can be seen that for each of the glass types investigated, the velocities of fragments from the untreated panes are significantly greater than those from the panes treated with shatter-resistant film. This must be due to the difference in the areas of the fragments since, for any one glass type, the weight/unit area and the breaking pressure of a window are essentially the same with or without shatter-resistant film. Thus, after failure, a treated glass pane — which tends to be removed as a single 'fragment' — has a significantly lower velocity than that of the many smaller fragments produced upon failure of an untreated pane.

The influence of breaking pressure and weight/unit area appear to produce opposite effects on the fragment velocity. Thus, from Figure 7a it can be seen that, for a given window area, the velocities after failure of 3 and 5 mm thick glass panes treated with shatter-resistant film are essentially the same, even though the breaking pressures of the two types of glass pane differ considerably.

These data suggest that, for a given size of window, the velocities of the fragments produced upon failure will depend more on the sizes of the pieces than on the type of glass used. This is demonstrated in Figure 8, which indicates that, for a given window area, the velocity after failure of a treated glass pane is virtually indepedent of the weight/unit area (or thickness) of the glass, i.e. it does not depend on glass type. Further, this velocity is significantly smaller than that of untreated 6.5 mm Georgian-wired glass fragments which, although sizeable, are usually only 5 to 20% of the area of the corresponding 'fragment'produced on failure of a treated glass pane. In turn, the velocities of the much smaller fragments produced on failure of plain glass windows are considerably in excess of those observed with untreated Georgian-wired glass.

These findings are in keeping with the fact that air resistance is a major factor in determining the velocities (and distance of travel) of fragments after window failure. The air resistance experienced by an object depends not only on its area but also on its shape, and it is the area normal to the direction of travel, rather than the geometric area, that ultimately determines the magnitude of the air resistance experienced. This would explain the wider spread in fragment velocities obtained for untreated glass panes (which produced fragments having random orientations and sizes) as compared with those for panes treated with shatter resistant-film, the failures of which led to very similar sizes and orientations of 'fragments' for each size of pane investigated.

The reduction in the distance of travel of fragments, as a consequence of the application of shatter-resistant film, is demonstrated in Figure 9, which includes data on plain glass, 6. 5 mm Georgian-wired glass and various types of patterned glasses. The data refer to window areas ranging from 0. 2 to 1. 6 m^2 and thicknesses from 3 to 6. 5 mm. Some of this data have been published previously (1).

Figure 9 indicates that for glass panes of the same area the application of shatter-resistant film will reduce the distance of travel of failed panes to approximately 60% of the distance traversed by fragments produced upon failure of untreated plain glass windows.

A somewhat different result is obtained from a comparison of untreated 6. 5 mm Georgian-wired glass and plain glass windows. Comparing glass panes of the same area (but not necessarily the same breaking pressure) the maximum distance of travel of Georgian-wired fragments is about 90% of that of fragments produced by failure of 5 mm thick plain glass windows. However, it can be as much as 50% greater than the distance traversed by fragments from 3 mm thick glass panes. This is a consequence of the significant differences in the breaking pressures of 3 mm glass panes and Georgian-wired panes of the same initial areas (see Table 3 and Figures 2 and 5).

DISCUSSION

It is apparent from the data presented that the failure of a glass window can present a serious hazard, not only in terms of the number and velocities of glass fragments produced but also with regard to the distances travelled. Although the hazard is similar for window failure due to internal and external explosion pressures, it is convenient to discuss these two situations separately.

Internal Explosions

It has been demonstrated that, in the event of internal explosions, windows can act as effective explosion reliefs, thereby minimising damage to the main load-bearing structure of a building [(1), (2) and (4)]. Therefore, any method employed to lessen the hazard due to glass fragments consequent to window failure should not, preferably, reduce this effectiveness. In particular, the breaking pressure and weight per unit area of the glass should not be increased significantly, nor the glass area decreased, otherwise the effectiveness of a window as an explosion relief may be reduced to such an extent that the explosion pressure developed may cause more than just window damage to the building concerned.

On this basis, the data presented do not support replacement of plain glass windows by Georgian-wired panes as a means of reducing the hazard of flying glass. Furthermore, although the number of fragments produced on window failure will be reduced by replacement with Georgian-wired glass, the distance of travel of these fragments can be substantially greater than before replacement, depending on the thickness of the glass originally used.

In contrast, the present data indicate that the application of a suitable shatter-resistant film to existing plain glass windows will, effectively, prevent the formation of a shower of glass fragments on window failure. Moreover, the distance of travel of a (failed) treated window will be significantly less than that of the fragments produced on failure of an untreated window. Thus, both the hazard and the 'hazard area' will be reduced. In addition, application of the shatter-resistant film was found to have no significant effect on the breaking pressure of a glass pane and hence does not reduce the effectiveness of a window as an explosion relief for internal explosions.

