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Assessment, Development, and Testing of Glass for Blast Environments

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Assessment, Development, and Testing of Glass for Blast Environments

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Abstract

Glass can have lethal effects including fatalities and injuries when it breaks and then flies through the air under blast loading ("the glass problem"). One goal of this program was to assess the glass problem and solutions being pursued to mitigate it. One solution to the problem is the development of new glass technology that allows the strength and fragmentation to be controlled or selected depending on the blast performance specifications. For example the glass could be weak and fail, or it could be strong and survive, but it must perform reliably. Also, once it fails it should produce fragments of a controlled size. Under certain circumstances it may be beneficial to have very small fragments, in others it may be beneficial to have large fragments that stay together. The second goal of this program was to evaluate the performance (strength, reliability, and fragmentation) of Engineered Stress Profile (ESP) glass under different loading conditions. These included pseudo-static strength and pressure tests and free-field blast tests. The ultimate goal was to provide engineers and architects with a glass whose behavior under blast loading is less lethal. A near-term benefit is a new approach for improving the reliability of glass and modifying its fracture behavior.

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Contents

Introduction

Work at Sandia National Laboratories in Albuquerque focused on three aspects of the glass blast problem. Sandia's Architectural Surety® program assesses the overall performance of buildings, facilities, and other infrastructure systems under normal, abnormal, and malevolent threat conditions (including terrorist bombings).[1] Section 1 of this report is a review of glass performance in blast environments and an assessment of some of the measures being used to mitigate the glass problem.

The second part of the program involved research directed toward modifying glass properties to obtain controlled fracture. Approaches investigated previously included modifying strength by the introduction of controlled flaws (indentations) and by spot annealing of thermally tempered glass.[2] Engineered Stress Profile (ESP) glass, developed at Penn State University and at the Universita' di Trento in Italy, was identified as a glass that could provide the controlled fracture properties that were needed. As part of this Laboratory Directed Research and Development (LDRD) program development and testing of ESP glass continued at Sandia and at the two universities.

ESP glass is produced using a two-step ion exchange process. This process results in a high compressive stress just below the glass surface that overcomes the high strength variability and catastrophic failure that is typical of glass. Strength distributions for ESP glass are very narrow. Cracks initiate only at intermediate stresses and they subsequently arrest. The glass fragment sizes can be controlled by changing the ion exchange time and/or temperature. Engineered stress profiles were obtained for both specialty glass compositions and soda lime silica glass.[3] General information about ESP glass can be found in Section 2. Detailed information can be found in the references cited in the next paragraph.

Research on ESP glass included evaluations of the strength properties and effects of surface damage on strength and crack propagation,[4] multiple cracking behavior, and the fragmentation behavior.[5,6] Finite element calculations were used to assess the effects of the multiple cracking behavior on crack shielding and on the strength of ESP glass as a function of loading rate.[7] Two new approaches for producing ESP glass were investigated. One used an ion exchange treatment followed by a heat treatment[8] and the other using an electric field to enhance the diffusion of the ions into the surface during the ion exchange.[9]

The final part of the program was an evaluation of the behavior of ESP glass in a blast environment. The focus of this part of the program was to measure and identify the blast parameters that cause failure of the glass and to develop an understanding of the relationship between static and dynamic fracture properties of glass. Free-field blast tests of small-scale samples were conducted to determine the pressure threshold and impulse to cause failure. Information about this testing can be found in Section 3.

References

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[1] R. V. Matalucci and S. O'Connor, "When Materials Matter-Analyzing, Predicting, and Preventing Disasters," Materials Research Society Conference Proceedings, San Francisco, Apr. 24-28, 2000.

[2] S. J. Glass, M. Abrams, and R. V. Matalucci, "New Glass Technologies for Enhanced Architectural Surety®: Engineered Stress Profiles (ESP) in Soda-Lime-Silica Glass," Sandia National Labs Report SAND2000-3001, Albuquerque, NM, Dec. 2000.

[3] E. K. Beauchamp and R. V. Matalucci, "Dynamics of Window Glass Fracture in Explosions," Sandia National Laboratories Report SAND98-0598, May 1998, Albuquerque, NM.

[4] M. B. Abrams, D. J. Green, and S. J. Glass, "Fracture Behavior of Engineered Stress Profile Soda Lime Silicate Glass," J. Non-Crystalline Solids, accepted for publication, Apr. 2003. (SAND2003-0292J)

[5] R. Tandon and S. J. Glass, "Controlling the Fragmentation Behavior of Stressed Glass," to be published in Fracture Mechanics of Ceramics, Vol. 14-15, proceedings of the 8th International Symposium on Fracture Mechanics of Ceramics, February 25-28, 2003, Houston, TX. (SAND2003-0775J)

[6] S. Kamat, E. K. Beauchamp, S. J. Glass and R. Tandon. "Finite Element Analysis of Fragmentation of Tempered and Ion-Exchanged Glass," in preparation.

[7] S. Kamat, E. K. Beauchamp, S. J. Glass and C. S. Watson, "Crack Shielding Effects on the Dynamic Strength of Engineered Stress Profile (ESP) Glass," in preparation.

[8] Personal communication from E. K. Beauchamp.

[9] C. S. Watson, "Modification of Glass Properties Using Ion Exchange Techniques," M. S. Thesis, New Mexico Institute of Mining and Technology, May 2001.

Assessment of the Glass Fracture Problem

This section of the report is an assessment of the problem of glass fracture in buildings that are subjected to terrorist bombings. It also describes some of the solutions that are being proposed or used to mitigate the problem and identifies some of issues associated with these choices.

Glass is a material with wonderful attributes that are often taken for granted. It is transparent, it has good chemically durability, it is made from cheap, readily available materials, and it is easy to form into numerous shapes, sizes, and thicknesses. Largely as a result of these properties it is heavily used in modern construction for architectural glazing (glass made to be set in frames). Glass is also being used in increasing quantities and in novel ways in recent construction, including being used as structural elements.[1,2] The normal function of glass in architectural applications is to provide a transparent barrier between the inside and outside, protecting the building occupants and the interior from the elements. Except in locations in which earthquakes are a concern the only structural performance requirement for a window is that it resists a specific wind loading. This specification is covered in ASTM E1300-98 (Standard Practice for Determining the Load Resistance of Glass in Buildings).[3] Failure of the window is defined as when it breaks. Other standards for glass performance are available.[4,5,6,7]

The different types of glazing materials that are used in architectural applications include:

- Monolithic glass
    - annealed
    - heat strengthened
    - thermally tempered
    - chemically strengthened
- Laminated glass
    - glass-clad polycarbonate
    - glass with PVB or resin interlayers
- Plastic glazing
    - polycarbonates
    - acrylics
- Insulating glass (can be combinations of any of the above products)
- Wire-reinforced glass for fire safety
- Glass with safety film (a clear polyester film adhesively bonded to the inside or outside)
- Glass block

One glass property that cannot be taken for granted is its brittleness. This means that it fails catastrophically without warning at stresses well below its theoretical strength. It also has very low reliability, i.e., it fails over a wide range of stresses. When glass breaks the resulting pieces (shards) are usually large and have sharp edges.

The property that is most important in controlling glass failure is its strength. Critical glass strength characteristics are the sensitivity of the strength to surface flaws[#], the strength variability, and the effect of loading rate on strength. The strength of glass is inversely proportional to the square root of the size of the largest flaw. The flaw sizes that produce failure in glass are small, often in the range of 50-250 microns (2-10 mil). Glass, like other brittle materials, exhibits wide variability in strength, typically in the range of ±25%.[8] This

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[#] Flaw = any feature in the glass that causes a stress concentration, e.g., scratch, impurity, impact damage. The use of the word flaw does not imply that it has been manufactured improperly.

variability is due to the wide distribution of flaw sizes in each glass sample and therefore a distribution in the size of the largest flaw for a group of samples. This strength variability may translate to windows in the same location, nominally under the same loading conditions, failing at very different loads, e.g., 1 vs. 2 psi for blast loading. The larger the glass sample or panel, the more likely that a flaw of a critical size will be present; thus lower strengths are measured for samples with a larger area or volume. Weathering of glass, due to exposure to the environment, can also lead to lower strengths of glass.[9] Weathering changes the surface condition of the glass, presumably increasing the number and size of flaws.

Different treatments can be used to strengthen the glass including thermal tempering and chemical strengthening (ion exchange). These treatments, which lead to precompression of the surface, can increase the glass strength by three to five times and they also result in the glass breaking into small fragments when it fails. The fragmentation occurs because of the release of energy stored in the tensile region in the interior of the glass.

The measured strength of glass increases as the loading rate increases, at least over the range of loading rates that are measured in conventional strength tests.[10] This time-dependence of the strength, which is due to subcritical crack growth (an environmental effect), has two implications for the behavior of glass windows. First, the glass strength is degrading over time in any environment in which the glass is being stressed; hence older glass will typically be weaker. Second, during an actual blast event the glass-stressing rate (how fast the glass is loaded by the air blast) may play a role in determining whether or not the glass fails. Most types of blasts load the glass very rapidly as the air blast propagates at supersonic velocity. The blast pressure typically reaches it peak value in a fraction of a second. Loading rates in free-field explosion tests have been estimated to be on the order of 200-500 psi/sec.[11] The parameters that define the characteristics of the blast are the magnitude of the overpressure (peak pressure), the impulse, which is defined as the area under the pressure-time curve, and the shape and rise time of the pressure pulse. Shorter rise times are usually worse in terms of their effects.[12]

Architects and designers select glass thickness and area for architectural applications using published standards.[13] These standards are based on industrial practice and experience; controlled test results for glass under wind loading, which is essentially static loading; and glass failure prediction models. Most glass failure prediction models incorporate both the strength variability and time-dependence of strength in some manner; however, these models have been used primarily for loading under conditions in which the pressure is uniform and did not change rapidly.[14] It is important not to use these models for conditions outside the regime for which they were developed and tested. Although failure prediction models for monolithic annealed glass can give predictions that match experiment results, the failure of glass laminates is much more complex and significantly less well understood.[15]

Glass failure occurs in a different manner under the extremely rapid loading rates and high pressure that are achieved in a blast environment than under the pseudo-static loading conditions under which glass strength is normally measured,[16] or assumed to occur under wind loading where the loading duration in ASTM E 1200-2000 is defined to be 60 seconds. In blast environments the large plates of glass that used in buildings often experience lateral deflections that greatly exceed the glass thickness. As a result membrane stresses can develop. In this case the tension that is developed in the plate can be very different than that predicted by elastic theory.

