SOME EXPERIMENTS ON THE USE OF LARGE GLASS PANELS

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EMERGENCY PRESSURE RELIEF DIAPHRAGMS

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FOREWORD AND ACKNOWLEDGEMENT

This report is based on an analytical and experimental study of the characteristics of glass pressure relief diaphragms undertaken by Dilworth, Secord, Meagher and Associates Limited with the collaboration of Prof. I.I. Glass of the Institute of Aerophysics. The investigation was conducted on behalf of Canadian General Electric Co. Ltd., Civilian Atomic Power Department in connection with the Nuclear Power Demonstration (NPD-2) Reactor project undertaken jointly by Atomic Energy of Canada Limited and the Canadian General Electric Company Ltd.

Program planning, direction and analytical work were performed by Dilworth, Secord, Meagher and Associates Limited, under the direction of Dr. I.J. Billington with consultation from Dr. I.I. Glass. The impact shattering experiments were conducted in the Institute of Aerophysics laboratories by Mr. L.E. Heuckroth and the explosive shattering tests were conducted in the Canadian Industries Ltd. laboratories by Dr. R.F. Favreau.

The authors are grateful to Canadian General Electric Co. Ltd. and Atomic Energy of Canada Ltd. for their permission to publish this work and to Dr. G.N. Patterson, Director, Institute of Aerophysics, for his interest throughout the course of this research.
SUMMARY

Two series of experiments have been conducted to assess the breaking characteristics of a proposed glass pressure relief diaphragm and the operating characteristics of the associated shattering mechanism for the NPD-2 nuclear reactor boiler room, in the case of a potential heavy-water steam explosion resulting from a coolant line failure.

In one set of tests a Ramset gun was used to shatter small scale glass panels under a small initial pressure loading. The experiments showed that the overall time constant of the firing and the breaking processes was too long to provide adequate pressure relief in the case of a severe emergency in the boiler room. Consequently, a second set of tests was conducted in which larger glass panels were shattered by a net of primacord explosive attached to the face of the panel. The data indicated that for the present panels a very satisfactory breaking performance and negligible resistance to subsequent outflow could be achieved in less than a millisecond. The results may have other useful applications where large pressure relief diaphragms are required.
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## APPENDIX A - Tabulation of Glass Shattering Experiments

## APPENDIX B - Summary of Useful Test Runs

## APPENDIX C - Blast Effects of Explosive Charge
I. INTRODUCTION

An earlier analytical study (Ref. 1) considered the pressure rise in the boiler room of the NPD-2 nuclear reactor power plant following the hypothetical failure of a main heavy-water coolant line. The room in question is connected to the outside atmosphere by a pressure relief duct whose entrance is sealed by a diaphragm designed to contain pressures up to 1.5 psig. In the event of an emergency, very rapid removal of the diaphragm is necessary to keep the building below a limiting pressure dictated by structural considerations.

Based on previous experience at UTIA with bursting diaphragms, glass was selected as the most appropriate relief duct sealing material because of its property of rapid shattering. On the other hand, the specification for containment of 1.5 psig over a large area (108 ft.$^2$) dictated the use of either thick self-supporting panels or thin panels supported by a back-up structure, which would represent some measure of blockage of the relief duct. Practical compromise between these conflicting requirements favoured glass thickness in the range 3/16 to 1-1/4 inches, depending upon the amount of backup structure provided. For glass panels of this thickness it was considered advisable to investigate the shattering and dispersion characteristics experimentally.

The general configuration of the diaphragm and shattering system is illustrated in Fig. 1. A set of pressure switches in the region of potential failure is arranged to close at a room over-pressure of 1.5 psig. When two or more of these switches close simultaneously, a signal is delivered to the shattering system. The original concept provided for the emergency signal to actuate solenoids which pulled the triggers of four Ramset guns located in the pressure relief duct immediately downstream of the glass diaphragm. The guns discharged and on impact the projectile shattered the glass diaphragm located at the relief duct inlet as indicated in Fig. 1. A first series of experiments investigated this impact method of glass shattering. A second experimental series investigated an alternative arrangement in which the actuating signal fired a fast acting detonating cap attached to a grid of explosive fastened directly to the back of the glass diaphragm. This case is also shown in Fig. 1.

The study of Reference 1 concluded that the time constant of the complete shattering phenomenon, from sensing of the emergency pressure in the boiler room to opening of the diaphragm to the point of negligible flow resistance, should be not greater than 20 milliseconds. The basic purpose of the experimental investigation described in the present report was to ascertain this time constant and to select a breaker and diaphragm configuration with satisfactory performance.
II. PRELIMINARY ANALYSIS OF GLASS SHATTERING AND FLOW DEVELOPMENT

Some preliminary consideration was given to the mechanism of the glass shattering problem in order to arrive at a useful model for test purposes.

Since the speed of sound in glass is approximately 20,000 ft/sec and the fracture or crack speed is about 10,000 ft/sec, it was anticipated that the time delay associated with the actual shattering would not be significant. It was not, however, clear how much additional time would be required for the individual glass particles to unlock and disperse to a degree which would permit the establishment of flow in the relief duct.

Some approximate calculations were made to estimate the accelerating forces on the glass particles due to the pressure loading. For these calculations it was assumed that a constant pressure differential of 1.5 psi existed over the entire cross section of a glass fragment. On this basis a particle 1.25 inches in thickness would experience an outward acceleration of approximately 10 "g". Thinner particles would experience greater accelerations because of their smaller mass. Curves showing the motion of fragments of 1/4 and 1/2 inch glass down the channel under this assumed accelerating force are plotted in Fig. 16. It might, therefore, be expected that these particles would travel outward in trajectories whose early portion was almost horizontal.

In practice, however, many deviations would occur from this simplified concept. Tumbling of the particles of glass would change the projected area and the pressure loading. Pressure differentials would be reduced due to airflow around the particles. Viscous forces would replace pressure differentials as the flow developed and mechanical interactions and collisions between glass fragments would have significant effects on the individual trajectories. All these factors considered, it was felt that the simplified calculation mentioned above should give a somewhat optimistic estimate of the speed at which the particles would move from the original plane of the diaphragm and that the true time dispersal relationship could only be determined experimentally.

III. IMPACT SHATTERING EXPERIMENTS

3.1 Relief Duct Model

Procurement of glass samples became more difficult and delivery times became longer as the thickness and area of the samples increased. It was, therefore, decided to construct an apparatus in which samples of various thicknesses could be tested, initially in one ft square panels but with the potential for handling panels of larger sizes up to 3 ft x 3 ft in cross-section. Using this device, tests could first be made with smaller, cheaper and more easily obtained samples with the possibility of
going to larger panels if this appeared desirable at a later stage in the experimental program.

The wooden test rig designed to meet these requirements, illustrated in Figs. 2 and 3, comprised a 3 ft x 3 ft pressure box and a 1 ft x 1 ft pressure relief duct. The two vertical walls of the relief duct were glass of quality suitable for observation with a schlieren system. An additional 1 ft square window of schlieren quality was installed in the back end of the box to allow viewing axially down the pressure relief duct. The front end of the box, including the pressure relief duct which was 3 ft in length, was constructed in such a manner that it could be easily removed and replaced should a duct of larger cross section become necessary during the experimental program. The interior of the pressure box was treated with automobile body undercoating in order to minimize leakage through cracks and faults in the wood. The test diaphragms were restrained along the top and bottom edges by steps cut in the ceiling and floor of the relief duct. A pressure seal around the samples was obtained by a strip of rubber glued to the floor, ceiling and the glass sidewalls.

The glass sample under test was mounted about 1.5 inches down the duct in order that the plane of the diaphragm would be visible when observing through the sidewalls. Initially, tempered glass panels in 1/4 inch and 1/2 inch thickness were procured, and most of the test runs were made using these sizes. A few tests of plate glass in 3/16, 1/4 and 1/2 inch thickness were also made for comparison.

3.2 Optical System

Observation of the diaphragm breaking and flow formation was made by means of a schlieren optical system with approximately a 10 inch field of view. A high speed multi-source spark camera (Ref. 2) was used to record the results. A series of sparks allowed eight photographic exposures, each of approximately 0.75 microsecond duration, to be obtained during each run. A conducting line painted on the glass near the point of impact on the Ramset fastener actuated a common triggering unit which started the eight time delays which could be individually adjusted to control the times at which the various spark gaps fired.