Similar results were obtained for Georgian-wired glass panes treated with shatter-resistant film, namely the application of the film reduced significantly the numbers, velocities and distance of travel of the fragments produced on window failure but did not alter the breaking pressure. Since, after failure, both the velocity and distance of travel of a treated glass pane of a given area are virtually indepedent of the type of glass (Figures 8 and 9), superficially, there would seem to be little to choose technically between the application of shatter-resistant film to existing glazing and replacement of the glazing by treated Georgian-wired glass. The significant difference, of course, is that application of a shatter-resistant film to existing glazing does not alter the effectiveness of a window as an explosion relief, whereas replacement with treated Georgian-wired glass could markedly reduce this effectiveness.

External Explosions

Resistance to blast wave pressures typical of those produced by the detonation of an explosive device requires different characteristics from those necessary for effectiveness as an explosion relief. In particular, as high a breaking pressure as is compatible with the rest of the structure is required in order to provide the maximum protection to personnel and plant inside a building. Thus, it would appear that there are conflicting requirements for windows, depending upon whether they are subjected to blast waves or the pressure effects resulting from an internal explosion.

This is not necessarily the case, however. Comparison of the data on the breaking pressure of glass panes subjected to internal air-gas explosions (Table 1) with the limited data on the failure pressures of windows subjected to blast pressures resulting from the detonation of explosives (7) suggests that it is the impulse acting on a window pane, rather than just the magnitude of the peak pressure experienced, that ultimately determines whether or not failure occurs. There are distinct differences in the pressure-time profiles typical of the two situations – relatively low magnitude, long duration overpressures generated in internal explosions and comparatively high magnitude, very short duration pressure pulses produced by the detonation of explosives. It is conceivable, therefore, that a glass pane which failed due to a pressure rise typical of those generated in internal air-gas explosions would, when subjected to the pressure loading generated by the detonation of an explosive charge, remain intact up to significantly higher peak blast wave pressures since the duration of the overpressure would be much shorter. Hence, a given window could be both effective as an explosion relief and resistant to blast wave pressures of moderate intensity.

However, at higher incident blast wave pressures, glass panes will fail and the same hazard as results from failure due to internal explosions -- the shower of glass fragments travelling at high velocities -- will ensue. The only difference between these situations is that window failure resulting from an internal explosion usually produces a shower of fragments outside the building in which the explosion occurs, whereas window failure consequent to the incidence of a blast wave can produce a shower of high velocity fragments either inside the building concerned or external to it, depending on whether window failure occurs during the positive pressure phase or the negative pressure ('suction') phase of the incident blast wave.

Whilst considerable effort has been directed towards protection of the general public from the consequences of terrorist bombings – a major hazard of which is injury from high-velocity glass fragments – recent incidents such have occured at Pernis, Flixborough, etc. have shown that similar effects can be produced by so called unconfined vapour cloud explosions, even though the maximum overpressure generated in such an explosion may be relatively small in comparison to that produced by the detonation of an explosive device.

At large distances from the point of origin of an unconfined vapour cloud explosion, the shape and magnitude of the pressure-time profile will be similar to that produced by the detonation of an explosive charge, and pressure effects will, therefore, be similar. In the near field, however, the profile shape is likely to be closer to that typical of internal air-gas explosions, i. e. of relatively low magnitude and long duration compared to the pressure-time profile characteristic of the ideal blast wave produced by detonation of an explosive charge. Hence, it is to be expected that close to the origin of a vapour cloud explosion, windows will fail at significantly lower pressures than those necessary to cause failure close to the site of detonation of an explosive charge. Furthermore, the different pressure-time profiles may not produce the same loadings on other structural components such as walls. This could affect any proposals for the redesign of control rooms, administration blocks, etc. on chemical plants suggested as a means of providing increased protection to personnel working in such buildings [Kletz (10)].

Regardless of how the overpressure is developed – by an internal air-gas explosion, bomb incident or an unconfined vapour cloud explosion – its effect on windows will be the same, i. e. to produce showers of high-velocity glass fragments. Logically, therefore, the method employed to reduce this hazard should also be the same in each situation.

Thus, although replacement of 3 mm and 5 mm plain glass window panes by Georgian-wired glass will provide an increased protection against external overpressures, because of the increased breaking pressure of Georgian-wired glass, this will still fail at relatively high incident blast wave pressures thereby producing high-velocity fragments capable of causing severe injuries to personnel (e. g. Flixborough).

It is suggested, therefore, that application of a shatter-resistant film to existing glazing would provide better protection against external overpressures since this would effectively prevent the formation of a shower of high-velocity fragments in the event of window failure. Others have arrived at a similar conclusion (10).

An unexpected benefit of the application of shatter-resistant film to glazing appears to be an additional resistance to blast wave pressures with the result that, in some cases a glass-pane — although shattered — will remain in the window frame whereas previously it would have been completely removed (7). This is in contrast to the observed behaviour under internal explosion conditions when no increase in breaking pressure of a pane of glass consequent to the application of shatter-resistant film was noticed (Table 1). The difference in behaviour may be due to the way in which the glass panes were secured in the window frame (e. g. different depths of rebate) although usually this is not considered to be a significant factor for plain glass windows (5). Equally, this difference in behaviour could be due to the dynamic response of a glass pane to the different pressure-time profiles typical of the two situations.

