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Explosive Tests For Evaluation of the Glass Fragment Mitigation Characteristics of 3M Security Window Films

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PREFACE

Applied Research Associates, Inc. (ARA) conducted a high explosive test series from January 12-19, 1998, in order to evaluate the glass fragment hazard mitigation characteristics of 3M security film products applied to large commercial window systems. Six tests were performed with four window systems in each test for a total of twenty-four windows tested. This report documents the findings of these tests.

The test series was performed at the Chestnut Test Site on Kirtland Air Force Base in New Mexico. This test site is owned and operated by the Defense Special Weapons Agency (DSWA) which is the US Government's lead agency for force protection. A special thanks is extended to DSWA for allowing ARA use of the test site.

The Security Engineering Group of ARA provided test structure design, test design, test planning and documentation of the results. Mr. Joseph L. Smith, ARA's Director of Security Engineering, was the principal investigator for this effort. Mr. Steven C. Lofton was the field test engineer. The ARA analysis team assigned to this project also included Mr. Scott R. Swatzell, Mr. James T. Brokaw and Dr. Larry M. Bryant. The Shock Physics Division of ARA was responsible for test bed preparation, construction, test instrumentation, data collection and test execution. Dr. Sue Babcock was the test director for this effort. The ARA testing team assigned to this project included Mr. Jack Babcock, Mr. Lonnie Bamert, Ms. Laura Shannon, Mr. Michael Cerny, Mr. Thomas Ralston and Mr. Ricky Albrecht.

This work was sponsored by the Specified Construction Products Division of 3M. Mr. James E. Mannix served as the project manager for 3M. He was assisted principally by Mr. Ken Smith and Mr. Dennis J. White. The support and efforts of the 3M team are acknowledged and greatly appreciated.

EXECUTIVE SUMMARY

Propelled by the forces of a terrorist bomb, glass fragments cause large numbers of serious injuries. In response to the heightened concern about terrorism, the US Government and private industry are developing and testing new technologies to mitigate hazards to people in the vicinity of a terrorist bombing. In cooperation with the Defense Special Weapons Agency, Applied Research Associates (ARA) conducted tests to assess the capability of 3M security window film to reduce the hazards of flying glass shards during an explosion.

The US General Services Administration (GSA) developed criteria for evaluation of acceptable levels of protection for the glass fragment hazard. This criteria is part of the comprehensive security criteria (GSA Security Criteria, Final Working Version, January 1997) developed by the GSA which includes physical security, electronic security and many other criteria for blast considerations. The GSA has indicated that manufacturers must test their window products against the criteria to evaluate the performance of these products in blast if they want to be considered for use in certain GSA buildings. Further, the GSA has indicated a preference for open-air high explosive testing rather than shock tube testing. This is because current shock tube technologies cannot adequately emulate air blast waveforms from real explosions and tend to be over energetic at the same peak blast pressure level versus real explosions.

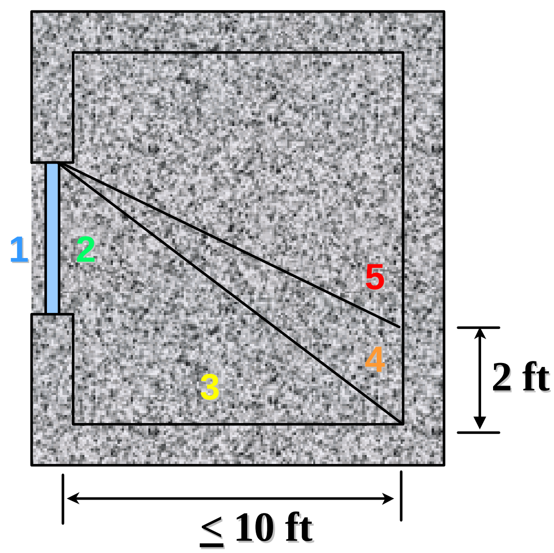
3M commissioned ARA to perform a series of open-air high explosive tests from January 12-19, 1998 to evaluate the performance of their security window film products. The test series consisted of six tests with four windows per test for a total of twenty-four windows.

The tests were designed to mimic the test procedures and window sizes used for the previous GSA tests. The windows were mounted in enclosed concrete reaction structures. The response of each window was captured with high-speed film. An exterior high-speed camera and an exterior normal speed video camera were used to capture the views of the structures and the explosion. The reaction structures were instrumented with pressure gages to measure the reflected pressure on the specimens and the internal pressure in the structures.