It was desired to view the diaphragm breaking phenomena both normal and parallel to the plane of the diaphragm. These views could not, of course, be obtained simultaneously but a series of runs using each thickness of glass was made with the schlieren beam passing through the back window and down the length of the discharge duct. Thereafter another series of runs using the same thicknesses of glass was made with the schlieren beam passing through the sidewalls of the pressure relief duct.
3.3 Ramset Gun and Associated Equipment

A prototype mechanical diaphragm breaker was designed for use in the experimental test program. This unit, illustrated in Figs. 4 and 5, was designed in such a way that it could be used as one of the guns in the actual NPD-2 relief duct. Consequently, the original Canadian General Electric design was followed as far as possible. Some modifications and additions were, however, made to facilitate the requirements of the proposed experimental program.

In order to cock a Ramset gun it is necessary to push the muzzle against some solid object with considerable force. This was allowed for in the experimental assembly by providing a muzzle support bracket drilled with a hole sufficiently large for a Ramset fastener to pass through. The support bracket was firmly bolted to a heavy base plate and the gun on its mount could be pushed forward against the bracket and held in position by a retaining pin, as can be seen in Fig. 4.

As in the General Electric design, a solenoid for pulling the trigger was mounted on a bracket attached to the butt of the gun. In order to minimize the time delay resulting from pulling of the trigger, the trigger was retracted on loading the gun to a point just short of the firing position and was held at this point by a retaining lever which could be dropped in front of the solenoid plunger (see Fig. 4).

Some difficulty was encountered in adapting the Ramset gun for the glass shattering experiments, since a projectile could not be fired down the pressure relief duct while viewing in the same direction because one of the schlieren parabolic mirrors was located immediately beyond the outlet of the relief duct. A solution of this problem was finally proposed by Ramset Fasteners Limited. A two inch diameter steel arresting disc with a hole drilled in its centre (see Fig. 6) was interposed between the muzzle of the gun and the muzzle support bracket. A special adapter was fitted to the muzzle of the gun to hold these discs in position (see Fig. 5). Fasteners with a 2.5 inch shank were used with this arrangement. The hole in the arresting disc was large enough to allow the shank of the fastener to pass through to strike the glass diaphragm. The threaded rear portion of the fastener was, however, too large to pass through the disc and the fastener was arrested as can be seen in Fig. 6. This arrangement was most satisfactory.

The gun mount and muzzle support bracket were subsequently modified as shown in Fig. 5 to allow the gun mount to be placed inside the pressure chamber while the muzzle projected down the duct to the diaphragm station.
3.4 Breaker System Time Constant Tests

Initially the experiments were arranged in such a way as to measure the overall time constants of the system from the instant of closing the pressure switch to the instant at which the fastener left the muzzle of the gun. The pressure signals for this set of tests were generated in the UTIA 3 inch x 3 inch wave interaction shock tube (described in Ref. 3). The general arrangement for these experiments is shown in Fig. 7. A signal generated by rupture of the shock tube diaphragm was used to start an electronic counter chronograph. The expansion wave in the shock tube chamber closed the pressure switch and actuated the gun firing circuit. The Ramset fastener, on leaving the muzzle of the gun, broke a fine wire stretch across its trajectory just beyond the muzzle support bracket. The breaking of this wire provided a stop signal for the chronograph. The system time constant was discovered to be approximately 60 milliseconds.

Subsequently the individual time constants of the pressure switch, relay, solenoid and gun were separately measured. It is of interest to note that the "lock-time" of the gun (from release of the firing pin until emergence of the projectile) was only 5 milliseconds. The large portion of the system time constant resulted from the electro-mechanical operations of pulling the trigger.

3.5 Procedure for Glass Shattering Tests

In preparation for each test run the Ramset gun was loaded, cocked and placed inside the pressure box. The box was then pressurized to 1.5 psig.

The firing solenoid was actuated by a hand switch on the pressure control panel. On impact with the test panel the Ramset fastener interrupted a conducting circuit previously painted on the glass and thus started the spark time delays as described in Section 3.2 above. All times were measured from the instant of impact.

The experimental runs conducted in this part of the program are tabulated in Appendix A.

3.6 Experimental Results

A typical photographic result is reproduced in Fig. 8 from run No. 7. The eight exposures are arranged chronologically in a clockwise direction with the earliest exposure in the "1 o'clock position". The circular cut-out in the lower right hand corner of some of the exposures is the shadow of the Ramset gun housing. The times corresponding to the various exposures are indicated in Fig. 11 and it is evident that although the glass is completely cracked as early as 20 microseconds after the impact of the Ramset fastener a period of approximately 20 milliseconds is required before the fragments begin to disengage from each other. At 30 milliseconds
an appreciable open area has appeared in the duct. It should be emphasized that in this view, looking down the discharge duct in an axial direction, it is not possible to determine how far the individual particles have travelled from their original location. Neither is it possible to determine whether or not particles are all at the same axial distance down the duct. It is, however, evident from Fig. 8 that by 40 milliseconds after impact of the Ramset fastener no appreciable duct blockage remains.

Figure 9 shows four frames selected from run No. 8 using 1/4 inch tempered glass. The exposure of Fig. 9 (a) was taken at 9.6 microseconds after impact and it can be seen that the cracking of the glass has travelled out radially from the point of impact but has not yet encompassed the whole of the glass diaphragm. This exposure illustrates the fact that the actual cracking of the glass is accomplished in a very short interval of time. The other three exposures in Fig. 9 were taken at 20, 25 and 30 milliseconds after impact and show the progressive break up of several large particles of the broken diaphragm. Figure 10 reproduces the exposure of Fig. 9 (a) and also a later exposure at 13.9 microseconds which shows the progression of the radial compression wave shattering the glass.

Comparison of Figs. 8 and 9 shows that the thinner glass sample is well fragmented after 20 milliseconds whereas in the case of the thick sample the particles are only beginning to disengage at the same time. It is also evident from these photographs that although the glass initially cracks in a very fine honeycomb pattern, the small cells of this pattern do not all break apart. Large fragments with dimensions of an inch and greater were commonly found after a trial run. Some examination of these particles indicates that the initial cracking occurs only in the central portion of the glass between the two hardened outer skins. Both plain surfaces of these fragments appear at first sight to be undamaged but examination under a magnifying glass suggests that some fine hair-line cracks may exist in these surfaces.

Figure 11 shows some exposures from run No. 10, viewing a 1/4 inch tempered glass sample through the sidewalls of the relief duct with flow from right to left. The thick vertical line in these exposures is the silhouette of the diaphragm and its supporting rubber gasket. The short thin vertical lines are scale marks painted on the glass sidewall at one inch intervals. The four exposures in Fig. 11 were taken at 20, 30, 40 and 60 milliseconds respectively after the time of impact. In this run a 1/2 inch sample was being broken. The sequence of events observed here is the same as that seen in Fig. 11 but again it is evident that the thicker glass opens up more slowly. A photograph looking up the pressure relief duct and showing the results of run No. 3 is reproduced in Fig. 13. It is seen that a considerable portion around the top and one edge of the 1/2 inch tempered glass sample has remained in its initial position. In two other runs using 1/2 inch tempered glass even poorer results were obtained with only a small portion in the neighbourhood of the gun muzzle breaking out. It is probable that this result is due in part to edge effects with the small samples used with these tests and
it is therefore anticipated that better results would probably be achieved with larger panels. Using 1/4 inch thickness tempered glass the diaphragm broke out completely in all runs. In Fig. 13 the debris on the floor of the discharge duct can be seen to be made up very largely of fragments of substantial cross-section, thus showing that even impact with the duct floor is not sufficient to complete the break-up of the glass.

Some experiments were made using plate glass and selected photographic results from runs No. 1 and 9 are presented in Fig. 14 for 3/16 inch samples. Figure 14 (a) shows the cracks in the plate at 8.5 milliseconds after the time of impact. The other three exposures show views through the sidewalls at 20, 30 and 40 milliseconds respectively. It is evident from these results that the plate glass breaks into fragments much larger than those observed for the tempered glass. These large jagged fragments are clearly visible in Fig. 14 (b). Figure 15 shows a view up the pressure relief duct after run No. 6 using 1/2 inch plate glass. In this case the Ramset fastener has merely punched a small hole in the glass and most of the diaphragm is still in position. In general the plate glass samples were found to be definitely inferior to the tempered glass.