Use of a shatter-resistant film will not, of course, always prevent window failure, and under high incident blast pressures treated glass panes will occasionally be removed from their frames. In this event the glass, although shattered, would remain attached to the film and the pane would fail as a whole, leaving the frame at a relatively high velocity and travelling some distance before coming to rest. This in itself could constitute a hazard to personnel, who, although not liable to cuts from such a missile, could suffer other types of injury on being hit by the pane.

In addition, it has been observed that impact of a failed, treated window against a rigid object (such as a pillar or a desk) can lead to removal of glass from the shatter-resistant film with, consequently, the creation of a secondary shower of glass fragments and, although the velocities of these fragments can be relatively low, they still constitute a hazard, particularly in the case of Georgian-wired glass.

Hence, it is advisable to provide a back up barrier, the function of which is to catch a failed (treated) window and prevent its projection across a room, thus eliminating possible injury to personnel as a result of impact or the creation of glass fragments. The proportions and the material of the barrier are important for its proper function. Terylene net curtain (90 to 100 denier) has been found to be a suitable material for this duty [Private communication].

In general, the width of the curtain should not be less than twice that of the window aperture. The curtain should be fitted as close to the window as possible and the full width contained within the window aperture. For normal sill height windows, the length of the curtain should extend to floor level. In order to comply with this requirement, where obstructions beneath a window inhibit the free vertical hanging of curtains, the excess length may be housed at sill level in a trough. In the case of floor to ceiling windows, the length of the curtain should not be less than $1\frac{1}{2}$ times the height of the glazing. To be effective, the bottom of the curtain should be threaded with a continuous weight. Plastic venetian blinds, when lowered, will also act as a back up barrier but have not been found to be as effective as properly installed curtaining.

Neither venetian blinds nor curtaining will effectively contain the high-velocity fragments deriving from the failure of windows not treated with a shatter-resistant film.

Although terylene curtains (and, to a lesser extent Venetian blinds) will provide an effective back-up barrier to contain failed, treated windows, their use is restricted essentially to commercial premises (e. g. office blocks) and some other system is required for industrial locations such as workshops, control rooms etc. In these situations, catch wires appear to provide a simple, but effective method of restraint. However, even though a failed window can be prevented from travelling a considerable distance by means of catch wires, a significant proportion of the glass can be removed from the film as the travel of the pane is arrested.

The number of fragments produced depends on the velocity of the pane (and hence the magnitude of the incident blast pressure) and the type of shatter-resistant film used. As the thickness of the film (and strength of adhesion between glass and film) is increased, the percentage of glass removed decreases. Some glass will, however, always be removed – particularly at the corners of the pane – although in the limit the total area of glass removed could be only a few percent of the pane area.

CONCLUSIONS

The hazard due to the shower of high-velocity glass fragments produced on window failure as a result of explosion pressures or blast wave incidence, can be reduced significantly by replacing existing glazing with glass panes treated with a shatter-resistant film (or by applying such a film to exisitng glazing). Replacing existing glazing by untreated Georgian-wired glass panes does not significantly reduce the hazard and could, in fact, lead to an increased hazard, depending on the type of the original glass replaced. Application of shatter-resistant film will not reduce the effectiveness of a window as an explosion relief but could result in an increased resistance to blast wave pressures of relatively low amplitude.

REFERENCES

1. Cubbage, P. A., and Marshall, M. R., 1973, Instn Gas Engr Commun. No. 926.
2. Astbury, N. F., et al, 1970, Br. Ceram. Res. Assoc. Special Publication 68.
3. Astbury, N. F., et al, 1972, Br. Ceram. Res. Assoc. Special Publication 74.
4. Rasbash, D. J., 1969, JFRO Fire Research Note No. 759.
5. Cubbage, P. A. and Marshall, M. R., 1972 Instn Chem. Engr Symposium Series No. 33.
6. Mainstone, R. J., 1971, Building Research Establishment Current Paper 26/71.
7. Institute T. N. O., 1972, Report No. B1-72-6 04302520.
8. 3M (UK) Ltd., SJ2510X Shatter-resistant film; Home Office Trials, published by 3M United Kingdom Ltd.
9. Reuter, R., 1975, Chemie-Engr-Tech. Document No. MS 207/75.
10. Kletz, T. A., 1975, A. I. Ch. E. Loss Prevention Vol. 9.