Data that describes and specifies the behavior and failure of glass in blast environments is very limited. Additionally, there is a great deal of variability in quoted overpressures that cause glass failure, ranging from 0.5-4.3 pounds per square inch (psi).[17] Some of the variability can be explained by the fact that not all of the failures occur in the positive pressure phase of the blast. Under certain conditions the negative phase may be more likely to cause failure.[18] This is the reason that glass is often found outside the building. Some of the many factors that influence glass failure under blast loading are the type and proximity of the blast, atmospheric conditions,[19] the thickness and area of the glass (breaking pressure is inversely related to the square of the glass dimensions), the attachment and framing method, and the glass properties, primarily the strength and stiffness. The glass strength will vary depending on the type of glass (e.g., annealed, thermally tempered, laminated, etc.) and the age and condition of the glass.

One set of criteria used to define the blast resistance of various glazing materials is shown in Table 1.[20] Failure is defined by the blast load that is calculated to produce a maximum principal stress in the window that exceeds the design stress. The values in the table are based on a failure probability of P_f=0.001. Note that other standards specify different values and that there is a great deal of variability in the strength data for different materials and the underlying assumptions about that data.[21]

Table 1. Design stress values for glazing materials.

Glazing	Maximum Stress (ksi)	Maximum Stress (MPa)
Annealed Glass	4	28
Semi-Tempered Glass	7.6	52
Chemically Strengthened	8	56
Thermally Tempered Glass	16	110
Polycarbonate	9.5	86

The many factors that determine the blast strength of glass are often not systematically varied even during controlled blast testing. In addition, much of the available blast data has been collected for uncontrolled explosions, for which many of the parameters, including the blast pressure, could only be estimated.[22] The time and expense required to conduct large-scale tests of glass in building settings are large and usually prohibitive. For example, a set of tests conducted by DTRA's Antiterrorism Program on Kirtland Air Force Base in Sept. 2001 cost approximately $750,000 per test.[23] The high cost of the tests is due to the need for extensive instrumentation, security, manpower needed to analyze the data, and due to the cost of structures that need to be built or rebuilt to conduct the tests.

Window performance data from blast tests are also very limited and sometimes of questionable value, given the some of the uncontrolled conditions and the expected variability in the response of the windows in different locations. Even under the much more controlled conditions of shock-tube testing, there is a limited amount of data that can be collected when only one or two panes of glass of a given condition can be tested at each pressure. The current test standard (F1642-96) specifies "a minimum of three test specimens representative of a glazing or glazing systems shall be tested a given level of airblast..."

The critical role of broken glass in the injuries and fatalities, both at ground zero of a blast and in the vicinity, has been recognized.[24] Excluding the Murrah Building victims, 39% of the people injured in the Oklahoma City bombing suffered glass related injuries.[25] Information about blast effects on glass, including the effect of peak blast pressure on object velocity and the velocities of objects as a function of size is available along with information about glass penetration wounds.[26] Windows that stay together as they are blown out of their frames tend to have significantly lower velocities than window fragments. The higher the pressure the higher the glass shard velocity, with a pressure of 1.9 psi giving velocities of 108 ft/sec and a pressure of 8.5 psi giving a velocity of 286 ft/sec. Failed glazing often leads to other injuries due to the direct exposure of the occupants to the air blast including hearing injuries, thrown body impact, and secondary debris impact.[27]

Glass breakage requires relatively low overpressures; therefore glass can fail in a wide area around a blast. In the 1995 Alfred P. Murrah Federal Building explosion in Oklahoma City, glass in some 300 nearby buildings was broken and glass in buildings as far away as one mile was broken. Flying glass shards injured more than 400 people.[28] In the 1945 Trinity Test the blast was reported to have broken windows in Silver City, NM and possibly as far away as Gallup, NM.

Terrorist bombings and the resultant fatalities, injuries, and property destruction have become of increasing concern to the General Services Administration (GSA), the US Department of Defense (DoD), the US State Dept., the Defense Threat Reduction Agency (DTRA), the United States Air Force (USAF) Force Protection Battlelab, the US Army Corps of Engineers Waterways Experimental Station, and the US Department of Energy (DOE), including Sandia National Labs. Much of the concern and the resultant blast mitigation activities were prompted by the bombing of the Marine barracks in Beirut in 1983. Following the bombing of the Murrah Federal Building in Oklahoma City blast mitigation for US federal and military facilities has become an even higher priority for the government. Other events that spurred further interest in blast mitigation and glass failure were the bombings of the Khobar Towers in Saudi Arabia in 1996, and the US Embassies in Nairobi, Kenya and Dar es Salaam, Tanzania in 2000, and the Sept. 11, 2001 tragedy. Commercial glass vendors and their association (Protective Glazing Council) and architects and engineers have also been considering, evaluating, and implementing "solutions" to the problem of glass breakage.[29] Because of the complexity of the problem there is no one single solution that fits all needs.[30]

Because of the huge number of buildings at risk (GSA alone manages 8000 federal buildings nationwide), prioritization for blast mitigation retrofits is necessary and is being done using tools such as RAMPART (Risk Assessment Method — Property Analysis and Ranking Tool), software developed by Sandia National Laboratories for the GSA. RAMPART is risk-based approach to building management to assess the risks of terrorism, natural disasters and crime. RAMPART looks to the future probability of events occurring and what there is to lose if those events take place.[31]

Blast mitigation activities by the various groups listed above include research aimed at characterizing blast effects, quantifying the structural response, understanding and classifying the injuries that result from each of these factors, [32] and the development, design and testing of technologies that minimize the effect of the building materials failure in new construction and in retrofits. The numerous approaches for minimizing the glass hazard in a blast can be categorized as follows:

- Eliminate the glass
- Minimize the use of glass, especially in vulnerable areas
- Prevent glass fracture by increasing its blast resistance by:

  - Using thicker glass
  - Decreasing the area of the window
  - Strengthening the glass[@]
- Maintain the glass in place following fracture using:
  - Laminated glass
  - Self adhesive window films
  - Mesh curtains
  - Blast bars
- Minimize the size and velocity of glass fragments by controlling the glass fracture behavior

Many of these solutions will not be adopted by building owners and managers for practical, financial, or esthetic reasons.[33] There is always going to be a tug-of-war between the actions needed to enhance the safety, the needs for attractive, livable and functional workspace, and the costs associated with any modifications.

New buildings can be designed to eliminate or minimize glass exposure where the building is most vulnerable. The best approach for protecting buildings and minimizing glass failure is to provide sufficient standoff between the structure and potential locations for vehicle-based bombs. This is less intrusive and costly than using thick walls and small windows of bulletproof glass.

In the huge number of existing buildings, where increased standoff or removing the glass are not options, the structure including the windows may need to be modified to strengthen (or harden)it to the assumed threat. The primary objective of the remainder of the approaches has been to prevent glass fracture or to minimize the quantity of flying glass shards. Some windows are being replaced with new glass products and existing windows are being covered with a limited-lifetime adhesive film. Minimizing the quantity of flying glass shards was the subject of a recent review on blast-resistant glazing by Norville and Conrath.[34] They recommend the use of laminated glass to reduce flying and falling glass shards, to maintain closure of the fenestration, and to minimize the need for immediate replacement. Their focus is not on preventing the glass from breaking, but controlling its post-fracture behavior to eliminate or minimize flying or falling glass. Other ways to minimize flying glass after fracture are to use mesh curtains and catch bars.

One key consideration for the solution to the glass problem is that not all of the glazing needs to receive the same degree of attention (or protection or reinforcement). Another key consideration is that whatever is done to the glass to enhance its blast performance must allow the glass to perform its normal functions without significant additional cost or maintenance.

Evidence that hardened windows can protect personnel is provided by the performance of the new windows in the renovated section of the Pentagon when it was struck by an airplane on Sept. 11, 2001. Recently completed retrofits to the structure included installing thermally tempered and laminated windows designed for blast resistance. Many of these windows did not fail even when they were exposed to the aircraft fuel fireball, thereby preventing fire from entering many of the offices around the crash location.[35]

Some glass modifications and building designs are being made with little or no supporting scientific evidence that they are safety improvements, especially when the overall response of the building is considered. Some actions taken to "improve" glass safety may degrade

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[@] Increasing the thickness does not increase the intrinsic glass strength. The load carrying capacity or failure pressure, which are both size and thickness dependent, is increased.

the glass strength, its regular performance, or put new loads on it that cause it to fail under "normal" operating conditions. For example, the application of surface films may damage the underlying glazing and degrade its strength when the film is installed improperly. The film itself is easily scratched and can become hazy. It is also difficult to avoid bubbles between the film and the window when it is installed.

Modifications that are aimed at preventing the glass from breaking may result in a greater degree of loading of a buildings' structural elements and may lead to partial or full building collapse. When windows break they can serve as pressure relief valves.[36] Stronger and/or thicker windows also require stronger frames and frames that are secured to the building with more robust attachments to prevent the unbroken strengthened window and its frame from being blown into the building.

An unintended consequence of using thick, laminated glass to strengthen windows and to prevent their fracture is that this may hamper rescue and recovery, and fire-fighting efforts. One of the difficulties in fighting the fires at the Pentagon on Sept. 11 was the great difficulty fire department personnel had in penetrating the windows to gain access to the building's interior. Smoke inhalation injuries and deaths can become a greater risk when the glass cannot be broken to allow venting. Escape from a building may also depend on the ability of the occupants to penetrate the glass.

There are several technical manuals available within the DoD to aid its engineers in the design of structure subject to blast loadings including TM5-855-1.[37] There is information in this manual about protective design for conventional weapons that has direct application to security engineering. The blast analysis and design tools created for the military can be applied to the design and construction of civilian structures.