Despite the use of schlieren photograph, very little evidence of flow development was observed. This is presumably due to two factors, first the low pressure ratios involved and second the fact that the bursting of the diaphragm and tumbling of the glass particles obscured some of the initial flow field which would be of interest.

3.7 Analysis of Results

From the photographic records obtained when viewing through the glass sidewalls of the relief duct it is possible to measure the position of the leading glass particles as a function of time and this has been plotted for three runs in Figure 16. For comparison, theoretical distance-time curves (obtained as described in Section 2 above) for 1/4 and 1/2 inch fragments are shown in the same figure. It can be seen that the leading fragments travel at almost the theoretical speed but at a delayed time.

In general, it is not possible to identify any but the leading fragments in more than one frame. However, in some of the photographic records a specific trailing particle can be identified in several consecutive exposures. In this case approximate measures of position can be taken and these allow an estimate of particle acceleration and velocity to be made. This has been done for several particles with the result in all cases giving an average velocity of approximately 0.1 inches per millisecond. The motion of two such particles has been superimposed on Fig. 16 and it is seen that these travel considerably more slowly than the leading fragments, and hence must undergo an acceleration less than the theoretical.

Although the number of experimental runs was limited, an estimate has been made of the pressure loss likely to result from the blockage
due to glass particles in the relief duct flow. As a first step an average open area versus time curve was drawn (see Fig. 17) from the photographic records for 1/4 inch tempered glass diaphragms.

From the numerical analysis reported in Ref. 1 the development of duct dynamic pressure (q) can be calculated following the opening of the diaphragm. After diaphragm rupture the duct flow jumps instantaneously to its initial value as the primary shock wave passes down the duct and thereafter continues to increase gradually as successive pressure pulses arrive. Although this dynamic pressure actually corresponds to the unblocked flow assumed in Ref. 1 it has been applied as an approximation to the present case by choosing the initial discontinuity in q to coincide with the time at which the duct was 50 percent open (see Fig. 17).

From Fig. 17 values of dynamic pressure and percent open area can be obtained for any given time. An empirical relationship between percent open area and pressure loss coefficient across the fragments has been obtained from data in Ref. 4 and from experimental work in connection with other projects. The pressure drop (Δp) across the glass fragments has thus been calculated as a function of time and plotted in Fig. 17. It is seen that this pressure loss is at a maximum immediately after diaphragm opening but rapidly decays as the fragments disperse.

For comparison the rate of pressure rise in the closed boiler room has been superimposed on Fig. 17. It is apparent that the delay between impact and diaphragm opening results in a pressure rise greater by an order of magnitude than differential across the glass fragments.

The picture presented in Fig. 17 is, of course, an oversimplification. In practice the increasing room pressure would probably hasten diaphragm opening and impart a greater acceleration to the fragments. The stronger primary shock wave in the duct would also provide a higher initial dynamic pressure. Nevertheless, it is apparent that the opening delay is more significant than the fragment blockage after shattering.

3.8 Summary

The diaphragm configuration and breaker mechanism investigated in this series of tests did not have satisfactory performance as recommended in Ref. 1. For 1/4 or 1/2 inch tempered glass the overall time constant of the system, from sensing of the critical overpressure until disintegration of the diaphragm to the point of negligible flow resistance, was found to be 90 to 100 milliseconds. Re-examination of the calculations reported in Ref. 1 suggested that this delay would result in approximately 1.2 psig increase above the peak pressure calculated in the former study.

The large time constant was attributable in part to the shattering mechanism and associated circuitry and in part to the delays inherent in the diaphragm itself. Although glass panels thicker than 1/2 inch were not
tested it was apparent from the results obtained that the time delay associated with shattering the diaphragm would be even greater if 1.25 inch thick glass were used.

Review of the impact shattering experiments revealed the following shortcomings inherent in this diaphragm arrangement:

1) The design of an electro-mechanical shattering mechanism with acceptably short time constant presents serious difficulties.

2) The impact of a projectile on a thick glass panel shatters the glass but does not impart sufficient energy to the glass to disengage all the fragments from one another.

3) The initial 1.5 psig pressure differential across the glass diaphragm does not provide a large accelerating force to the panel fragments, and this is undoubtedly one of the main reasons for the long time delays associated with the disintegration and dispersal of the glass.

IV. EXPLOSIVE SHATTERING EXPERIMENTS

4.1 Basic Concept

As an alternative technique which would avoid the shortcomings of the impact shattering method the use of the explosive, glued directly to the diaphragm and fired by an electric detonator, suggested itself. It would have the following advantages:

a) The explosive could be detonated electrically, thus eliminating almost all of the time delay associated with the present mechanical breaker.

b) The glass would be more completely fragmented and the individual particles would be given a greater outward acceleration by the force of the explosion.

A further series of experiments was undertaken to investigate the explosive shattering technique. The primary objectives of this program were to measure the time delay between receipt of a detonating signal and the initial opening of the glass panel, to study the subsequent motion of the glass fragments and to determine the percent open area of the diaphragm as a function of time. Secondary objectives were to evolve a suitable diaphragm configuration and an appropriate type and arrangement of explosive charge and, if possible, to assess any adverse effects that the explosion might have on nearby equipment in the boiler room.
In the earlier tests the acceleration of the glass fragments under pressure loadings was studied. For the explosive tests it was therefore decided not to impose any pressure loading on the test panel so that acceleration of the glass would be due only to the action of the explosive. In the final installation combination of the explosion and the pressure load should result in improved performance.

Removal of the requirement for a pressure differential allowed considerable simplification of the test procedure and apparatus, which in turn permitted the testing of larger glass panels. The requirements of the full scale NPD-2 diaphragm were reconsidered at this stage to determine the most useful scale for the experimental program. In this case, compromise was required between the low mass of the glass panels and the high strength needed to carry 1.5 psi. Tempered glass (see Ref. 5) is thus more suitable than plate glass. Using a 3/16 inch glass, 16 panels 2'3" x 3'0" would be required and using 1/4 inch glass, two panels each 6'0" x 9'0" could be used but would require a back-up structure giving a basic unsupported panel size of 3'0" x 4'6". A test frame was therefore designed to hold 4'6" x 3'0" panels of 1/4 inch glass. The same frame could be used to hold 2'3" x 3'0" panels supported on three sides only. This test frame is illustrated in Figs. 18 and 19.

4.2 Configuration of Explosive Charge

The original concept for the explosive shattering technique involved the use of sheet explosive such as DuPont EL-506A (described in some detail in Ref. 6). This material is flexible and can be easily cut to any required shape and glued to another surface. Furthermore, it is safe to handle and can be reliably initiated with an electric blasting cap.

Some early runs using 1/8 inch plate glass panels were made with this type of explosive. In order to minimize the total charge the lowest density of EL-506A was used. The sheet was cut into strips 1/8 inch wide and these strips were glued in a grid to the glass. It was found that the fragmentation of the panel was not good using this explosive configuration. Compared with similar charge densities of other types of explosives tested later, the glass fragments resulting from these tests were large. Furthermore, a tendency to incomplete detonation of the EL-506A was observed, probably due to the narrowness of the strips employed. However, it did not appear possible to overcome either of these problems without resorting to a charge density much higher than that necessary for effective shattering using other forms of explosive.

The majority of the experimental tests employed a PETN explosive supplied by Canadian Safety Fuse Co. Ltd. This is in the form of a cord and detonates, as does the EL-506A, at approximately 7,000 meters per second. During the experiments four grades were tested, 40 grains, 10 grains, 5 grains and 2 grains PETN per foot respectively. The 40 grain charge with the trade name Primacord was plastic covered and the other grades known as Mild Detonating Fuse (MDF) were covered with a lead sheath.
Some early runs used Primacord in the form of a cross but for most tests the Primacord was attached to the panel in a spiral configuration, as shown in Fig. 20 (a), with a detonating cap at the end of the cord in the centre of the spiral. The lighter charges were attached in a criss-cross grid composed of three strands as shown in Fig. 20 (b); the spacing between adjacent strands was 1.5 inches and the three strands were brought together at one end and attached to a common detonator cap. For all the experimental tests using these explosives the cord was fastened to the glass panel using small strips of tape at intervals, as can be seen in Fig. 21.