The test charge was 600 lb of Ammonium Nitrate and Fuel Oil (ANFO) which is equivalent to 500 lb of TNT. The standoff distance to the structures was varied to affect specific peak pressures on the test specimens.

A thorough test matrix was developed to explore the effect of glass type, glass thickness, film attachment, film thickness and window frame type. The nominal window size for the tests was 4 ft by 5-1/2 ft. Glass types included annealed glass (AG), heat strengthened glass (HSG) and thermally tempered glass (TTG). Monolithic glass thicknesses varied from ¼ inch to ½ inch with most emphasis on the more common ¼-inch thickness. Insulated glass units were also tested. Various methods for attaching or anchoring the window film to the window frame included: four- and two-sided mechanical batten bar systems; four-sided wet glazed or adhesive attachments; and day-lite applications where the film is applied to the vision surface of the glass only and is not attached to the window frame. Four-, six- and seven-mil thick film products were tested. Most windows were tested in rigid steel frames consistent with the GSA tests. Four of the windows were tested in a typical storefront aluminum frame.

The GSA glass fragment hazard rating scheme is presented graphically in the figure below and is described in the table provided on the next page. The approach compares potential hazards based on the type and location of glass fragments interior and exterior to the test cubicle. These criteria indirectly reflect the velocity (hence lethality) of fragments based on their distance from the window.



Condition	Description	Glass Fragments		Hazard Level	Protection Level
		Exterior to Structure	Interior to Structure		
1	Glass not cracked, fully survived and/or fully retained by frame and no glass fragments either inside or outside structure.	None	None	NA	Very high
2	Glass may be cracked but is retained by the frame.	Yes	No significant fragments. Dusting or very small fragments near sill or on floor acceptable.	Very Low	Very High
3	Glass failed and not fully retained in frame.	Yes	Yes - land on floor no more than 10 ft from window	Low	High
4	Glass failed and not fully retained in frame.	Yes	Yes - land on floor more than 10 ft from window and impact a vertical surface located not more than 10 ft behind the window no higher than 2 ft above floor level.	Medium	Medium
5	Glass fails catastrophically.	Yes	Yes - land on floor more than 10 ft from window and impact a vertical surface not more than 10 ft behind window above a height of 2 ft.	High	Low

The results of the tests are documented in the following tables and photo figures. The 3M security films provided significant reductions in glass fragment hazards versus unprotected windows. The films performed well at mitigating hazard for both monolithic windows and insulated windows. Many specimens tested performed to specified criteria for GSA Level C buildings up to a 4-psi peak blast pressure level. The tests showed that both the aluminum batten and the wet glazed adhesive provided an adequate attachment to typical aluminum frames.

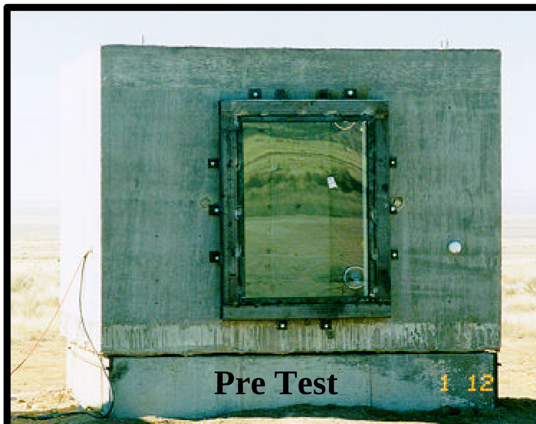
TEST 1 SUMMARY

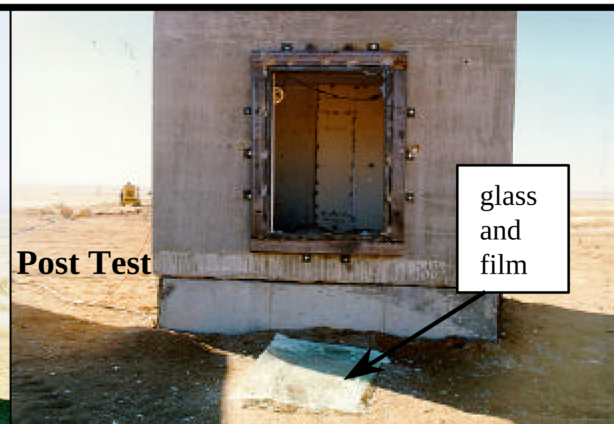
Date:	12 January 1998
Nominal Charge Weight, lb ANFO:	600.0
Standoff to each structure, ft:	190
Avg. Measured Peak Pressure, psi:	4.2
Avg. Measured Positive Impulse, psi-ms:	28.4
Time of Detonation:	14:00
Ambient Temperature, deg F:	58.0