Engineers and architects are just beginning to systematically consider malevolent threats including explosions during the design, construction, and retrofit phases of buildings and facilities. The selection of glass for a potential explosive environment is a critical component of these new activities given the hazardous effects of glass breakage under blast-loading conditions. One of the existing test standards for glazing (ASTM F 1642-96)[38] is currently being revised to incorporate information on blasts due to bombs rather than just considering the risks associated with accidental explosions. This will allow users to collect the necessary data to meet safety requirements for a specific design threat bomb.[39] The GSA has also adopted a standard test method,[40] which is a modified version of ASTM 1642-96, and a standard test protocol.[41] They both include performance criteria or protection levels that rate the tested glazing or glazing system in terms of the location of the glass or fragments after explosive testing as shown in Table 2. These criteria were adopted from a rating system developed in the UK and have been used by GSA and its contractors in testing conducted since 1996.

Table 2. Summary of the GSA requirements for glass for each protection level.

Performance Condition	Protection Level	Hazard Level	Description of Window Glazing Response
1	Safe	None	Glazing does not break. No visible damage to glazing or frame.
2	Very High	None	Glazing cracks but is retained by the frame. Dusting or very small fragments near sill or on floor acceptable.
3a	High	Very Low	Glazing cracks. Fragments enter space and land on floor no further than 3.3 ft. from the window.
3b	High	Low	Glazing cracks. Fragments enter space and land on floor no further than 10 ft. from the window.
4	Medium	Medium	Glazing cracks. Fragments enter space and land on floor and impact a vertical witness panel at a distance of no more than 10 ft. from the window at a height of no greater than 2 ft. above the floor.
5	Low	High	Glazing cracks and window system fails catastrophically. Fragments enter space impacting a vertical witness panel at a distance of no more than 10 ft. from the window at a height no greater than 2 ft. above the floor.

In addition to the GSA (General Services Administration), there are many other federal agencies that are involved in setting standards and specifications for protective glazing for federal facilities including the:

- Federal Emergency Management Agency
- Dept. of Defense
- Army Corps of Engineers
- Dept. of Justice
- US Marshall's Service
- State Dept.
- Office of Chief Architect
- Dept. of Transportation
- Dept. of Energy

There are several analysis codes that allow users (civil engineering and construction professionals) to determine the expected loading on glazing due to wind loads and blasts and to predict the performance and hazards associated with various types of glazing. These include:

- AT Blast
- BLASTOP
- Blast Resistant Glazing Design for Architectural Applications (BRGD)
- Comprehensive Window Glass Design (CWGD) and GWDG PLUS
- HAZL*
- SAFEVUE
- WinDAS*
- Window Glazing Analysis Response and Design (WINGARD). Available from GSA (www.oca.gsa.gov). This program is the GSA and ISC standard for windows subjected to blast loading.

- Window Lite Analysis Code (WINLAC).* Available from the Dept. of State. Versions higher than 4.0 are derivative versions of WINGARD and are adapted to meet US Dept. of States' unique requirements.
- Wind Loads on Structures According to ASCE7 (WLS)

* These programs also include information on the post-fracture behavior of glass

Exploratory research was previously conducted at Sandia National Labs to examine the possibility of modifying fracture of glass in the blast environment.[42] The intent was to explore strategies that would change the glass fracture leading to the reduction in the number and severity of injuries in the blast environment. The work compared the fracture and post-fracture fragment behavior of annealed and thermally tempered glass both in the as-processed state and for glass that was deliberately weakened. The approach pursued in the present project to help address the glass problem was to conduct research on how to control the glass fracture, both in terms of narrowly defining the glass strength and strength distribution, and in terms of controlling the glass fragmentation (fragment size). Research on the glass processing and its properties including its performance in a blast environment were conducted as two parts of this effort and are the subjects of the remainder of the report. The glass that was developed and tested in collaboration with Penn State University and the Universita' di Trento in Italy is called Engineered Stress Profile (ESP) glass.[43,44] The strength and cracking behavior of ESP glass is controlled by producing a specified residual stress profile at the glass surface.[45,46,47] The fragmentation behavior is controlled by magnitude of the central tension and the glass thickness.[48] Work was also conducted in a previous project that showed that beneficial stress profiles could be created in glass with a soda lime silicate composition, the glass composition that is most commonly used for architectural and automotive glass applications.[49]

Summary

- Glass is a brittle material. Therefore its practical strength is low and its strength variability is high. It normally breaks into large shards with sharp edges.
- Glass fracture is a safety risk to people in buildings exposed to adverse environments (terrorist attacks, natural gas explosions, abnormal weather, etc.). Many deaths and injuries in these events are due to flying glass. The risk of hearing injuries, thrown body impact, and secondary debris impact are also increased when building windows are broken and the occupants are directly exposed to the air-blast.
- Glass fracture (The "glass problem") has received a significant amount of attention from various groups, government agencies, and companies since the bombing of the Marine barracks in Beirut in 1983 and the bombing of the Oklahoma City Murrah Federal Building in 1995.
- The glass problem is being addressed by a wide variety of participants including glass manufacturers, manufacturers of the adhesive materials used in laminated glass and for the adhesive films used on the exterior of glazing, users (architects, engineers, safety personnel), government agencies and the military, government and private labs, universities, and standards committees.
- Because of the urgent concern for personnel safety, modifications are being made to windows in existing buildings and in the design of new buildings to prevent glass from fracturing or to control or eliminate flying glass.
- Glass modifications and other proposed solutions to the glass problem may not be based on scientific principles. Some modifications may make the glass problem worse or create new problems.

- Glass behavior and the solution to the glass problem should not be considered in isolation. The overall building response and other factors (e.g., fire and rescue) need to be addressed.
- Blast behavior (dynamic loading) of glass was not considered in the standards used in the construction of most existing buildings. Most current standards for selecting glass for architectural glazing are based on glass behavior under what is an essentially static loading condition. New standards are just being written and implemented that address air blast loading conditions due to bomb explosions.
- Blast testing of glass is being conducted to help understand the problem and to evaluate proposed solutions. Tests are generally expensive, the results are not widely available, and they need a solid scientific underpinning before they are used to substantiate the selection of one type of glass (and framing) over another. Tests are usually done on a very limited number of samples.

Conclusions and Recommendations

- The glass problem can only be solved through a coordinated effort by government agencies, glass and adhesive manufacturers, framing providers, architects and engineers, and the research community. Coordination of diverse and parallel efforts will provide the greatest benefit to the public.
- There is a need to develop standards that are based upon the results of validated and calibrated tests. A suggested starting point is the development of a science-based methodology that allows comparisons to be made between different types of blast tests with different types of glass, with different thicknesses and areas. From the blast-loading perspective, this will require an examination of the scaling behavior in blast tests, an understanding of the relationship between different blast environments, and an understanding of the scaling behavior of different sizes and shapes of glass windows in blast tests. From the glass perspective, this study should include an evaluation of the effects of glass surface condition (flaw size distribution) and the effects of loading rate in the explosive loading rate regime. The final goal should be a standardized test, or series of tests that will allow engineers, glass manufacturers, research personnel, and users to be able to make valid comparisons of different glasses and glass systems.
- Validated glass performance data and tools for glass selection should be readily accessible not only to government users, but also to industry.

References

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[1] S. Behling, "Glass Technology Live! Building the World Without Destroying the Environment," pg. 15-19 in International Glass Review," Issue 3, 2000.

[2] *Glass-Structure and Technology in Architecture*, Edited by S. Behling and S. Behling, Prestel, 2000.

[3] ASTM E998 - Standard Test Method for Structural Performance of Glass in Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Nondestructive Method

[3] ASTM E1300-98 - Standard Practice for Determining the Load Resistance of Glass in Buildings.

[4] ASTM E1886 - Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors and Storm Shutters Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials

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[5] ASTM E1996 - Standard Specification for Performance of Exterior Windows, Curtain Walls, Doors and Storm Shutters Impacted by Wind Borne Debris in Hurricanes

[6] ASTM E330 - Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference

[7] ASTM E997 - Standard Test Method for Structural Performance of Glass in Exterior Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Destructive Method

[8] R. W. Davidge, *Mechanical Behavior of Ceramics*, Cambridge University Press, New York, 1986.

[9] H. S. Norville and J. E. Minor, "Strength of Weathered Window Glass," Am. Ceram. Soc. Bull., 64 [11] 1467-70 (1985).

[10] D. J. Green, *An Introduction to the Mechanical Properties of Ceramics*, Cambridge University Press, New York, 1998.

[11] H. S. Pal and W. Pennington, "Strength of Window glass Plates Subjected to Rapid Loading," Texas Civil Engineer, pg. 11-16, Apr. 1988.

[12] R. Lane, B. Craig, and W. Babcock, "Material EASE-Materials for Blast and Penetration Resistance," AMPTIAC Quarterly, 6 [4] pg. 39-45, (200?).

[13] A. C. Fischer-Cripps and R. E. Collins, "Architectural Glazings: Design Standards and Failure Models," Building and Environment, Vol. 30, No. 1, pp. 29-40, 1995.

[14] A. C. Fischer-Cripps and R. E. Collins, "Architectural Glazings: Design Standards and Failure Models," Building and Environment, Vol. 30, No. 1, pp. 29-40, 1995.

[15] S. J. Bennison, A. Jagota, and C. Anthony Smith, "Fracture of Glass/Poly(vinyl butyral) (Butacite®) Laminates in Biaxial Flexure," J. Am. Ceram. Soc., 82 [7] 1761-70 (1990).

[16] ASTM C 1161-02b, Standard Test Method for Flexural Strength for Advanced Ceramics at Ambient Temperature.

[17] D. K. Pritchard, "Breakage of Glass Windows by Explosions," J. Occupational Accidents, 3, pp. 69-85 (1981).

[18] T. Krauthammer and A. Altenberg, "Negative Phase Blast Effects on Glass Panels," International Journal of Impact Engineering, 24, p. 1-17 (2000).

[19] J. Reed, "Climatological Assessment of Airblast Propagations from Explosion Tests at White Sands Missile Range," Sandia National Labs Report SAND86-1346, Aug. 1986.

[20] P. F. Mlakar, "Security Window Design," pp. 5-1 to 5-20 in Structural Design for Physical Security – State of the Art Practice, American Society of Civil Engineers, 1999.

[21] H. S. Norville, P. M. Bove, D. L. Sheridan, and S. L. Lawrence, "Strength of New Heat Treated Window Glass Lites and Laminated Glass Units," J. Struct. Engr., 119 [3] pp. 891-901 (1993).

[22] R. J. Mainstone, "The Response of Buildings to Accidental Explosions," pp. 173-88 in Proc. Inter. Conf on the Performance of Building Structures, Published by Pentech Press, Devon, England, 1976.