4.3 Experimental Arrangement

The test runs described here were made inside a steel firing tank at the Explosives Research Laboratories at Canadian Industries Limited. The test firing chamber is a large cylindrical steel tank with hemispherical ends equipped with small plexi-glass observation windows and connections for firing and instrumentation leads as can be seen in Fig. 21. The firing controls and instrumentation are in adjoining rooms and safety measures appropriate to this type of work are observed at all times. The test frame was suspended from the ceiling of the firing chamber as shown in Fig. 19. The flexibility of this type of support did not present any problem, the inertia of the frame and the glass sample being sufficient that no motion of the whole assembly occurred until well after the shattering was complete.

The experimental tests were observed using a Fairchild HS101 16 mm high-speed framing camera, which was focused on the test panel through an observation port in the firing chamber (see Fig. 22). This camera used a 100 foot roll of Kodak Tri-X reversal film at each firing and it was arranged that the main firing button started the camera motor. When the film reached full speed a signal generated within the camera initiated the detonating cap attached to the explosive charge on the test panel. For most of the experimental runs a camera speed of approximately 6,000 frames per second was used, the exact speed at the time of shattering being determined from a set of timing marks superimposed on the film.

4.4 Measurement Techniques

The primary instrumentation was the high-speed framing camera described above. Two alternative viewing angles were used during the tests, parallel to and perpendicular to the plane of the test panel (see Fig. 23).

Considerable difficulty was experienced in obtaining the correct exposure for the photographic records. In the earliest runs light from 4 photoflood bulbs was used to illuminate the glass panel but it was found that the light generated by the exploding Primacord was so intense that it completely exposed the film. Even after the initial detonation bright clouds of luminous gas, presumably products of combustion, were observed in the neighbourhood of the initial charge. In order to overcome the luminosity
problem the front of the glass panels were sprayed with several coats of paint to render them opaque to the light generated by the explosive. When viewing from the front of the panel (the explosive charge being attached to the back) no external light source was employed and the fracturing and opening of the diaphragm could be observed as light penetrated through the glass fragments from behind.

When viewing the shattering phenomena from the side the problem of explosively generated luminosity was somewhat more complex. It was necessary to shield the camera from the intense light at the back of the panel by using cardboard or metal screens extending back three or four feet from the edge of the test frame. Other shields, in the plane of the test frame and around its edges, were required to prevent spillage of luminous gas around the edges of the frame. (These shields are shown in Fig. 23 and have been removed for the photographs in Figs. 18 and 19). In this way the light from the exploding charge could be almost completely masked, except for luminous gas coming through the open diaphragm after fragmentation of the glass. With this configuration external illumination was used in two alternative locations. One lamp position is illustrated in Fig. 23, in which case the camera receives reflected light from any particles or fragments traversing the area downstream of the diaphragm. The alternative arrangement, shown in Fig. 24, used an illuminated screen beyond the test frame thus providing a shadow effect where any solid or opaque objects passing in front of the screen would be observed as a darkening of the field of view.

The photographic records were studied, both as motion pictures and as individual frames on a projection screen. Portions of interest were also examined using a Hilger model T500 Universal Measuring Projector.

As described elsewhere in this report there was considerable difficulty in obtaining a quantitative assessment of what was happening during the shattering process. This appears to have been due to the fact that the glass panels were shattered into extremely small fragments which could not be seen individually on a photographic film but rather appeared as an opaque cloud. Thus, while it was relatively easy to determine the rate of motion of the front of this cloud, it was not possible to calculate with any precision the open area of the diaphragm as a function of time. Therefore, some additional visualization techniques were employed during the latter experimental runs.

One such technique employed was the use of a "rake" of blast probes supported some distance in front of the diaphragm and extending toward the face of the glass, as shown in Fig. 23. These probes were made of 1 inch diameter cardboard mailing tubes with approximately 1/32 inch thick walls. The probes were all of different lengths and were arranged at different distances from the camera in an effort to improve the visual observation of the shattering process and cloud formation. When illuminated as shown in Fig. 23 these probes appear as in Fig. 36.
Another technique which was employed was the use of small "targets" each being formed of a short length of cardboard mailing tube of the same size as described above. These were visible when the diaphragm was observed edge-on. In the first exposure of Fig. 36 four such targets are visible as short horizontal lines protruding from the plane of the diaphragm. It was hoped to study the motion of these targets during the test run but as can be observed in Fig. 36 the targets vanished immediately into the cloud. After the run, however, the targets were retrieved undamaged from the floor of the test chamber.

Several of the experiments were conducted using fine resistance wires attached to the front of the panel in an attempt to determine the exact time at which fracturing of the glass occurred. In the earliest runs of this type a grid of resistance wires at 4 inch spacings was taped over the entire surface of the test panel. The grid was connected across the terminals of a constant current generator and the grid voltage was observed as a function of time on a cathode ray oscilloscope screen in order to determine the rate at which resistance wires in the grid were broken. This technique was later refined to the use of short strips of resistance wire glued to the glass at various locations. Each wire was connected in series with a resistor and all the loops so formed were connected in parallel across the terminals of a constant current generator. The values of the resistors were chosen in such a way that it was possible to deduce from the step discontinuities in the resultant oscilloscope trace which wires were broken and which remained intact at any given time. As many as five different resistance wires could be employed using this technique. Usually the output of the resistance wire network was applied directly to the oscilloscope. However, in some cases a variation was employed and the output was applied directly to a counter chronograph which was started by a signal from a probe imbedded in the explosive itself and was stopped by a signal from the breaking resistance wire.

4.5 Fragmentation Observations

Runs using plate glass with 40 grain Primacord spirals resulted in fragmentation of the glass to a degree never achieved in the previous impact experiments. The entire panel was reduced to sandlike particles as illustrated in Fig. 25.

In direct contradiction to the earlier results (where tempered glass shattered better than plate glass under the same circumstances) experiments with the 3/16 inch tempered panels and the spiral Primacord configuration did not give results as satisfactory as those obtained using plate glass. While there was a considerable quantity of tiny particles there were also many large fragments of cracked but not shattered glass (see Fig. 26) similar to those obtained in the gun experiments. Close study of the high speed photographs suggests that most of these large pieces actually came from the four corners of the test panel which were remote from any part of the spiral. This conclusion was strengthened by the tests using 10 grain Mild Detonating Fuse in a grid. In this case all portions of the glass panel were within 3/4 inch of
Primacord strands and the shattering characteristics were very much better. Again the entire panel was reduced to tiny fragments, a great deal of the residue even having the consistency of flour (see Fig. 27). This fine dust was uniformly spread over the test chamber walls and floor after each experimental run.

Experiments using 1/4 inch tempered glass exhibited the same excellent fragmentation characteristics when shattered by a 10 grain Primacord grid. Figure 28 illustrates the result of one such run. In this case only the lower half of the test panel could be seen in the camera field of view and the Primacord grid was attached to the back of this portion only of the glass. The front of the lower half of the glass was painted silver and the front of the upper half was painted green. After this detonation the chamber was filled as usual with glass dust but the floor surrounding the test frame was covered with larger green painted fragments, cracked in the cellular pattern characteristic of tempered glass. Samples of glass dust and green fragments are shown separated in Fig. 28.

Some runs using 3/16 tempered panels with 5 grain and 2 grain Mild Detonating Fuse in the grid configuration were made to check the effect of further reduction in total charge. The results of these experiments indicated progressively poorer fragmentation and progressively slower acceleration of the glass particles as the charge was reduced.

It can be concluded from the observations of fragmentation that better results are obtained as the same total charge is distributed more uniformly over the surface of the glass panel. From the point of view of undesirable blast effects it is worthwhile to keep the total charge as small as possible. However, it is seen that ultimately reduction of the total charge results in poor fragmentation. From the various configurations examined it appears that a 10 grain Primacord grid, as used in these experiments, achieved the most satisfactory results.

4.6 Discussion of Photographic Results

A summary of the useful explosive shattering tests is given in Appendix B. Some portions of selected high speed films have been reproduced in this report and are described below. The clarity and resolution of these exposures has been somewhat reduced by the several steps involved in the reproduction process.