	Window 1	**Window 2**	**Window 3**	**Window 4**
Specimen Description	1/4-in. mono AG, Ultra 400, day-lite	1/4-in. mono AG, Ultra 400, 4-sided batten	1/4-in. mono AG, 7-mil film, 4-sided batten	1/4-in. mono AG, no film
Damage Description	Glazing failed and window left frame, landed 18 inches from front of structure	Glazing failed and film tore with most film retained in frame	Glazing failed and film tore but was retained in the frame, film pulled out of batten at left edge	Glazing failed and most glass entered the structure at high velocity
Glass Fragment Locations	Small dicing and a few fragments inside, no impact on witness panel, frags to 20 ft in front of structure, about 95-97% glass retained on film	Small dicing and a few fragments inside, no impact on witness panel, frags to 26 ft in front of structure, large piece of film and glass 12 inches from front of structure, about 40% glass retained on film	Small dicing and a few fragments inside, no impact on witness panel, about 5-10% glass retained on film, frags to 78 ft in front of structure	~95% glass entered structure with 5% outside to about 12 ft in front of structure, 98 impact on witness panel- 82 below 2-ft height and 16 above 2-ft height
Fragment Hazard to Occupants	Minor hazard to occupants within 10 ft behind window	Minor hazard to occupants within 10 ft behind window	Minor hazard to occupants within 10 ft behind window	Significant hazard to persons within 10-15 ft behind window
Condition	3-SHR	3-SHR	3-SHR	5

Test Notes:

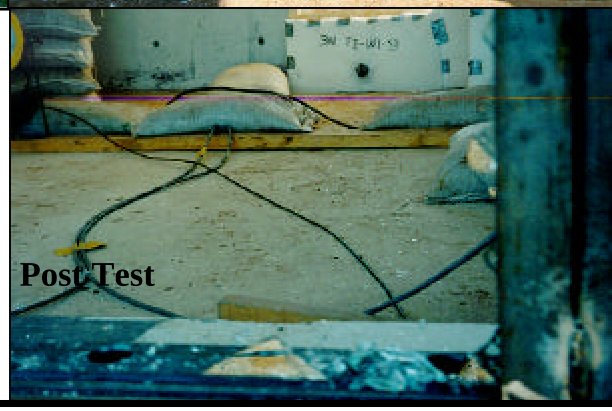
1) Windows were mounted in heavy steel frames unless otherwise noted.
2) Window sizes for all steel framed windows were: pane = 48 x 66 inches; clear opening = 46 x 64 inches.
3) Window sizes for aluminum framed windows were: pane = 46-1/8 x 64-1/8 inches; clear opening = 45.5 inches x 63.5 inches.
4) AG = annealed glass, HSG = heat strengthened glass, TTG = thermally tempered glass.
5) Witness panels were located 116 inches behind window.
6) Percentages reported are percentage of all glass from a specimen unless otherwise noted.
7) The SHR stands for significant-hazard-reduction. This designation is used to distinguish a significantly reduced glass fragment hazard obtained with a protective window system versus a highly hazardous uncontrolled failure with no protective measure that is given the same GSA hazard condition. The SHR designation can be given for GSA conditions 3-5.

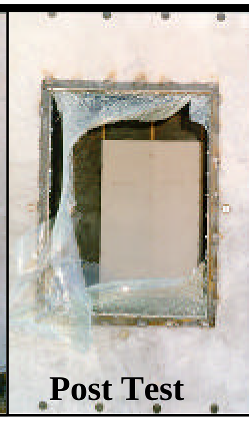




Test 1, Window 1, 4.2 psi

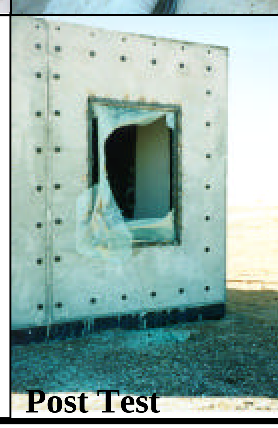
- 1/4-in. mono AG, Ultra 400, day-lite
- Glazing failed and window left frame
- Small dicing and a few fragments inside, no impact on witness panel