---

[23] M. Navrot, "Blast Could Make Buildings More Attack-Proof," Albuquerque Journal, Aug. 29, 2001.

[24] S. Mallonee, S. Shariat, G. Stennies, R. Waxweiler, D. Hogan, and F. Jordan, "Physical Injuries and Fatalities Resulting from the Oklahoma City Bombing," JAMA, Aug. 7, 1996, V. 276, No. 5, pp. 382-387.

[25] H. S. Norville, N. Harvill, E. J. Conrath, S. Shariat, and S. Mallonee, "Glass-Related Injuries in Oklahoma City Bombing," J. of Performance of Constructed Facilities, pp. 50-56, May 1999.

[26] S. Glasstone and P. J. Dolan, The Effects of Nuclear Weapons, 3rd Edition, Published by the US Dept. of Defense and the Energy Research and Development Administration, 1977.

[27] Army Report TM 5-1300, "Structures to Resist the Effects of Accidental Explosions," Nov. 1990.

[28] H. S. Norville, J. L. Swofford, M. L. Smith, and K. W. King, "Survey of Window Glass Broken by the Oklahoma City Bomb on April 19, 1995," Revised, March 1996.

[29] Protective Glazing Council, "A White Paper on the Fenestration Industry Focus on Protective Glazing Systems." Sept. 20, 2002.

[30] E. E. Hinman, "Blast-Mitigating Window Design," Structural Engineer, Nov. 2000.

[31] R. L. Hunter and B. Healey, "RAMPART: Status and Planned Improvements, Presentation and Proceedings of PSAM6: International Conference on Probabilistic Safety Assessment and Management, June 23-28, 2002, San Juan, Puerto Rico.(SAND2002-0294C)

[32] W. Babcock and D. Rose, "US Government Initiatives Reduce Terrorist Threat to Personnel and Structures," AMPTIAC Quarterly, Vol. 6, No. 4, Special Issue 2002.

[33] P. F. Mlakar, "Security Window Design," pp. 5-1 to 5-20 in Structural Design for Physical Security – State of the Art Practice, American Society of Civil Engineers, 1999.

[34] H. S. Norville and E. J. Conrath, "Considerations for Blast-Resistant Glazing Design," J. Architectural Engr., Sept. 2001, pp. 80-86.

[35] D. Coltharp and R. L. Hall, "Blast Retrofit Research and Development: Protection for Walls and Windows," AMPTIAC Quarterly, Vol. 6, No.. 4, Special Issue 2002.

[36] R. J. Harris, M. R. Marshall, and D. J. Moppett, "The Response of Glass Windows to Explosion Pressures," 6th I. Chem. E. Symposium Series No. 49, pg. 83-97, 1977.

[37] Army Report TM 5-855-1, Fundamentals of Protective Design for Conventional Weapons.

[38] ASTM F1642-96. Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings.

[39] "New Methodology for Blast-Resistant Glass is Designed to Reduce Flying Shards from Explosions," pg. 12 in ASTM Standardization News, April 2003.

[40] US General Services Administration (GSA) Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings.

---

[41] US General Services Administration (GSA) Standard Test Method for Glazing and Window Systems Subject to Dynamic Overpressure Loadings. GSA Test Protocol GSA-TS01-2003, Jan. 2003.

[42] S. J. Glass and R. V. Matalucci, "Preliminary Results of Blast Testing of Engineered Stress Profile Glass," Sandia National Laboratories Report to the USAF Force Protection Battlelab, Nov. 15, 2001.

[43] S. J. Glass, M. Abrams, and R. V. Matalucci, "New Glass Technologies for Enhanced Architectural Surety®: Engineered Stress Profiles (ESP) in Soda-Lime-Silica Glass," Sandia National Labs Report SAND2000-3001, Albuquerque, NM, Dec. 2000.

[44] D. J. Green, R. Tandon, and V. M. Sglavo, "Crack Arrest and Multiple Cracking in Glass Through the Use of Designed Residual Stress Profiles," Science, Vol. 283 (5406) pp. 1292-1295, Feb. 26, 1999.

[45] V. M. Sglavo and D. J. Green, "Flaw Insensitive Ion-Exchanged Glass: I Theoretical Aspects," J. Am. Ceram. Soc., 84 [8] 1827-1831 (2001).

[46] V. M. Sglavo and D. J. Green, "Flaw Insensitive Ion-Exchanged Glass: II Production and Mechanical Performance," J. Am. Ceram. Soc., 84 [8] 1832-1838 (2001).

[47] D. J. Green, V. M. Sglavo, E. K. Beauchamp, and S. J. Glass, Using Designed Residual Stress Profiles to Produce Flaw-Tolerant Glass," Fracture Mechanics of Ceramics, Vol. 13, pp. 99-105, edited by R. C. Bradt, D. Munz, M. Sakai, V. Y. Shevchenko, and K. White, Kluwer Academic/Plenum Publishers, NY, 2002.

[48] R. Tandon and S. J. Glass, "Controlling the Fragmentation Behavior of Stressed Glass," to be published in Fracture Mechanics of Ceramics, Vol. 14-15, presented at 8th International Symposium on Fracture Mechanics of Ceramics, February 25-28, 2003, Houston, TX.

[49] S. J. Glass, M. Abrams, R. Matalucci, "New Glass Technologies for Enhanced Architectural Surety: Engineered Stress Profiles (ESP) in Soda-Lime Silica Glass, Sandia National Laboratories Report, SAND2000-3001, December 2000.

Engineered Stress Profile (ESP) Glass – Processing, Properties, and Performance

ESP glass has several unique attributes that may prove very beneficial for its use in architectural and other applications.[1, 2, 3, 4, 5] Its biaxial flexure strength (550 MPa or 80 ksi) is as much as five times higher than regular annealed glass (100 MPa or 15 ksi). It has very high reliability as a result of its narrow strength distribution. The narrow strength distribution is characterized by Weibull modulus values as high as 60. (Glasses and ceramics normally have Weibull moduli in the range of 5-15.) Figure 1 demonstrates how the Weibull modulus affects the failure probability as a function of the applied stress. For a glass with a Weibull modulus of 60, there is a negligible probability of failure (2 in 1 million) at a stress that is 80% of the characteristic strength (similar to the average strength). In contrast, a glass with a Weibull modulus of 5 has a 30% failure probability at the same stress level. The combination of high strength and high reliability for ESP glass should allow engineers and architects to use thinner glass and design with smaller safety margins. Additionally ESP glass has a high degree of insensitivity to surface damage.[6] As a result its strength is less likely to degrade over long periods of time, an attractive design feature for glazing applications.

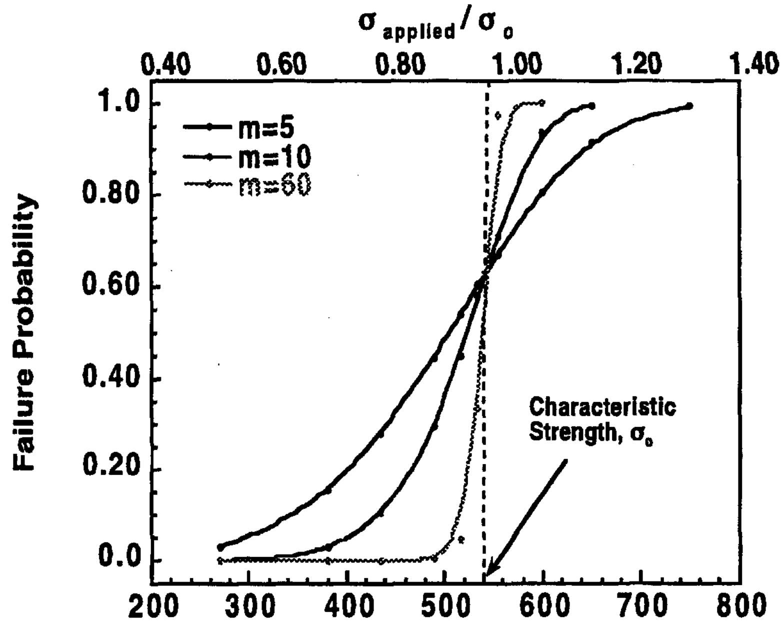

Figure 1. Failure probability vs. applied stress for glasses with different Weibull moduli.

On loading above a critical stress, ESP glass cracks non-catastrophically, forming an array of shallow cracks that arrest at stresses below the failure stress as shown in Figure

2. The appearance of the cracks has been enhanced by acid etching. The crack density is proportional to the tensile load that has been applied to the glass thus providing a warning of how close the glass has come to its failure stress.

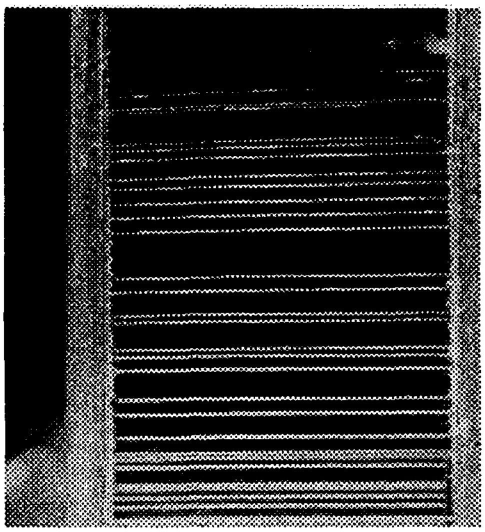

Figure 2. Non-catastrophic surface cracks that develop in ESP glass at stresses below the fracture strength. (View is looking down on tensile surface of bend bar).

ESP glass, like other pre-stressed glasses, has stored elastic strain energy that is available to produce dicing behavior during fracture (Figure 3). When dicing occurs the glass fragments are much smaller and less lethal than the large sharp shards produced during the failure of annealed glass.