When viewing test panels from the front, the burning of the Primacord charge can be detected in the first few frames of the high speed film. This is seen in Fig. 29 which reproduces selected frames from a high speed film of 3/16 inch tempered glass shattered by a 40 grain Primacord spiral. This panel was viewed from the front and the progression of the detonation from the centre to the outside of the spiral can be seen in Fig. 30 which is drawn by super-position of features from the first few frames showing the shattering of 1/8 inch plate glass. In this case also a 40 grain Primacord spiral was used.
for the detonation and the approximate initial position of this spiral is indicated in the drawing. The entire front of the glass panels, with the exception of a small cross in the centre, was painted to render it opaque to the light generated by the exploding charge at the back. In the first two frames of the film the cross appears to be illuminated by light from the detonation at the centre of the spiral.

It can be seen from the results shown in Fig. 29 that after the burn-out of the explosive charge the entire field of view becomes much darker. In all cases of viewing perpendicular to the plane of the test panel this darkening was observed to persist for two to three milliseconds and was then followed by a gradual lightening of the field. After this it was often possible to distinguish certain features in the photographs. In the final photograph of Fig. 29 it appears that the entire central portion of the glass has been removed but a jagged and cracked residue of glass remains in the corners of the test frame. This phenomenon is also apparent in Fig. 30 where the approximate edge of the remaining glass becomes fairly evident at about 5 milliseconds and remains stationary for many frames thereafter.

A likely interpretation of the events observed in Figs. 29 and 30 is the following. As the Primacord detonates, luminosity from the explosion is visible due to fragmentation of the glass in the immediate vicinity. However, as shattering proceeds the entire central portion of the panel is pulverized and reduced to a cloud of sand and dust-like particles which is opaque to the luminosity behind it. As this cloud disperses the luminosity from the rear can again penetrate to the photographic film and hence results in a lightening of the field of view. The corners of the glass panel which are not in close proximity to any part of the Primacord spiral and which are restrained by the edges of the test frame are not immediately set in motion because of the absence of a direct pressure differential in these areas. It should be noted, however, that corner particles must ultimately move since no significant amounts of glass were ever observed to remain in the test frame after the conclusion of an experimental run.

Figure 31 shows selected exposures from an early high speed film of detonation of a 40 grain Primacord spiral attached to a 1/8 inch plate glass. This test was viewed edge-on with the plane of the test panel vertical as indicated by the dotted line on the first frame and with the charge on the back of the glass (at the left in Fig. 31). No external light source was used for this run and it is seen that considerable luminosity exists at all times behind the plane of the test panel. Light appearing to the front of the test panel may be interpreted as reflected light from the cloud of glass fragments flying outward. Even after the detonation is complete it is seen in the last two exposures that considerable luminosity, presumably due to products of combustion, remains at the back of the diaphragm. Due to this intense light near the diaphragm it was necessary in subsequent runs to shield this area from the view of the camera and to illuminate the downstream side of the panel by external light sources as illustrated in Fig. 23.
Figure 32 illustrates the case of a 1/4 inch tempered glass panel shattered by a grid of 10 grains Mild Detonating Fuse. This test panel is also viewed edge-on and the broad light band down the centre of the initial exposures is due to light reflecting from the front surface of the glass which is inclined at a very small angle to the camera axis. The explosive grid burned from bottom to top as viewed in these photographs. It can be seen that a bright cloud forms, starting at the bottom shortly after initiation of the explosive and progressing toward the top in subsequent frames, and moves outward from the plane of the diaphragm. It is concluded that this bright cloud is composed of fine glass particles which reflect the light from the photoflood lamps located as shown in Fig. 23. This interpretation was strengthened by further runs in which the illumination was provided by a floodlit screen behind the test panel as shown in Fig. 24. In this case the cloud issuing from the plane of the diaphragm appeared as a dark shadow moving across the light background. High speed photos of this case are not reproduced here.

The fragments of Fig. 28 were obtained from the run illustrated in Fig. 32.

4.7 Analysis of Photographic Data

Superposition of traces showing the approximate location of the front of the emerging cloud in various frames from a high speed film of a 3/16 inch tempered glass panel shattered by a 10 grain Primacord grid is illustrated in Fig. 33. From such plots, or from direct measurements from individually projected frames of the high speed films, the average distance travelled by the front of the cloud is obtained as a function of time. Plots for four of the test runs are compared in this way in Fig. 34. In one or two of the photographic records what appeared to be the rear end of the advancing cloud was visible. In Fig. 35 the front and rear cloud boundaries are plotted as a function of time for 1/4 inch tempered glass shattered by a 10 grain MDF grid. The average slopes of cloud front plots such as shown in Figs. 34 and 35 represent the velocity of the cloud front. These velocities have been calculated for several test runs and are tabulated in Appendix B. It is seen from these results that cutting down the total charge has a marked effect on the velocity of the cloud front. This is also evident in Fig. 34 where reduction of the charge from 10 to 5 grains per foot on the same thickness of glass significantly reduces the cloud front velocity. The results in Appendix B also show that, as would be expected, the same charge affixed to a thicker glass panel results in a lower cloud front velocity.

The weakest charge employed in a test run was a grid of 2 grain per foot of PETN. In this case the observed fragmentation was very poor, with a number of large pieces of glass being among the debris. Selected frames from the high speed film of this test are presented in Fig. 36. This was the only film in which individual fragments of the glass could be discerned. The horizontal bars which are visible in these photographs are the blast probes arranged as illustrated in Fig. 23. The fact that use of weaker charges results in slower motion of the advancing front and a generally more irregular appearance of the cloud supports the theory that the cloud is composed of glass dust.
It is not possible from the photographic results obtained in this study to construct graphs of open area of the diaphragm as a function of time, as was done in Fig. 17 for the impact shattering. However, one comparison with the former results was made in the following manner. By cross-plotting the data for 1/4 inch panels from Figs. 16 and 17, a curve showing percent open area against distance travelled by leading fragments can be obtained. Then, selecting the middle dotted curve of Fig. 34 as a means of scaling the time compared to Figure 16, a new curve (Fig. 17) can be constructed giving the variation of open area as a function of time. Although the validity of this method is open to some question, the results do suggest that the diaphragm has disintegrated to the point of negligible flow resistance in a small fraction of the 20 milliseconds established as a maximum permissible time period for safe performance.

Several further observations concerning the probable blockage of the duct can also be made. In the first place, if the observed cloud is in fact composed of very small glass particles and dust and if these particles are dispersed over the fairly large axial distances indicated by the photographs the actual blockage of the duct will be much less than that due to the large fragments observed in the earlier glass-shattering experiments. Secondly, the very high velocities achieved by the glass particles in the present case are greatly in excess of the airflow velocities which would be expected in the duct in the early stages of flow development. Therefore, the glass particles should have the effect of inducing additional flow in the duct. Finally, the indications are that the glass in all portions of the diaphragm near the explosive charge is completely gone after about 5 milliseconds, at which time it is again possible to observe the diaphragm from the downstream side. Although the study of the photographic results does not permit a direct quantitative assessment of the amount of blockage remaining at any time, judgement based on the above observations is that the diaphragm will open in a satisfactory manner when actuated by the 10 grain Mild Detonating Fuse grid. Furthermore, it must be borne in mind that the tests were conducted in the absence of a pressure differential across the glass; the differential which would be present in the full-scale installation would improve the results reported here.

4.8 Electronic Measurements

A series of experimental points obtained from the resistance wire method is shown in Fig. 38. This figure shows the recorded times at which wires attached to the front surface of the glass plate were broken. Distinction is made between detectors immediately opposite strands of the Primacord spiral and detectors placed midway between two strands of the spiral. In all cases the detectors were glued to the front surface of the glass whilst the explosive charge was fastened to the back surface. The results illustrated in Fig. 38 indicate clearly that the detectors further from the centre of the spiral broke at later times, which is consistent with the direction of burning of the spiral. Also, in general, the detectors immediately opposite a spiral strand broke very much more quickly than those remote from such a strand. It is likely that in some cases the breaking of wires, particularly those located
between spiral strands, might not have occurred until after the wire or the piece of glass to which the wire was fastened had been broken from the main panel. This would present an unduly pessimistic estimate of the fragmentation time. On the other hand, it is possible that wires might be broken during the initial cracking of the glass even though the fragments to which the wires were attached were not set in motion until a later time. Nevertheless, it is felt that the results presented in Fig. 38 tend to verify the conclusions, drawn from the photographic records, viz. that the shattering occurs well within the prescribed maximum time interval of 20 milliseconds.