Acknowledgements

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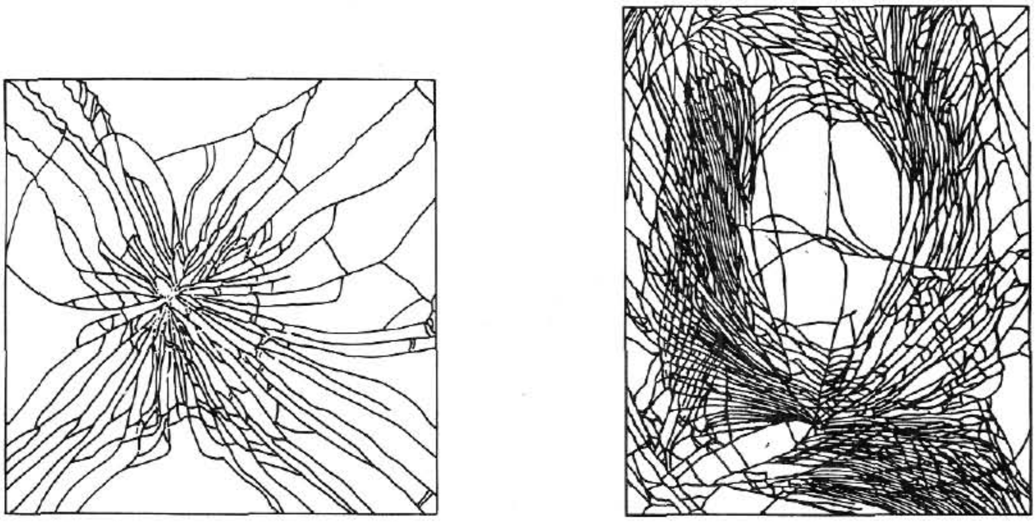


Radial

Circumferential

Fig. 1 Fracture modes of glass panes.

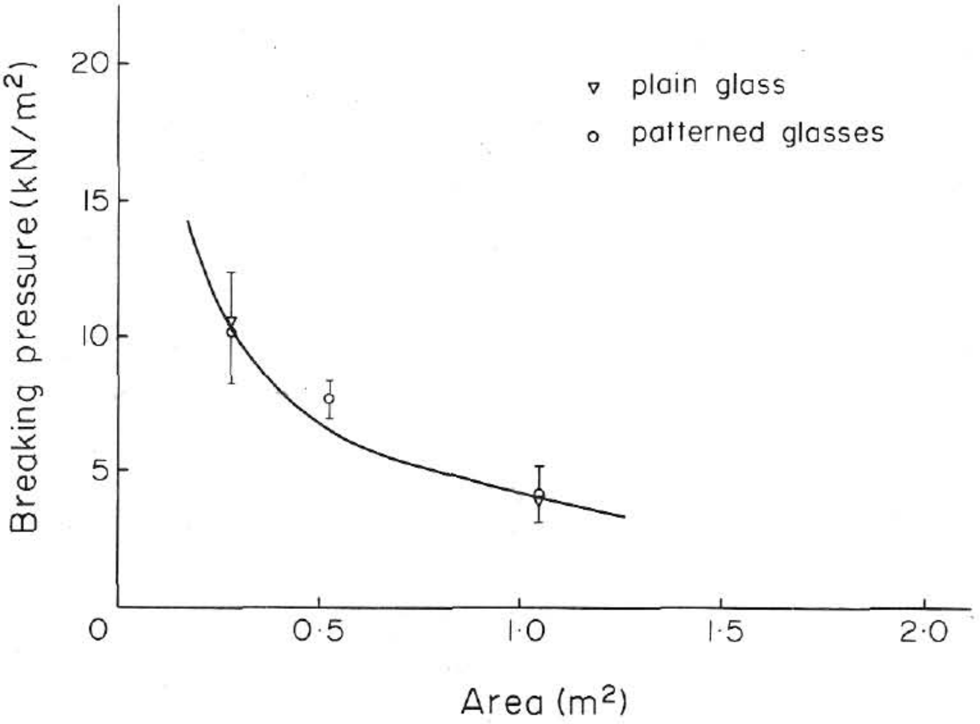


Fig. 2 Breaking pressure as a function of area for 3 mm thick (24 oz) glass panes.