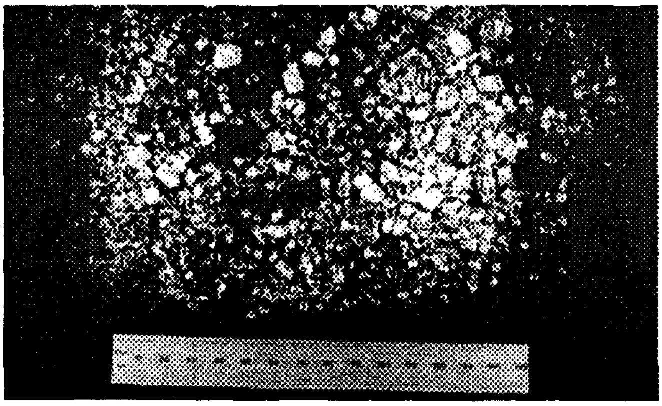

Figure 3. Small fragments are produced when ESP 0317 glass is fractured.

References

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[1] D. J. Green, V. M. Sglavo, E. K. Beauchamp, and S. J. Glass, "Using Designed Residual Stress Profiles to Produce Flaw-Tolerant Glass," Fracture Mechanics of Ceramics Conf., High Tech Ceramics Research Centre in the Russian Academy of Sciences, Moscow, July 20-22, 1999.

[2] D. J. Green, R. Tandon, and V. M. Sglavo, "Crack Arrest and Multiple Cracking in Glass Through the Use of Designed Residual Stress Profiles," Science, Vol. 283 (5406) pp. 1292-1295, Feb. 26, 1999.

[33] V. M. Sglavo, L. Larentis, and D. J. Green, "Flaw-Insensitive Ion-Exchanged Glass: I Theoretical Aspects," J. Am. Ceram. Soc., 84 [8] 1827-31 (2001).

[4] V. M. Sglavo and D. J. Green, "Flaw-Insensitive Ion-Exchanged Glass: II Production and Mechanical Performance," J. Am. Ceram. Soc., 84 [8] 1832-38 (2001).

[5] S. J. Glass, M. Abrams, and R. V. Matalucci, "New Glass Technologies for Enhanced Architectural Surety®: Engineered Stress Profiles (ESP) in Soda-Lime-Silica Glass," Sandia National Laboratories Report SAND2000-3001, Dec. 2000.

[6] M. Abrams, "Processing and Properties of an Engineered Stress Profile Soda Lime Silica Glass," M. S. Thesis, Penn State University, Sept. 2001.

Free-Field Blast Testing of ESP Glass

Introduction

This section documents blast loading (transient pressure pulse) tests conducted on Corning 0317 Engineered Stress Profile (ESP) and annealed Corning 0317 glass disks. The overall objective of this part of the project was to evaluate how ESP glass performed in a blast environment. Quasi-static pressure tests conducted previously, as part of another program, showed failure pressures that ranged from 140-328 psi (five tests) for the annealed glass samples and pressures between 1800 and 2160 psi (average of five tests=2052±150 psi) for the Corning 0317 ESP glass.[1] These pressures are in good agreement with predicted failure pressures for the ESP glass (Table 1), using the flexural strength of the glass in calculations for the case of a simply supported disk (i.e., not clamped). The support perimeter was assumed to be 0.125".

Table 1. Glass parameters and predicted failure pressures.

Glass	Biaxial flexure strength (MPa)*	Disk thickness (inches)	Disk diameter (inches)	Disk support radius (inches)	Predicted failure pressure (MPa)	Predicted failure pressure (psi)
Corning 0317 ESP	540	0.085	1.0	0.375	15.6	2259
Corning 0317 ESP	540	0.085	3.26	1.505	1.0	140
Corning 0317 ESP	540	0.085	4.5	2.125	0.5	70

* Measured on samples with 1.0" diameter.

The specific objectives of this part of the project were:

1. To study the free-field blast behavior of ESP glass and compare it to the behavior of annealed glass.
2. To determine the initial pressure and impulse levels needed for shock tube tests conducted at Wilfred Baker Engineering in San Antonio, TX on larger glass panels (15"x15") of the ESP and annealed versions of Corning 0317 glass.[2]
3. To determine the blast loading parameters including the blast pressure threshold and impulse threshold that control the glass failure.
4. To correlate the glass breakage pressure threshold from blast loading to the previously measured quasi-static failure pressures.
5. To determine whether test results obtained for small glass samples could be correlated with results for larger samples and samples tested in a shock tube environment.[#]
6. To measure fragment size distributions and velocities.[☆]

[#] Only one size of sample was tested because of time and funding limitations.

Experiments

Details about the samples and the testing are provided in the following sections: [3,4,5,6,7,8,9]

Samples

Tests were conducted using Corning 0317 glass disk samples with the following dimensions:

1. Diameter: 1.0 inches
2. Thickness: 0.085 inches

Two types of Corning 0317 glass were tested; annealed samples and ESP samples that had undergone a double ion exchange treatment. The first step in the double ion exchange treatment was a 24 hr exchange in KNO_3 at 500°C, followed by a second treatment for 30 min in a $KNO_3/NaNO_3$ mixture at 400°C. The biaxial flexure strength of the Corning 0317 ESP samples, measured using ring-on-ring testing is 540 MPa (73 ksi). The flexure strength for the annealed samples is approximately 100 MPa. Flexural strength testing is a static strength test.

Explosive Geometry and Materials:

The geometry of the explosive was a sphere. Composition - C4 (COMP C4) was used for all of the tests. This explosive is readily available and is of a putty-like consistency that allows it to be compacted into the sphere geometry. The density of this explosive is about 1.3-1.5 g/cm^3 after compaction. Its detonation velocity is about 7 Km/s. An RP-83 detonator was used to initiate the explosive.

Test Sites

Tests were conducted at two sites. The first series of 0.5 lb charge tests was conducted inside, in the 11 ft. diameter by 17.8 long chamber at Sandia's Explosive Components Facility (ECF). Subsequent tests, including a second series of tests using the 0.5 lb charge, were conducted outside, at the Gun Site, Building 6570 in Area III.

Blast Test Configuration

The explosive charge was positioned at a standoff from the glass sample as shown in Fig. 1. The center of the explosive charge was located along the centerline of the glass sample and 30 inches above the floor or ground. The explosive was suspended along a rail attached to the top of a steel frame and at the desired standoff. Nylon, tape, or some other light material straps were used to suspend the explosive sphere. A 30-gallon steel drum was similarly suspended from this rail to catch some of the glass fragments. The main structure holding the glass fixture was designed to be re-used on all tests. The glass fixture design is shown in Fig. 2. The glass disks were held in place in the fixture, which

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* Time and funding constraints did not allow this tested to be conducted.

was hand tightened. In the initial series of tests no rubber gasket was used between the glass and the fixture. Tests of the annealed glass seemed to indicate no difference with or without the gasket so later series of tests (5 and 6) were conducted with a gasket.

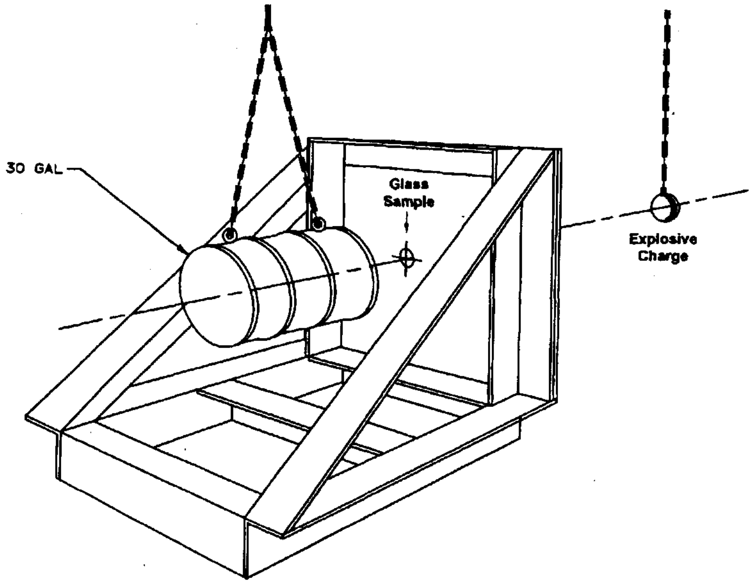

Fig. 1 Blast test configuration.

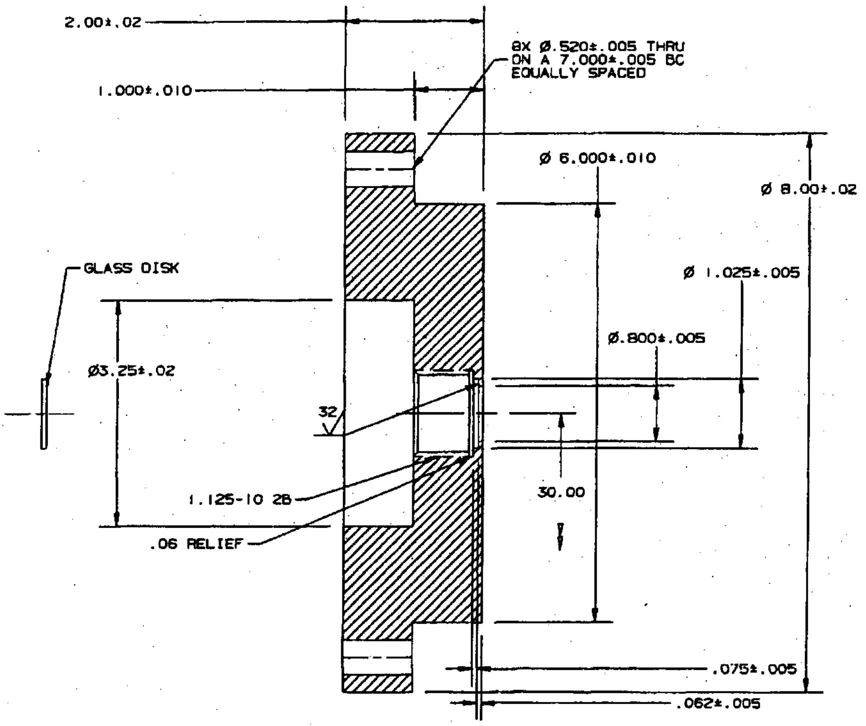

Fig. 2 Fixture for holding glass disk for blast testing.