4.9 Summary

One of the primary objectives of the explosive shattering study was the measurement of time delays associated with the opening and dispersal of the diaphragm. The Seismocaps recommended for use as a detonator fire in 0.3 milliseconds when supplied with the specified firing current. (see Ref. 7 for a discussion of this problem). The burning rate for the explosive strands as used here is 7,000 meters per second so that the entire charge will be detonated in less than 1 millisecond. As observed from the high speed motion pictures the opening of the glass diaphragm commences within 0.25 milliseconds of the initiation of the charge. As the detonation of the charge progresses across the panel the fracturing and initial motion of the glass particles progress in the same direction. Thus fragments from the portion of the diaphragm close to the detonating cap are seen to be in motion even before the complete charge has burned out. The results presented here apply to the test charge configuration and should be improved by using the configuration, recommended (see Section 5 below) for the NPD-2 installation, in which the entire charge would be burned out more rapidly.

When the above time delays are added to the time constant for a fast acting pressure switch it is evident that initial glass fragments will be moving outward from the plane of the diaphragm in less than 5 milliseconds after a critical overpressure is sensed in the region of potential coolant line failure.

The second objective of this study was the investigation of blockage effects resulting from the subsequent motion of fragments of the glass diaphragm. Unfortunately it is not possible from a study of the high speed photographic records or from any of the other measuring techniques employed in this investigation to observe directly the percent open area as a function of time as done in the previous experiments. This is largely due to the fact that the glass panels, under the recommended detonating procedure, are completely pulverized by the explosive charge so that no particles sufficiently large for individual identification are formed. This conclusion is borne out both by the photographic records which show the presence of a cloud-like formation and by examination of the residual particles and fragments in the firing chamber after shattering of test panels.
It was concluded from careful study of the explosive test data that the diaphragm is completely removed in considerably less than the 20 milliseconds recommended in Ref. 1. In fact, all the evidence points to the probability that the diaphragm is completely pulverized and adequately dispersed within about 3 milliseconds from the detonation of the Seismocap. The velocity of the front of the moving cloud of glass particles, as calculated from the high speed motion pictures, is very much higher than the velocity to be expected of the air in the pressure relief duct immediately after opening of the diaphragm. Thus the glass particles will not retard or block the flow but may be expected, if anything, to impart an acceleration to the duct air in the desired downstream direction.

V. APPLICATION TO FULL SCALE DIAPHRAGM

5.1 Recommended NPD-2 Configuration

Based both on the availability of glass and on the concept of minimum aerodynamic blockage, a diaphragm configuration was proposed by Canadian General Electric Co. Ltd., comprising four sheets of 1/4 inch thick tempered glass. Each sheet was to be 4'6" x 6'0" in area and each sheet would be supported by a cruciform back-up structure. The basic test panel size in the explosive shattering tests was therefore half scale. The test panels were supported somewhat more rigidly than the panels in the full scale configuration; as a consequence it would be expected that the test results might be slightly pessimistic due to more pronounced edge effects.

The explosive configuration recommended for the full scale NPD-2 installation is illustrated in Fig. 39. It is seen that this configuration differs somewhat from the test configurations of Fig. 20. Additional detonators were recommended and the arrangement, although not the spacing, of the charge was altered to obtain more rapid burning. The configuration of Fig. 39 would be repeated on each of the four panels of the full scale diaphragm.

The recommended arrangement has several advantages. It is easy to assemble. Detonation of the 40 grain per foot Primacord directly by Seismocap is very reliable. The 10 grain per foot Mild Detonating Fuse is fired more reliably by the Primacord than directly by a cap and looping the Mild Detonating Fuse around the Primacord has been shown to give reliable cross-detonation. Using this configuration the time for detonation of all the explosives is only 0.25 milliseconds and the maximum delay for the cap itself is 300 microseconds, provided the necessary firing current is supplied.

For attaching the explosive charge to the glass several liquid adhesives were investigated. Accelerated hot storage tests were undertaken at CIL to evaluate the life of the bond from these cements. Final results showed B. F. Goodrich Plyobond to be the most suitable from all points of view.

To obtain reliable detonation of the Primacord directly from an electric detonator it was recommended that the Primacord be looped tightly
in a U-shape over the end of the cap and that the cap and the Primacord be then taped together. To ensure a firing time of not more than 300 microseconds a minimum of 5 amperes should be supplied to each cap; for the 16 Seismocaps required for the complete diaphragm, 80 amperes current is needed. The resistance of each Seismocap is about 2.5 ohms, so that the parallel resistance of four caps is 0.16 ohms. The minimum voltage required is therefore 12 volts. It is important that the source of power should be able to deliver 80 amperes; otherwise longer firing times will result. Alternatively, a condenser discharge could be used; in this case 320 millijoules would be required for the 16 detonators.

5.2 Blast Effects

Some calculations of the possible blast effects due to the detonation of the explosive charge in the full-scale NPD-2 diaphragm are given in Appendix C. On a straight comparison of energy release it is shown that the entire explosive charge on the full-scale diaphragm will release less than one tenth of one percent of the energy released into the boiler room in the form of internal energy of the heavy water vapour. In fact some considerable portion of the energy release from the explosive charge will appear as kinetic energy of the glass particles and this, as has been mentioned earlier, will have a beneficial effect upon flow in the pressure relief duct. An estimate of the glass velocities which could be expected if the entire energy of the explosive charge was converted into kinetic energy of the fragments has been made in Appendix C and is plotted in Fig. 40 and compared with the measured velocities listed in Appendix B.

The detonation of an explosive in air produces a high transient pressure peak which attenuates quickly with distance. Some tests were carried out to determine the peak pressures as a function of distance from a flat charge similar to those used in the glass shattering experiments. These tests were carried out in the open air using the highest loading density of PETN previously tried, namely a 13 ft spiral of 40 grain per foot Primacord.

For the pressure determinations spirals of Primacord were taped to cardboard and hung vertically at a height of about 5 ft above the ground. Piezoelectric gauges located at various distances from the charge were used to pick up the pressure pulse. The results are reproduced in Fig. 41.

Examination of the blast probes (Fig. 23) and observation targets which were used in some of the test runs also suggests that the effect of blast and fragmentation will not be severe. The cardboard blast probes, some of which were only two inches in front of the shattered test panel, exhibited almost no damage, as did the small cardboard targets initially glued to the glass. The metal test panel support frame was used throughout the test program without damage. It may therefore be concluded that no damage to the boiler room or to equipment within it would be experienced due to detonation of the explosive charge or fragmentation of the pressure relief diaphragm.
VI. CONCLUSIONS

The study described in this report was directed to the solution of a specific problem - the evolution of a satisfactory pressure relief diaphragm for the NPD-2 boiler room. However, the glass shattering tests were felt to be of sufficient interest to warrant their publication in the present form.

The following basic results, derived from this study, are of general interest with respect to the use of large glass panels as emergency pressure relief diaphragms.

1) Under impact loading from a projectile, tempered glass panels shatter more uniformly than do plate glass panels of equal thickness.

2) The time required for the fragments of glass panels, shattered by impact loading, to disengage from each other is very long compared to the actual shattering time. This situation persists even in the presence of moderate pressure loading on the panel.

3) The use of electrically detonated explosive charges to shatter a diaphragm provides very much shorter opening times and better fragmentation.

4) For explosive shattering the most desirable explosive configuration is one which provides a relatively low but uniform charge density.