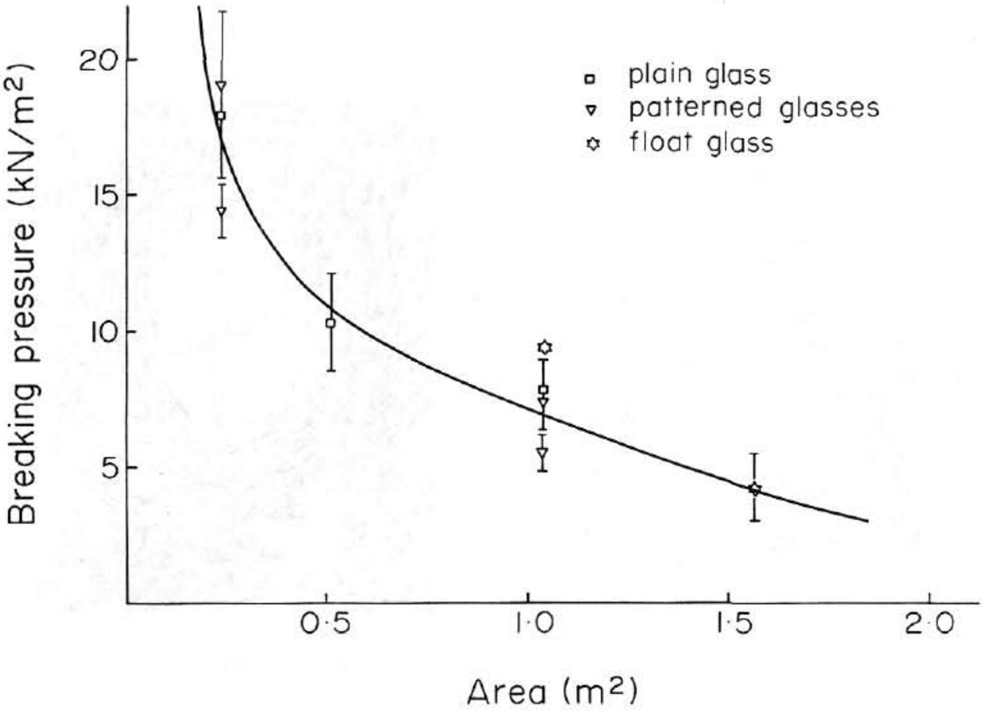


Fig. 3 Breaking pressure as a function of area for 5mm thick (40 oz) glass panes.

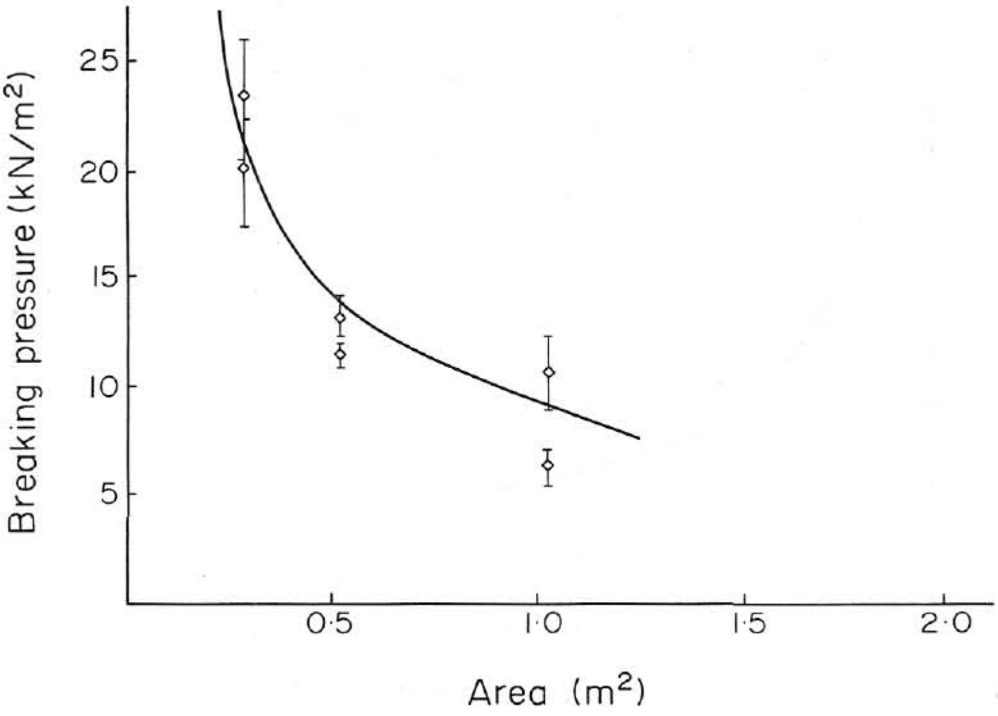


Fig. 4 Breaking pressure as a function of area for 6·5mm thick Georgian - wired glass panes.