Selection of Initial Incident Reflected Pressure Levels

From previous testing the quasi-static overpressure required to break the glass was between 1800 and 2200 psi. Although the dynamic, transient, blast loading pressure threshold could vary significantly from the quasi-static threshold, an initial average overpressure of 2000 psig was chosen for this development work. For an incident overpressure of 2000 psig, the scaled distance, Z,[10] is 0.7 where,

$$Z=R/W^{1/3}$$

Where R=standoff distance (distance between glass and explosive charge)
W=initial charge weight

The initial standoff distance for each charge weight was chosen using the above equation and Z=0.7. If the glass survived the first standoff distance a new standoff distance (smaller) was chosen either by the test operator or was selected using the Neyer routine. The Neyer routine, also known as the Neyer D-Optimal test, was used for some test series to minimize the number of tests required to converge on the 50 % glass failure pressure threshold.

Test Series

Spherical COMP-C4 explosive charges of 0.5, 3.8, and 5.0 pounds were used in seven series of tests. The three charges and different standoff distances were selected to establish a curve for variations in threshold pressure and impulse parameters.

Blast Parameter Determination

Free-field blast theory was used to calculate the pressures and other blast parameters for this study.[11,12] Pressure verifications using transducer measurements were planned for the second phase of testing (not completed).

Results

The results for the seven series of tests are shown in Table 2. Test series 5 and 6 were conducted to obtain more crossovers in the pressure threshold to obtain better estimates of the blast pressure to cause failure for the 0.5 and 3.8 lb charges, respectively.

Table 2. Threshold reflected pressure and standoff distances for all test series.

Test Series	Glass type	Charge (lb)	Test Location	Samples Tested	Reflected Pressure Threshold, P_r (psi)	Standoff (inches) P_r threshold	Comments
1	ESP	0.5	ECF Chamber	12	1516	20	Neyer routine not used. Low P break in 2nd test led to many low P tests. Two crossovers obtained.
2	ESP	3.8	Gun site	6	1927	36	No crossovers
3	ESP	5.0	Gun site	7	907	52	Three crossovers
4	Annealed	3.8	Gun site	9	320	68	Obtained seven crossovers. Last two tests were conducted with rubber gaskets. Same P_r obtained.
5	ESP	0.5	Gun site	12	1150	23	One crossover. Gaskets used.
6	ESP	3.8	Gun site	14	477	59	Two crossovers. Gaskets used.

Glass blast test data for all of the tests in Test Series 1-6, including calculated values of the reflected pressure, are shown in Tables 3-6. Some tables contain additional calculated blast parameters such as the reflected impulse.

Table 3. ESP glass free-field blast test results for the 0.5 lb charge.

Test No.	Standoff (inches)	Glass breakage (yes/no)	Pr Reflected Pressure (psi)
1	16.5	YES	2400
2	30.5	YES	459
3	55.0	NO	80.6
4	42.75	NO	167.8
5	32.75	NO	480
6	31.75	NO	525
7	31.25	NO	510
8	31.0	NO	500
9	30.0	NO	590
10	28.0	NO	690
11	20.0	YES	1516
12	22.0	NO	1181
13	9	YES	7350
14	11	YES	5500
15	13	YES	4000
16	15	YES	3000
17	18	YES	1950
18	23	YES	1200
19	28	NO	700
20	28	NO	700
21	25.5	NO	900
22	24.24	NO	1050
23	23.5	NO	1100
24	24	NO	950

TESTS 1 – 12: April 23 - 27, 2001, TESTS 13 – 24: May 2002

Table 4. ESP glass free-field blast test results for the 3.8 lb charge

Test No.	Standoff (inches)	Glass breakage (yes/no)	Pr Reflected Pressure (psi)	Ir Reflected Impulse (psi-ms)	Ps Static Pressure (psi)	Is Static Impulse (psi-ms)	Ta Shock Arrival time (ms)	Td Positive Phase Duration (ms)	Vs Shock Velocity (ft/s)
1	36	NO	1927	170	290	33	0.362	1.1	4692
2	30	YES	3048	219	418	29	0.263	0.602	5569
3	33	YES	2409	191	346	31	0.310	0.807	5097
4	34.5	YES	2141	179	315	32	0.337	0.948	4879
5	35.5	YES	1995	173	298	33	0.354	1.047	4753
6	36	YES	1927	170	290	33	0.362	1.1	4692
7	35	YES	2067	176	307	32	0.345	0.996	4816
8	36.5	YES	1861	167	282	34	0.371	1.156	4633
9	38	YES	1666	157	259	35	0.400	1.351	4449
10	41.5	YES	1315	140	215	37	0.469	1.819	4084
11	43	NO	1197	133	200	37	0.499	1.984	3949
12	42.25	YES	1254	136	2-7	37	0.484	1.906	4016
13	42.75	YES	1216	134	202	37	0.494	1.959	3971
14	43.25	YES	1179	132	197	37	0.504	2.007	3928
15	44.0	YES	1117	129	189	36.2	0.523	2.074	3854
16	47.0	YES	930	118.3	164	35	0.589	2.221	3614
17	53.5	YES	641	99.8	123.2	31.9	0.750	2.364	3182
18	65	NO	360.6	77.8	79.3	26.7	1.082	2.286	2640
19	58	YES	507	90	102	29.7	0.872	2.367	2943
20	60.5	NO	446	85	93	28.6	0.945	2.344	2825

Tests 1-6: April 23 - 27, 2001, Tests 7-20: Aug. 2002.

Table 5. ESP glass free-field blast test results for the 5.0 lb charge.

Test No.	Standoff (inches)	Glass breakage (yes/no)	Pr Reflected Pressure (psi)	Ir Reflected Impulse (psi-ms)
1	36	YES	2440	211
2	72	NO	350	84
3	54	NO	813	122
4	45	YES	1355	155
5	50	YES	1009	135
6	52	YES	907	128
7	53	NO	856	125

Test Dates: May 1- 4, 2001

Table 6. Annealed glass free-field blast test results for the 3.8 lb charge.

Test No.	Standoff (inches)	Glass breakage (yes/no)	Pr Reflected Pressure (psi)	Ir Reflected Impulse (psi-ms)	Comments
1	60	YES	458	86	
2	70	NO	289.5	70.92	
3	65	YES	362	77.91	
4	67.5	YES	339.9	75.87	
5	68.5	NO	301.7	72.16	
6	67.5	YES	339.9	75.87	
7	68.5	NO	301.7	72.16	
8	67.5	YES	339.9	75.87	With gasket
9	68.5	NO	301.7	72.16	With gasket

Test Dates: August 6 - 10, 2001

Figures 3-5 show the reflected pressure vs. test number for some of the series of tests on the ESP glass for the 0.5, 3.8 and 5 lb charges. This type of graphical display demonstrates how the threshold pressure was identified. In some cases the Neyer routine was used to identify the next test pressure after a sample survived or failed a test, in other cases the test operator selected the pressure.

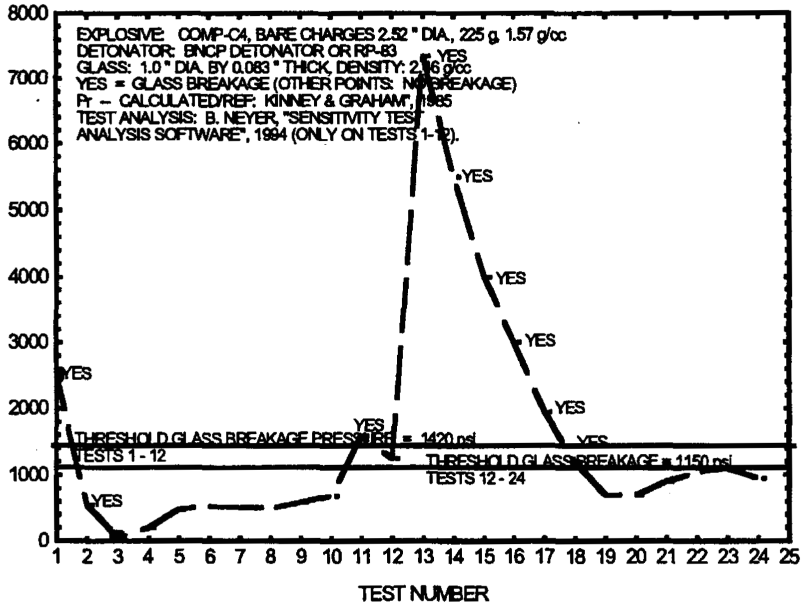

Fig. 3. Reflected pressure (psi) vs. test number for 0.5 lb charge tests (Series 1 and 4) of ESP glass.

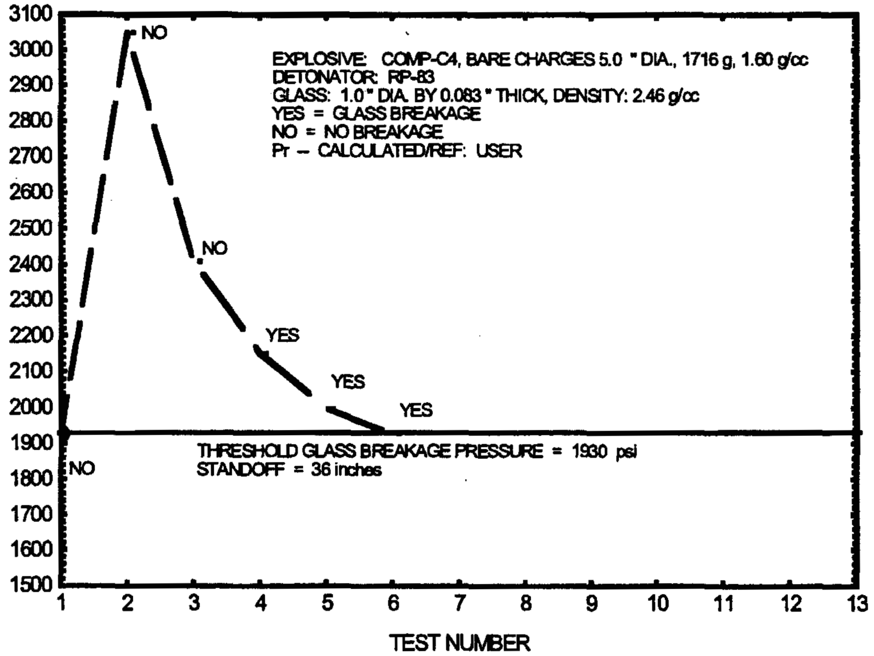

Fig. 4. Reflected pressure (psi) vs. test number for 3.8 lb charge tests (Series 2) of ESP glass.