Test 1, Window 2, 4.2 psi

- 1/4-in. mono AG, Ultra 400, 4 sided batten
- Glazing failed and film tore with most film retained in frame
- Small dicing and a few fragments inside, no impact on witness panel




Pre Test


Post Test


Post Test

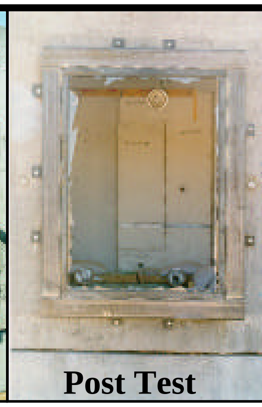

Post Test

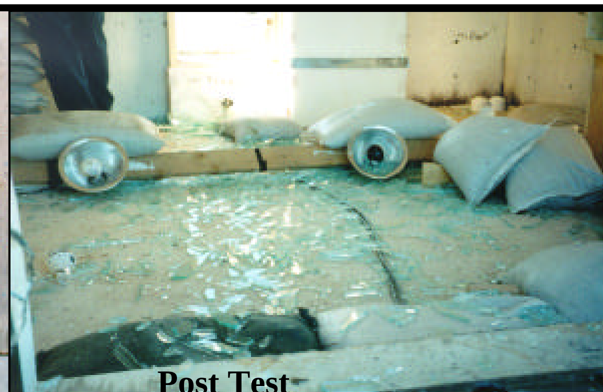
Test 1, Window 3, 4.2 psi

- 1/4-in. mono AG, 7 mil film, 4-sided batten
- Glazing failed and film tore but retained in the frame
- Small dicing and a few fragments inside, no impact on witness panel


Post Test


Pre Test


Post Test


Post Test

Test 1, Window 4, 4.2 psi

- 1/4-in. mono AG, no film
- Glazing failed and most glass entered the structure at high velocity
- 98 impact on witness panel-82 below 2 ft height and 16 above 2 ft height


Post Test

TEST 2 SUMMARY

Date:	13 January 1998
Nominal Charge Weight, lb ANFO:	600.0
Standoff to each structure, ft:	190
Avg. Measured Peak Pressure, psi:	4.1
Avg. Measured Positive Impulse, psi-ms:	28.7
Time of Detonation:	12:30
Ambient Temperature, deg F:	49.0

	Window 1	Window 2	Window 3	Window 4
Specimen Description	1/4-in. mono HSG, Ultra 400, 4-sided batten	1/4-in. mono TTG, Ultra 400, 4-sided batten, aluminum frame	1/4-in. mono AG, Ultra 400, 4-sided batten, aluminum frame	1/4-in. mono AG, Ultra 400, 2-vertical sided batten
Damage Description	Glazing failed and film tore but was retained in frame	Glazing failed and film tore in one corner but was retained in frame, aluminum frame bent inward at jambs	Glazing failed and film tore across the middle with most film retained in frame, aluminum frame bent inward at jambs	Glazing failed and film tore, most film with glass attached landed about 34 inches in front of structure
Glass Fragment Locations	A few fragments inside, no impact on witness panel, frags to 73 ft in front of structure, about 30% glass retained on film	A few fragments inside, no impact on witness panel, frags to 42 ft in front of structure, about 20% glass retained on film	Several fragments inside structure, 7 impact on witness panel, about 5-10% glass retained on film, frags to 68 ft in front of structure, large piece film/glass to 15 ft in front of structure	A few fragments inside, no impact on witness panel, frags to 22 ft in front of structure
Fragment Hazard to Occupants	Minor hazard to occupants within 10 ft behind window	Minor hazard to occupants within 10 ft behind window	“hit or miss” hazard to persons within 10-15 ft behind window	Minor hazard to occupants within 10 ft behind window
Condition	3-SHR	3-SHR	5-SHR	3-SHR

Test Notes:
1) Windows were mounted in heavy steel frames unless otherwise noted.
2) Window sizes for all steel framed windows were: pane = 48 x 66 inches; clear opening = 46 x 64 inches.
3) Window sizes for aluminum framed windows were: pane = 46-1/8 x 64-1/8 inches; clear opening = 45.5 inches x 63.5 inches.
4) AG = annealed glass, HSG = heat strengthened glass, TTG = thermally tempered glass.
5) Witness panels were located 116 inches behind window.
6) Percentages reported are percentage of all glass from a specimen unless otherwise noted.
7) The SHR stands for significant-hazard-reduction. This designation is used to distinguish a significantly reduced glass fragment hazard obtained with a protective window system versus a highly hazardous uncontrolled failure with no protective measure that is given the same GSA hazard condition. The SHR designation can be given for GSA conditions 3-5.