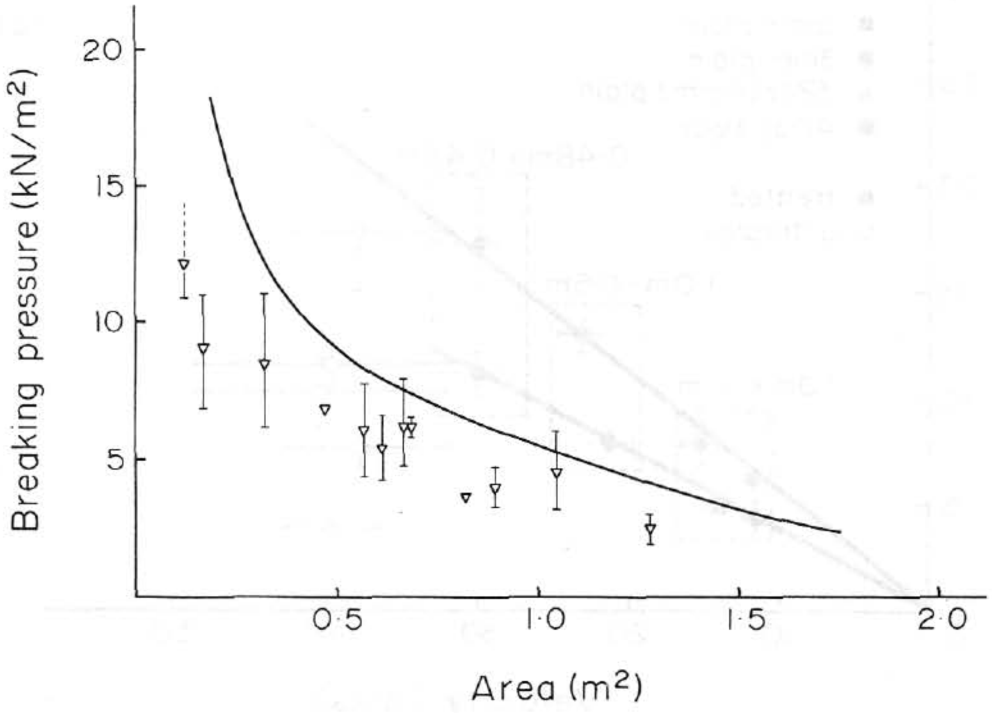


Fig. 5 Breaking pressure as a function of area for 32 oz glass panes.

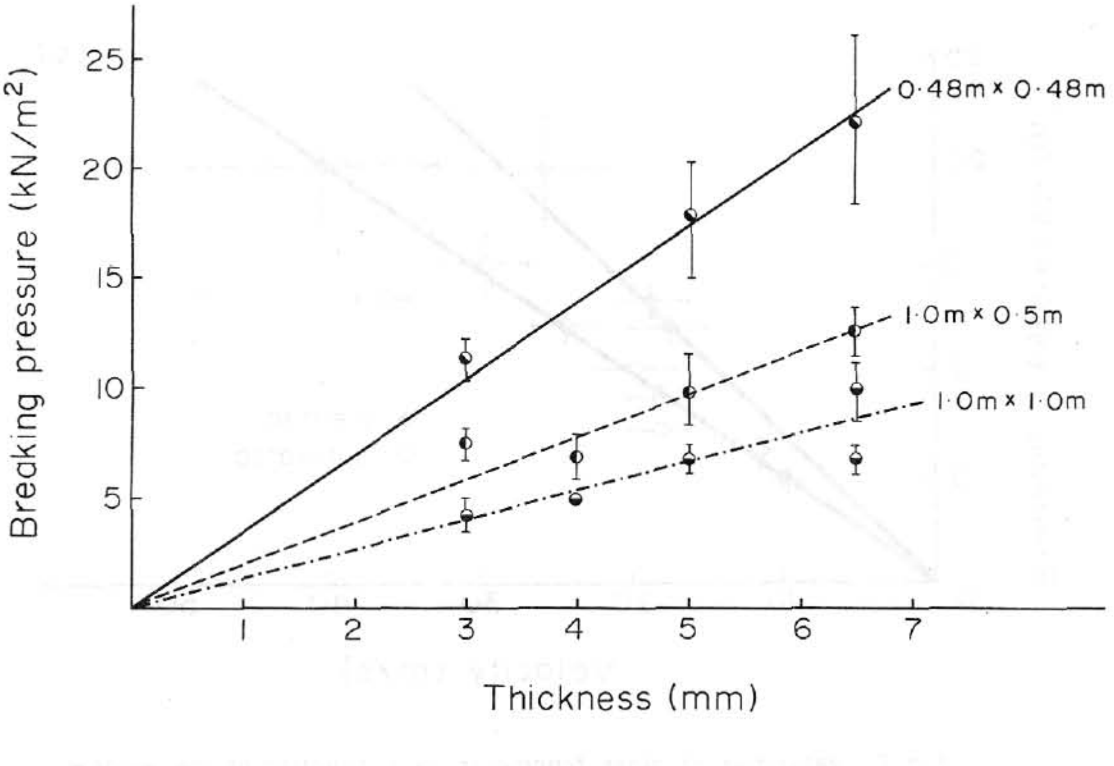
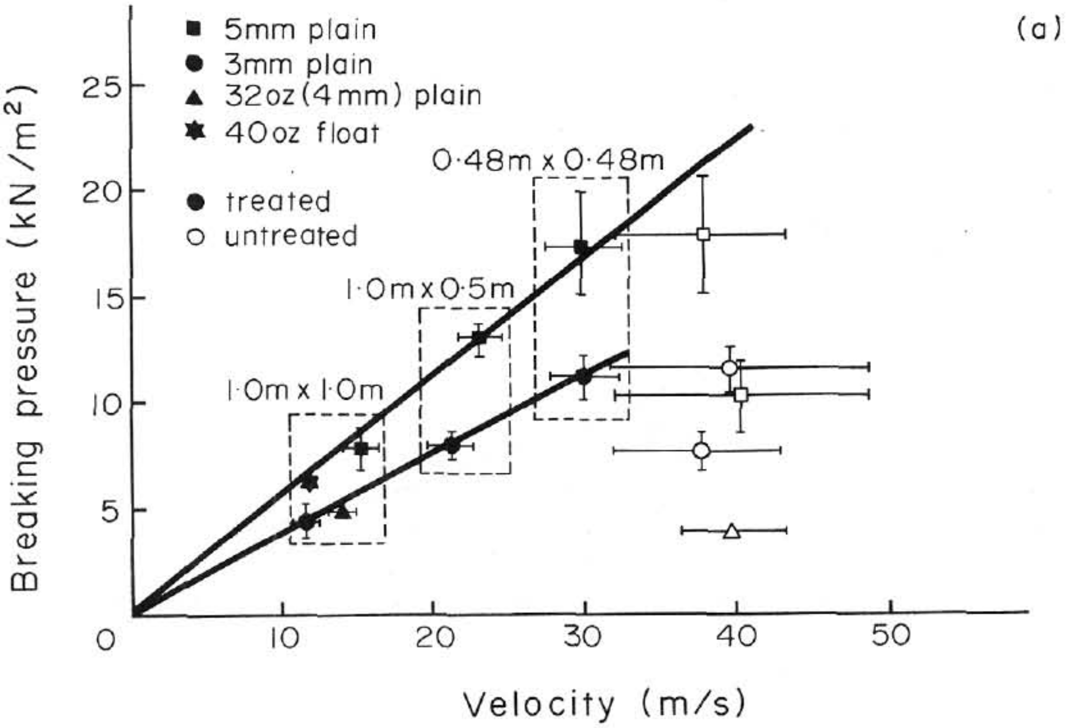