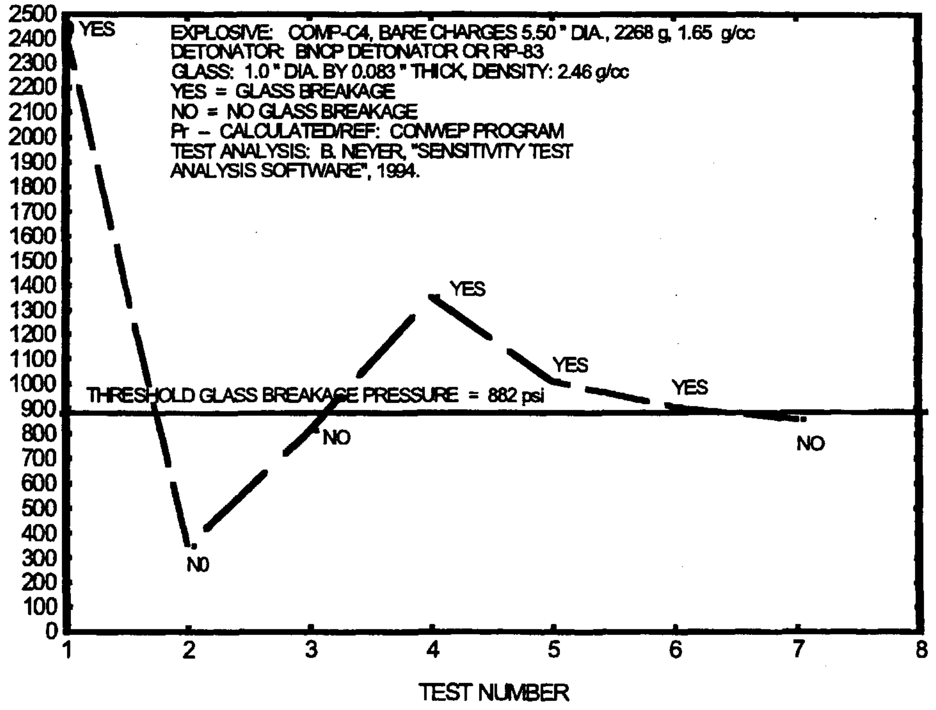

Fig. 5. Reflected pressure (psi) vs. test number for 5.0 lb charge tests (Series 3) of ESP glass.

Discussion

Using the data obtained for all three charges, the reflected blast pressures required to fracture small ESP glass disks is in the range of 1000-2000 psi. These pressures are similar to the 1800-2200 psi required to fracture very similar size disks in quasi-static pressure testing. For the annealed Corning 0317 glass disks the reflected pressures of 320 psi (for a charge of 3.8 lb) are similar to the quasi-static pressures required to break the same material (140-328 psi). As the diameter to thickness ratio of these samples is quite small (D/t~12), the deflection prior to fracture is much smaller than it is for window-size plates (e.g., width/thick. =48"/0.25"=192). Thus the deflection is likely still in the linear elastic regime and the failure mode is the same in both quasi-static and blast loading tests for these small samples. A similar failure mode may not occur for windows that undergo large deflections under blast loading.

Additional tests were planned to determine how the glass failure blast parameters changed for larger samples for which the deflection prior to failure will be larger; however, time and funding did not allow these tests to be conducted.

After the first series (1-3) of tests had been completed for each charge the data were plotted as shown in Fig. 6, 7, and 8. Figure 6 shows the free field reflected blast pressure threshold for ESP glass breakage versus standoff for explosive charges of 0.5, 3.8, and 5.0 lbs. Figure 7 shows the reflected impulse threshold for ESP glass breakage versus standoff for the three charges. Figure 8 shows the free field blast reflected pressure threshold for ESP glass breakage versus reflected impulse.

As shown in Figures 6 - 8, the pressure and impulse data are significantly different for the three charges. The reflected pressure and impulse for the 3.8 lb tests were expected to fall between those for the 0.5 and 5.0 lb tests; however, in each plot they appear to be anomalously high. To obtain a better value of the threshold pressure additional tests were conducted (Series 6) with the objective of obtaining more crossovers in the threshold pressures. Unfortunately the data for the 3.8 lb charge in the two series of tests appeared to give different thresholds, one high and the other low as shown in Fig. 9.

Combining the results for the repeated tests and averaging the results for them gives the parameters shown in Table 6. The results of two series of 0.5 lb charge tests on ESP glass were combined. The results for ESP glass for the 5.0 lb charge and annealed glass at 3.8 lb are from one series of tests. Results for both series (2 and 4) of 3.8 lb tests on ESP glass results are shown. Because there were large discrepancies between the two series of tests and because there were so few crossovers obtained for the threshold pressure, the average of the two series of tests was taken. Although further testing is necessary to obtain an improved estimate of the threshold pressure for this charge this result seems sensible relative to the results for the other two charges, i.e., it yields a result that falls between them.

Table 6. Summary of blast parameters for glass failure.

Glass	Charge size (lb)	Total No. of Tests	Standoff distance (in)	Reflected Pressure (psi)	Reflected Impulse (psi-ms)
ESP	0.5	24	21	1420	71.8
ESP	3.8	20	36 & 59 Avg. =48	1927 & 477 Avg. = 1202	
ESP	5.0	7	52.5	907	126.5
Annealed	3.8	9	68	320	~73

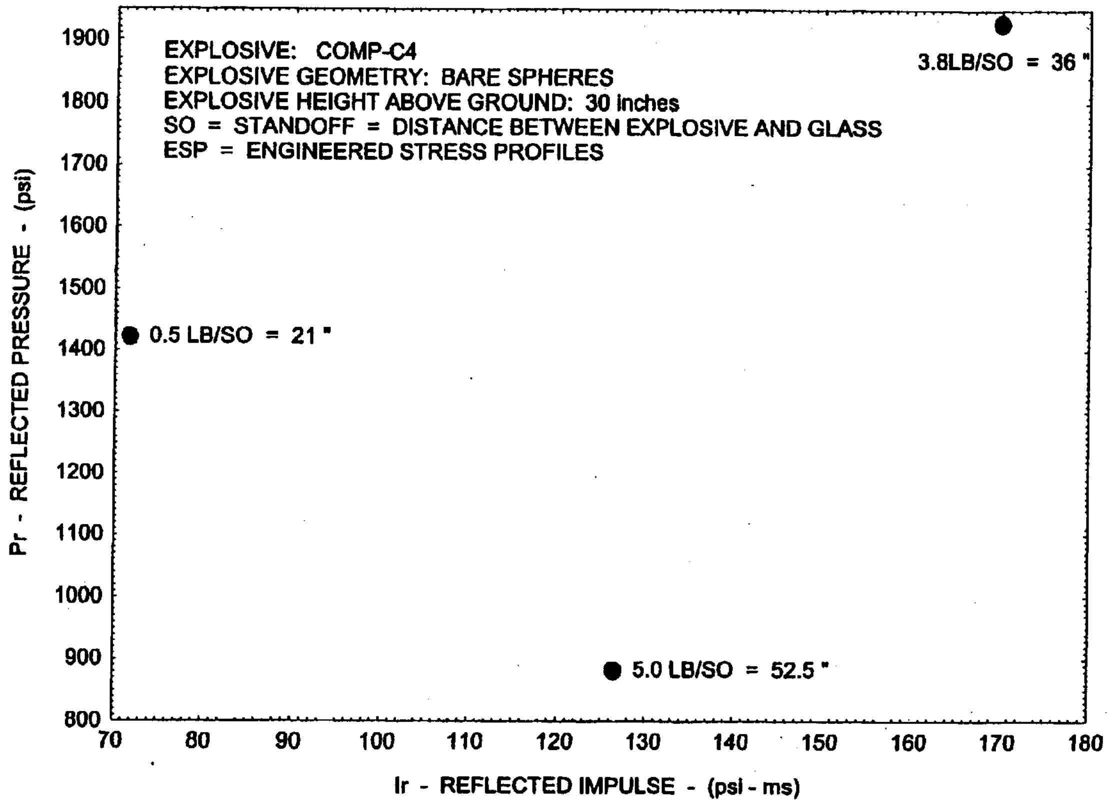

Fig. 8 Reflected pressure vs. impulse for Test Series 1-3 for ESP glass.

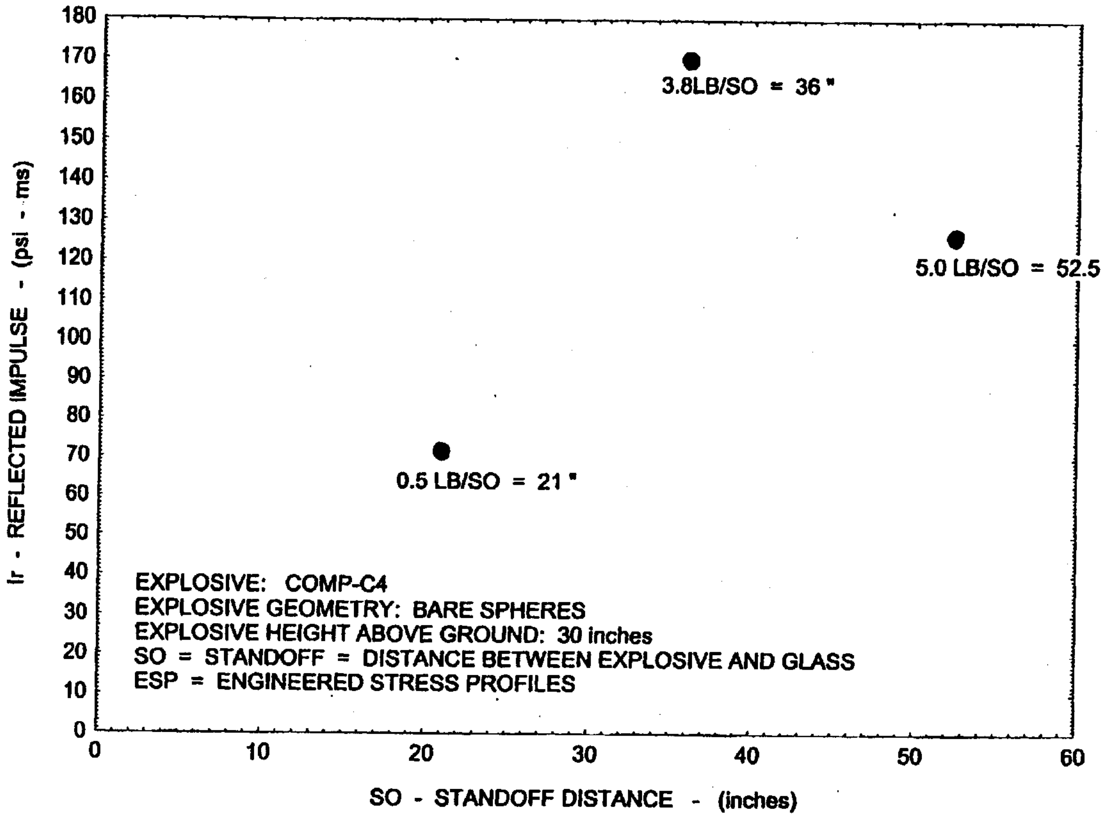

Fig. 7 Reflected impulse vs. standoff distance for Test Series 1-3 for ESP glass.