5) The pressure measurements taken in the vicinity of an exploding Primacord charge corroborate the theoretical analysis which predicted that blast effects would not be significant. Furthermore, these tests have indicated that damage to surrounding structures due to the impact of glass fragments will be negligible.
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<th>Author(s)</th>
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<tr>
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<td>S. F. Hoerner</td>
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REFERENCES
FIGURE 1 CONFIGURATION OF DIAPHRAGM AND ALTERNATIVE SHATTERING SYSTEMS
FIGURE 2

TEST RIG FOR IMPACT SHATTERING EXPERIMENTS SHOWING BACK OF PRESSURE CHAMBER CLAMPED IN POSITION AND (at left) MULTIPLE SPARK SOURCE
FIGURE 3

TEST RIG FOR IMPACT SHATTERING EXPERIMENTS SHOWING GLASS-WALLED PRESSURE RELIEF DUCT AND (at left) CAMERA
FIGURE 4

RAMSET GUN MOUNTING FOR TIME CONSTANT MEASUREMENTS
FIGURE 6

RAMSET FASTENER, ARRESTING DISC AND ARRESTED FASTENER
FIGURE 7

EXPERIMENTAL ARRANGEMENT FOR TIME CONSTANT MEASUREMENTS
FIGURE 8

PHOTOGRAPHIC RECORD OF SHATTERING OF 1/2 INCH TEMPERED GLASS VIEWED NORMAL TO PLANE OF DIAPHRAGM. Times indicated in milliseconds after impact of Ramset fastener.
FIGURE 9
SHATTERING OF 1/4 INCH TEMPERED GLASS VIEWED NORMAL TO PLANE OF DIAPHRAGM

(a) 9.6 microseconds
(b) 20 milliseconds
(c) 25 milliseconds
(d) 30 milliseconds
FIGURE 10

ENLARGEMENT OF FIG. 9(a) AND SUBSEQUENT FRAME FROM SAME RUN
FIGURE 11

SHATTERING OF 1/4 INCH TEMPERED GLASS VIEWED THROUGH SIDEWALLS OF PRESSURE RELIEF DUCT. Flow from Right to Left.
FIGURE 12

SHATTERING OF 1/2 INCH TEMPERED GLASS VIEWED THROUGH SIDEWALLS OF PRESSURE RELIEF DUCT. Flow from Right to Left.
FIGURE 13
VIEW UP PRESSURE RELIEF DUCT FOLLOWING TEST OF 1/2 INCH TEMPERED GLASS DIAPHRAGM
FIGURE 14

SHATTERING OF 3/16 INCH PLATE GLASS SAMPLES

(a) 8.5 milliseconds (viewed normal to plane of glass)

(b) 20 milliseconds (viewed through relief duct walls)

(c) 30 milliseconds (through walls)

(d) 40 milliseconds (through walls)
FIGURE 15

VIEW UP PRESSURE RELIEF DUCT FOLLOWING TEST OF 1/2 INCH PLATE GLASS DIAPHRAGM
FIGURE 16

THEORETICAL MOTION OF GLASS FRAGMENTS FOLLOWING IMPACT OF RAMSET FASTENER AND COMPARISON WITH EXPERIMENTAL RESULTS
NOTE
ROOM PRESSURE = 1.5
AT TIME = 0

FIGURE 17
TIME VARIATION OF OPEN AREA, DUCT DYNAMIC PRESSURE, PRESSURE LOSS ACROSS GLASS FRAGMENTS AND BOILER ROOM PRESSURE RISE FOR CASE OF 1/4 INCH TEMPERED GLASS
FIGURE 18
EXPERIMENTAL ARRANGEMENT INSIDE TEST FIRING CHAMBER SHOWING TEST FRAME IN FOREGROUND AND CHAMBER ENTRANCE AT LEFT

FIGURE 19
TEST FRAME IN POSITION WITH LIGHTING ARRANGED FOR SHADOW PHOTOGRAPHS
Figure 20

Primacord charge configurations used in explosive shattering tests.
FIGURE 21
CAMERA AND AUXILIARY EQUIPMENT
IN POSITION OUTSIDE OBSERVATION PORT

FIGURE 22
TEST PANEL IN POSITION SHOWING ATTACHMENT
OF PRIMACORD GRID TO LOWER HALF OF GLASS
ONLY. OBSERVATION PORT IS VISIBLE AT LEFT
FIGURE 23

NORMAL ARRANGEMENT OF TEST APPARATUS
FOR EXPLOSIVE SHATTERING TESTS
FIGURE 24

TEST ARRANGEMENT FOR SHADOW TECHNIQUE
FIGURE 25

TYPICAL SAMPLE OF GLASS FRAGMENTS FROM 1/8 INCH PLATE GLASS SHATTERED BY 40 GRAIN PRIMACORD SPIRAL

FIGURE 26

SAMPLE OF LARGER GLASS FRAGMENTS FROM 3/16 INCH TEMPERED GLASS SHATTERED BY 40 GRAIN PRIMACORD SPIRAL
TYPICAL SAMPLE OF GLASS PARTICLES AND DUST FROM 3/16 INCH TEMPERED GLASS SHATTERED BY 10 GRAIN MILD DETONATING FUSE GRID

FIGURE 27

GLASS SAMPLES FROM 1/4 INCH TEMPERED GLASS PANEL HALF COVERED BY 10 GRAIN MDF GRID AS SHOWN IN FIG. 21. LARGE FRAGMENTS AT RIGHT ARE IDENTIFIED AS COMING FROM UNCOVERED UPPER HALF OF PLATE.

FIGURE 28
FIGURE 29

HIGH SPEED PHOTOGRAPHS OF 3/16 INCH TEMPERED GLASS SHATTERED BY 40 GRAIN PRIMACORD SPIRAL (PANEL VIEWED FACE-ON). TIME IN MILLISECONDS FROM INITIATION OF DETONATOR IS INDICATED.
FIGURE 30 SHATTERING OF 1/8 INCH PLATE GLASS BY 40 GRAIN PRIMACORD SPIRAL ILLUSTRATED BY SUPERPOSITION OF FEATURES FROM HIGH SPEED PHOTOGRAPHS. GLASS PANEL INITIALLY PAINTED EXCEPT FOR CENTRAL CROSS.
FIGURE 31

HIGH SPEED PHOTOGRAPHS OF 1/8 INCH PLATE GLASS SHATTERED BY 40 GRAIN PRIMACORD SPIRAL. TEST PANEL VIEWED EDGE-ON. TIME IN MILISECONDS FROM BEGINNING OF DETONATION IS INDICATED. DOTTED LINE IN FIRST FRAME INDICATES INITIAL POSITION OF THE 27 INCH EDGE OF THE GLASS. EXPLOSIVE CHARGE WAS ATTACHED TO BACK OF GLASS (LEFT SIDE IN THIS VIEW)
FIGURE 32
HIGH SPEED PHOTOGRAPHS OF 1/4 INCH TEMPERED GLASS SHATTERED BY 10 GRAIN MILD DETONATING FUSE GRID (VIEWED EDGE-ON). TIME IN MILLISECONDS FROM BEGINNING OF DETONATION IS INDICATED. VERTICAL TEST FRAME EDGE AT LEFT IS 27 INCH HIGH. CLOUD IS OBSERVED MOVING TO THE RIGHT.
MOTION OF FRONT OF CLOUD ADVANCING FROM 3/16 INCH TEMPERED GLASS SHATTERED BY 10 GRAIN MILD DETONATING FUSE GRID (PREPARED BY SUPERPOSITION OF TRACES FROM EDGE-ON VIEW HIGH SPEED FILM)
FIGURE 34

MOTION OF FRONT OF CLOUD FROM EXPLOSIVELY SHATTERED GLASS PANELS
FIGURE 35

MOTION OF FRONT AND REAR OF CLOUD
FROM 1/4 INCH TEMPERED GLASS PANEL
SHATTERED BY 10 GRAIN MILD DETONATING FUSE
GRID
FIGURE 36

HIGH SPEED PHOTOGRAPHS OF 3/16 INCH TEMPERED GLASS SHATTERED BY 2 GRAIN MILD DETONATING FUSE VIEWED EDGE-ON. TIME IN MILLISECONDS IS INDICATED FOR EACH EXPOSURE. VERTICAL LINE AT LEFT IS 27 INCH EDGE OF TEST PANEL. HORIZONTAL LINES AT RIGHT ARE BLAST PROBES SHOWN IN FIG. 23.
FIGURE 37

PERCENT OPEN AREA OF EXPLOSIVELY SHATTERED 1/4 INCH TEMPERED GLASS DIAPHRAGM (ESTIMATE BASED ON COMPARISON WITH GUN EXPERIMENTS)
BREAKING TIME OF RESISTANCE WIRES FASTENED TO FRONT OF PANELS SHATTERED BY PRIMACORD SPIRALS

FIGURE 38
EXPLOSIVE CONFIGURATION RECOMMENDED FOR NPD-2 DIAPHRAGM
FIGURE 40

COMPARISON OF EXPERIMENTAL CLOUD FRONT VELOCITIES WITH THEORETICAL GLASS FRAGMENT VELOCITY FOR COMPLETE ENERGY TRANSFER
FIGURE 41