Fig. 6 Breaking pressures of glass panes as a function of glass thickness.



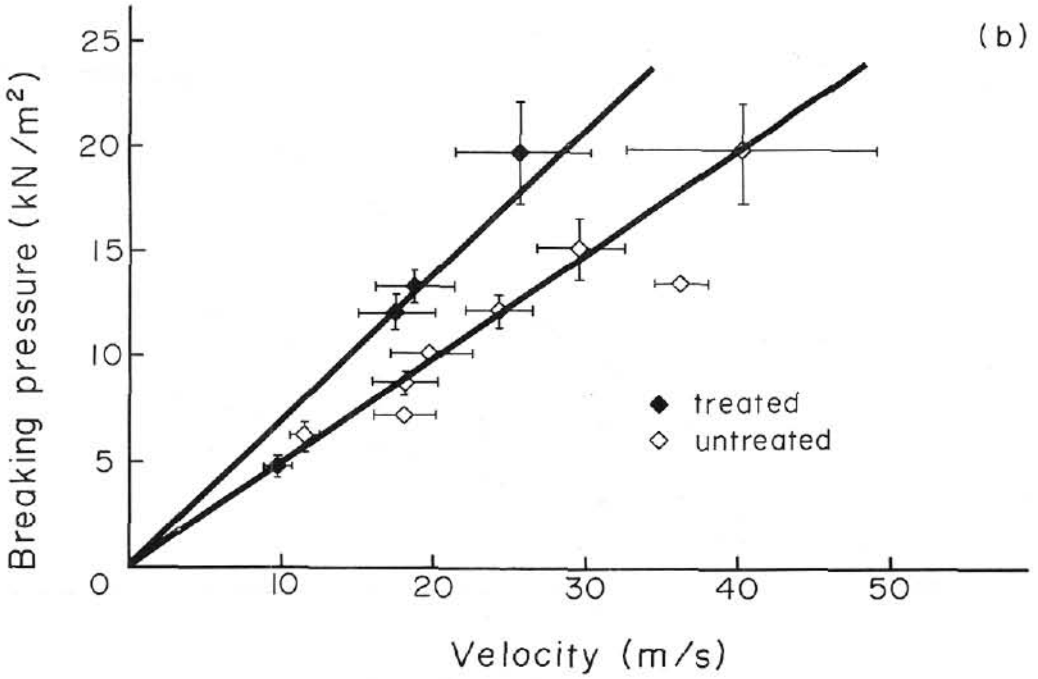


Fig. 7 Velocities of glass fragments as a function of the window *breaking pressure (a) treated and untreated plain glass* (b) treated and untreated Georgian-wired glass