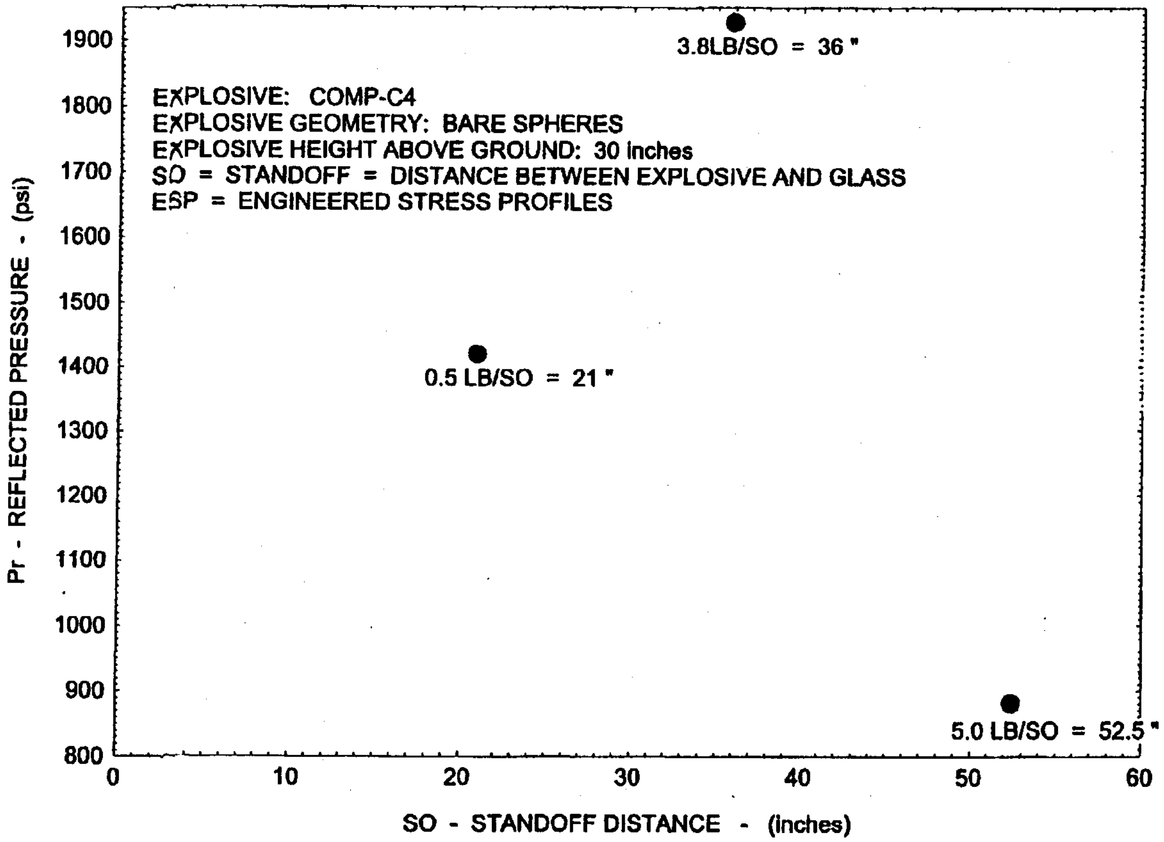

Fig. 6 Reflected pressure vs. standoff distance for Test Series 1-3 for ESP glass.

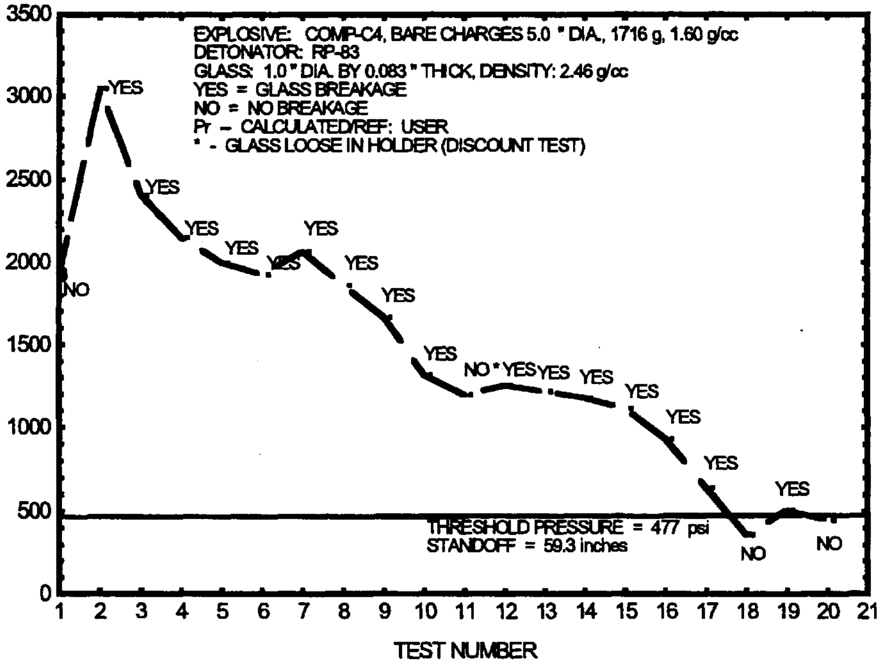

Fig. 9. Reflected pressure (psi) vs. test number for 3.8 lb charge tests (Series 2 and 6) of ESP glass.

Anomalies in the test data could be due to factors including:

1. Large flaws in the glass samples that caused them to fail at lower pressures.
2. Accuracy of the test measurements. For example wind could cause the standoff distance to change as the charge was suspended using a nylon cable. Charge size and density may have varied slightly from test to test.
3. Dirt or other flying debris hitting and breaking the glass samples rather than the blast pressure.
4. Insufficient number of data points and crossovers to unambiguously determine the failure pressure threshold.

Summary and Conclusions

This testing showed that ESP glass fails at pressures that are at least three times higher than those for annealed glass samples. The results of this part of the project demonstrated some of the difficulties inherent in blast testing of glass. Because the results were not consistent for a given set of conditions it was not possible to obtain a curve that defines glass failure for different pressures and impulses. Factors that may have affected the results include glass samples breaking due to other causes and incorrect pressures. The pressure and impulse parameters were calculated and have not been verified by measurements. Further evaluation of the data, test configuration, and samples, and additional testing must be performed before conclusions are drawn about the blast parameters that control the failure of small disk samples of glass.

References

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[1] S. J. Glass, E. K. Beauchamp, R. J. Kipp, C. S. Newton, S. D. Nicolaysen, R. T. Reese, R. G. Stone, and W. N. Sullivan, "Controlled Fracture of Prestressed Glass or Glass-Ceramic Rupture Disk," Sandia National Labs Report SAND2000-0828, April 2000.

2 . S. J. Glass and R. V. Matalucci, "Preliminary Results of Blast Testing of Engineered Stress Profile Glass," Report to the USAF Force Protection Battlelab, San Antonio, TX, Nov. 15, 2001.

[3] Internal Sandia memo from M. Vigil to Distribution, "Engineered Stress Profile (ESP) Glass/Blast Loading Development Tests," Apr. 4, 2001.

[4] Internal Sandia memo from M. Vigil and P. Cooper to Distribution, "Engineered Stress Profile (ESP) Glass/FYO1 Blast Loading, Glass Breakage Threshold Development Tests/Phase I," Apr. 12, 2001.

[5] Internal Sandia memo from M. Vigil to J. Glass and R. Matalucci, "Engineered Stress Profile (ESP) Glass Project/Blast Loading, Glass Breakage Threshold Tests/Phase I Preliminary Data," June 7, 2001.

[6] Internal Sandia memo from M. Vigil to J. Glass and R. Matalucci, "Standard Glass Blast Loading, Glass Breakage Threshold Tests," Aug. 13, 2001.

[7] Internal Sandia memo from M. Vigil to J. Glass, "Engineered Stress Profile (ESP) Glass Project/Blast Loading, Glass Breakage Threshold Tests/Additional Cross-Overs for 0.5, 3.5, and 5.0 Lb Spherical Charges" June 4, 2002.

[8] Internal Sandia memo from M. Vigil to J. Glass, "Update/Engineered Stress Profile (ESP) Glass Project/Blast Loading, Glass Breakage Threshold Tests/Additional Cross-Overs for 0.5, 3.5, and 5.0 Lb Spherical Charges" June 6, 2002.

[9] Internal Sandia memo from M. Vigil to J. Glass, "Update/Engineered Stress Profile (ESP) Glass Project/Blast Loading, Glass Breakage Threshold Tests/Additional Cross-Overs for 3.8 lb Spherical Charges" Aug. 17, 2002.

[10] W. E. Baker, P. A. Cox, P. S. Westine, J. J. Kulesz, and R. A. Strehlow, *Explosion Hazards and Evaluation*, Fundamentals Studies in Engineering, 5, Elsevier, New York, 1983.

[11] D. W. Hyde, "User's Guide for Microcomputer Programs CONWEP and FUNPRO, Applications of TM 5-855-1, "Fundamentals of Protective Design for Conventional Weapons", Department of the Army, Waterways Experiment Station, Corps of Engineers, Report # SL-88-1, June 9, 1988.

[12] Internal Sandia memo from P. Cooper to S. J. Glass and R. V. Matalucci, "Airblast Scaling" Nov. 19, 2001.

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