DECAY OF SHOCK WAVE PRESSURE PEAK RESULTING FROM DETONATION OF PRIMACORD SPIRAL
APPENDIX A

Tabulation of Glass Shattering Experiments

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Glass Thickness (inch)</th>
<th>Spark Time Delays (millisec)</th>
<th>Over Pressure psig</th>
<th>Opening Delay φ (millisec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Viewing Parallel to Flow</td>
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<td></td>
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<tr>
<td>1</td>
<td>3/16*</td>
<td>5</td>
<td>5.5</td>
<td>6</td>
</tr>
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<td>1/4</td>
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</tr>
<tr>
<td>3</td>
<td>1/2</td>
<td>5</td>
<td>5.5</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>1/4</td>
<td>7.9</td>
<td>25.1</td>
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<tr>
<td>5</td>
<td>1/4*</td>
<td>.015</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>1/2*</td>
<td>.015</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
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<td>.020</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>1/4</td>
<td>.0096</td>
<td>.0139</td>
<td>15</td>
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<td>Viewing Normal to Flow</td>
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<td></td>
<td></td>
</tr>
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<td>3/16*</td>
<td>.030</td>
<td>5</td>
<td>15</td>
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<td>1/4</td>
<td>15</td>
<td>17.5</td>
<td>20</td>
</tr>
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<td>11</td>
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<td>15</td>
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<td>25</td>
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<td>12</td>
<td>1/2</td>
<td>20</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>13</td>
<td>1/2</td>
<td>20</td>
<td>25</td>
<td>30</td>
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<td>14</td>
<td>1/4</td>
<td>25</td>
<td>30</td>
<td>35</td>
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<tr>
<td>15</td>
<td>1/2</td>
<td>25</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>16</td>
<td>1/4</td>
<td>15</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

* Plate Glass
# Poor or incomplete break
φ From Time of impact to first motion of glass fragments
### APPENDIX B

#### Summary of Useful Test Runs

<table>
<thead>
<tr>
<th>Glass * Thickness (inch)</th>
<th>PETN (GR/ft)</th>
<th>Charge Geometry</th>
<th>Total Charge (Kgm)</th>
<th>High Speed Film No.</th>
<th>Camera Viewing Angle</th>
<th>External Illumination</th>
<th>Camera Framing Time (ms/frame)</th>
<th>Cloud Front Velocity (ft/sec)</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>1/8</td>
<td>40</td>
<td>Spiral</td>
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<td>1</td>
<td>Front</td>
<td>Direct</td>
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<td>-</td>
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<tr>
<td>1/8</td>
<td>40</td>
<td>Cross</td>
<td>0.31</td>
<td>2</td>
<td>Front</td>
<td>Direct</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1/8</td>
<td>40</td>
<td>Cross</td>
<td>0.31</td>
<td>3</td>
<td>Front</td>
<td>Direct</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1/8</td>
<td>40</td>
<td>Spiral</td>
<td>1.16</td>
<td>6</td>
<td>Side</td>
<td>None</td>
<td>0.17</td>
<td>-</td>
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<tr>
<td>1/8</td>
<td>40</td>
<td>Spiral</td>
<td>1.16</td>
<td>7</td>
<td>Front</td>
<td>None</td>
<td>0.18</td>
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<td>Spiral</td>
<td>1.16</td>
<td>1</td>
<td>Front</td>
<td>None</td>
<td>0.14</td>
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<td>Demonstration for CGE and AECL</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>Misfire</td>
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<td>Side</td>
<td>Direct</td>
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<td>10</td>
<td>Side</td>
<td>Direct</td>
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<td>-</td>
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<td>Direct</td>
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<td>Luminosity test - Spiral without glass</td>
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<td>Grid</td>
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<td>12</td>
<td>Front</td>
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<td>-</td>
<td>Blast probes used</td>
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<td>13</td>
<td>Side</td>
<td>Direct</td>
<td>1.36</td>
<td>385</td>
<td>Targets fixed to glass - Camera Failed</td>
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<td>0.49</td>
<td>15</td>
<td>Side</td>
<td>Shadow</td>
<td>0.16</td>
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<td>0.24</td>
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<td>Direct</td>
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<td>Wire suspended in front of glass panel</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot; &quot; &quot; &quot;</td>
</tr>
</tbody>
</table>

NOTE: *
- The 1/8 inch panels were plate glass and the 3/16 and 1/4 panels were tempered glass.
- The weight of PETN required for the full-scale NPD-2 installation using the test geometry.
- 1 gm = 15.43 grains, 1 kgm = 2.2 lbs.
- Length of explosive used = Spiral - 13 ft.
- Grid - 47 ft.
APPENDIX C

Blast Effects of Explosive Charge

General Remarks

The recommended charge configuration requires the use of 47 feet of MDF (at 10 grains PETN per foot) on each basic area of 6.75 sq. ft. (the size of the test panels in the present test program). The four glass panels proposed for the full-scale NPD-2 diaphragm each has an area of 27 sq ft. The total weight of PETN per panel will be 4 (47) (10) / 15.43 = 122 grams. The energy release from PETN on detonation is approximately 1400 cal/gm. Then the energy release per panel will be (122) (1400) = 17 x 10^4 cal = 680 BTU. For the entire diaphragm the energy release will be 2720 BTU.

Some idea of the significance of this energy release can be obtained by comparing it with the energy added to the boiler room by the D_2O issuing from the ruptured main coolant line. In calculating this latter energy release it appears reasonable to consider only the energy required to vaporize the D_2O steam and to neglect the energy remaining in the residual water. From Ref. 1, considering the case of complete mixing in an isolated boiler room, only 34.6% of the injected heavy water will be vaporized and an equilibrium temperature of 268°F will be achieved. The initial temperature of the injected fluid is 530°F, and its internal energy is (from Ref. 8) E_{f_i} = 478.6 BTU/lb. The internal energy of the residual water at the equilibrium temperature will be E_{f_r} = 202 BTU/lb. Then the energy required to vaporize the D_2O steam from 25,000 lbs of injected heavy water is

\[ Q = 25000 (E_{f_i} - (1-0.346)E_{f_r}) \]

\[ = 8.67 \times 10^6 \text{ BTU} \]  

(1)

The ratio of the energy released by the explosive detonation to that added to the room as internal energy of the D_2O vapour is then

\[ \frac{\text{Explosive Energy}}{\text{Steam Energy}} = \frac{2.72 \times 10^{-3}}{8.67} = 0.00031 \]  

(2)

On this basis of comparison the effect of the explosive charge is of negligible importance. Furthermore, a considerable portion of the released energy will be converted into kinetic energy of the glass fragments. This is considered in more detail below.

Energy Absorption by Glass

Consider a glass diaphragm of area A sq. ft., thickness \( \delta \) ft and density \( \rho \) slugs/ft^3. Suppose the total amount of energy, \( H \), released by the explosion is converted into kinetic energy of this mass of glass. Then if all the glass fragments travel at the same velocity, \( V \) ft/sec,
\[ H = \frac{1}{2} \delta \rho V^2 \]  

(3)

and, with \( H \) expressed in BTU

\[ V = 39.5 \sqrt{\frac{H}{A \delta \rho}} \]  

(4)

This expression represents the maximum possible cloud velocity assuming complete and uniform energy transfer. In the present case \( \rho = 160 \text{ lb/ft}^3 = 4.97 \text{ slug/ft}^3 \), \( A = 109 \text{ ft}^2 \) and for 10 grain MDF \( H = 2720 \text{ BTU} \) (from above). Then

\[ V = 88.3/\sqrt{\delta} \]  

(5)

A plot of equation (5) is shown in Fig. 40 and is compared with the measured cloud front velocities listed in Appendix B. It is observed that the measured velocities are much less than the theoretical. This indicates, as would be expected, that complete energy transfer does not occur. If it is assumed that only 50 percent energy transfer is achieved the theoretical curve of Fig. 40 would be lowered by \( \sqrt{2} \) and would fall closer to the experimental points for 10 grain MDF.

The rupture energy of the glass panel and the dissociation energy of the hot combustion products have been ignored in these calculations.

Decay of Blast Pressures

That portion of the explosive energy which appears in the form of blast pressure will be divided between a plane shock wave travelling into the relief duct and a hemispherical shock wave travelling into the boiler room. The former wave will assist in establishing duct flow and the latter, being spherical, will decay rapidly and will not significantly affect the flow development in the room. The measured decay of pressures from a Primacord spiral detonated in air is plotted in Fig. 41.

It may be concluded that the detonation of the explosive charge will neither adversely affect the pressure relief duct flow nor damage the equipment within the boiler room.