Pre Test

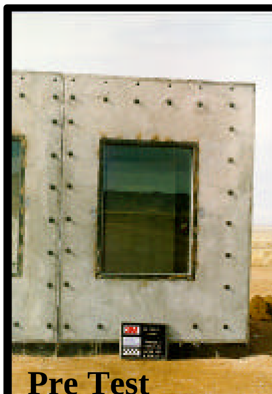

Post Test

Test 2, Window 1, 4.1 psi

- 1/4-in. mono HSG, Ultra 400, 4-sided batten
- Glazing failed and film tore but was retained in frame
- A few fragments inside, no impact on witness panel


Post Test


Post Test


Pre Test


Post Test

Test 2, Window 2, 4.2 psi

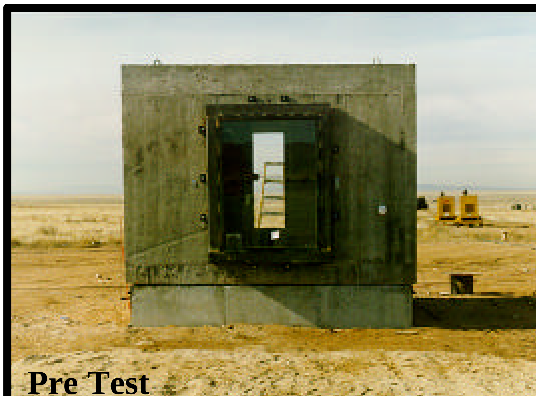
- 1/4-in. mono TTG, Ultra 400, 4-sided batten, aluminum frame
- Glazing failed and film tore in one corner but was retained in frame
- A few fragments inside, no impact on witness panel


Post Test

Post Test

Test 2, Window 3, 4.1 psi

- 1/4-in. mono AG, Ultra 400, 4 sided batten, aluminum frame
- Glazing failed and film tore with most film retained in frame
- Several fragments inside structure, 7 impact on witness panel



Test 2, Window 4, 4.2 psi

- 1/4-in. mono AG, Ultra 400, 2 vertical sided batten
- Glazing failed and film tore, most of window landed about 34 inch in front of structure
- A few fragments inside, no impact on witness panel

TEST 3 SUMMARY

Date:	14 January 1998
Nominal Charge Weight, lb ANFO:	600.0
Standoff to each structure, ft:	165
Avg. Measured Peak Pressure, psi:	5.3
Avg. Measured Positive Impulse, psi-ms:	33.4
Time of Detonation:	12:00
Ambient Temperature, deg F:	46.0

	Window 1	Window 2	Window 3	Window 4
Specimen Description	1/4-in. mono TTG, Ultra 400, 4-sided batten	1/4-in. mono TTG, Ultra 600, 4-sided batten	1/4-in. mono HSG, Ultra 600, 4-sided batten	1/4-in. mono TTG, Ultra 400, day-lite
Damage Description	Glazing failed and film tore significantly but was retained in frame wadded at sill	Glazing failed and film was retained intact in frame, small tear in corner and 10-inch film pullout on right edge	Glazing failed and film tore at vertical edges with all film retained in frame	Glazing failed, window left frame and landed inside structure with one corner protruding to outside
Glass Fragment Locations	A few fragments inside to back of structure, no impact on witness panel, frags to 56 ft in front of structure	Dusting/small fragments on sill, frags to 43 ft in front of structure, about 50% glass retained on film	A few fragments inside to back of structure, no impact on witness panel, frags to 89 ft in front of structure, most glass left film on rebound	A few fragments inside to back of structure, no impact on witness panel, frags to 33 ft in front of structure
Fragment Hazard to Occupants	Minor hazard to occupants within 10 ft behind window	No hazard to occupants	Minor hazard to occupants within 10 ft behind window	Minor hazard to occupants within 10 ft behind window
Condition	3-SHR	2	3-SHR	3