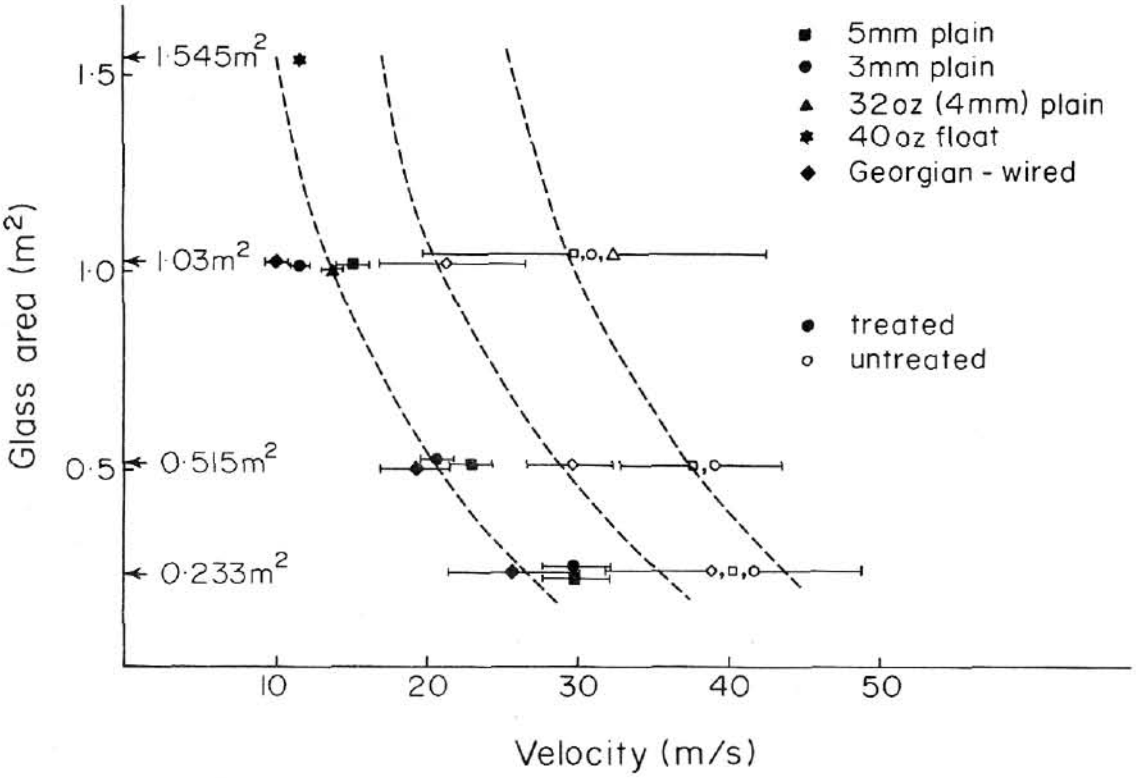


Fig. 8 Velocities of glass fragments as a function of window area

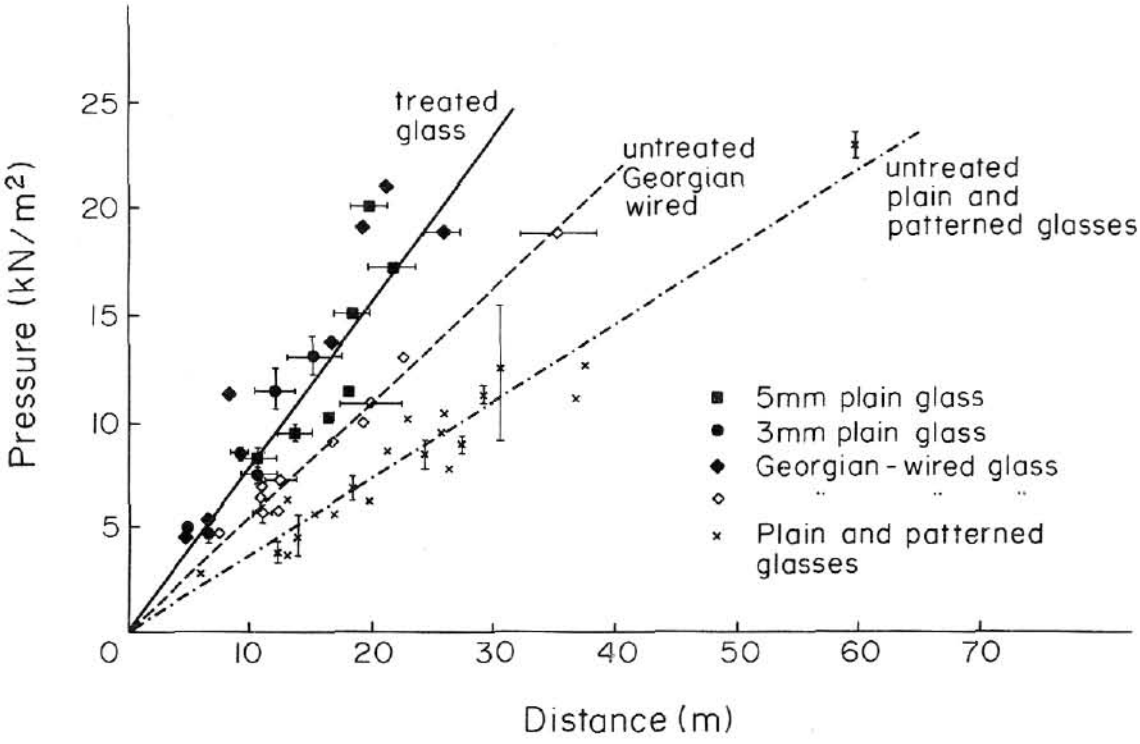


Fig. 9 Distance of travel of glass windows as a function of the explosion pressure generated.