Test Notes:
1) Windows were mounted in heavy steel frames unless otherwise noted.
2) Window sizes for all steel framed windows were: pane = 48 x 66 inches; clear opening = 46 x 64 inches.
3) Window sizes for aluminum framed windows were: pane = 46-1/8 x 64-1/8 inches; clear opening = 45.5 inches x 63.5 inches.
4) AG = annealed glass, HSG = heat strengthened glass, TTG = thermally tempered glass.
5) Witness panels were located 116 inches behind window.
6) Percentages reported are percentage of all glass from a specimen unless otherwise noted.
7) The SHR stands for significant-hazard-reduction. This designation is used to distinguish a significantly reduced glass fragment hazard obtained with a protective window system versus a highly hazardous uncontrolled failure with no protective measure that is given the same GSA hazard condition. The SHR designation can be given for GSA conditions 3-5.

Pre Test

Post Test

Test 3, Window 1, 5.3 psi

- 1/4-in. mono TTG, Ultra 400, 4 sided batten
- Glazing failed and film tore significantly but was retained in frame wadded at sill
- A few fragments inside to back of structure, no impact on witness panel

Post Test

Post Test

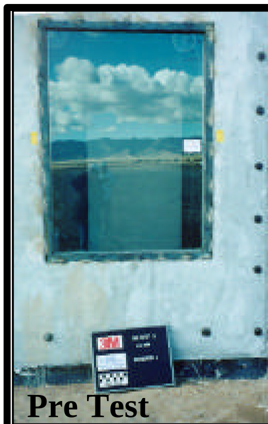
Pre Test

Post Test

Test 3, Window 2, 5.3 psi

- 1/4-in. mono TTG, Ultra 600, 4-sided batten
- Glazing failed and film was retained intact in frame with a 10 inch pullout of film at right edge
- Dusting/small fragments on sill

Post Test



Pre Test

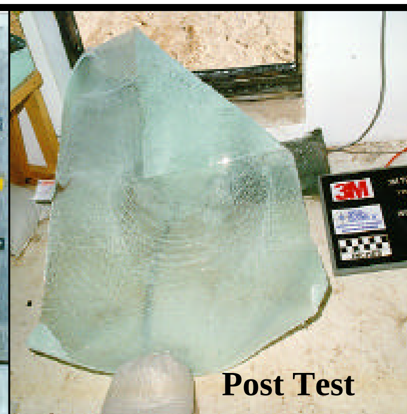
Post Test

Post Test

Test 3, Window 3, 5.3 psi

- 1/4-in. mono HSG, Ultra 600, 4 sided batten
- Glazing failed and film tore at vertical edges with all film retained in frame
- A few fragments inside to back of structure, no impact on witness panel

Pre Test



Post Test

Post Test

Test 3, Window 4, 5.3 psi

- 1/4-in. mono TTG, Ultra 400, day-lite
- Glazing failed, window left frame and landed inside structure
- A few fragments inside to back of structure, no impact on witness panel

TEST 4 SUMMARY

Date:	15 January 1998
Nominal Charge Weight, lb ANFO:	600.0
Standoff to each structure, ft:	190
Avg. Measured Peak Pressure, psi:	4.1
Avg. Measured Positive Impulse, psi-ms:	29.0
Time of Detonation:	12:30
Ambient Temperature, deg F:	51.8

	Window 1	Window 2	Window 3	Window 4
Specimen Description	1/4-in. mono AG, Ultra 600, 4-sided batten	1/4-in. mono TTG, Ultra 400, 4-sided wet glaze, aluminum frame	1/4-in. mono AG, Ultra 400, 4-sided wet glaze, aluminum frame	1/4-in. mono TTG, Ultra 400, 4-sided batten
Damage Description	Glazing failed and film tore in u-shape in the middle but was completely retained in frame	Glazing failed and film was retained intact in frame with no openings, aluminum frame bowed on all sides	Glazing failed and film was pulled from frame on top left corner with all film retained in frame, aluminum frame bowed on vertical edges	Glazing failed and film was retained intact in frame, film pulled out of batten about 22 inches each vertical edge
Glass Fragment Locations	A few fragments inside to back of structure, no impact on witness panel, frags to 44 ft in front of structure	No fragments inside structure, frags to 47 ft in front of structure, about 30% glass retained on film	A few fragments inside 2/3 to back of structure, no impact on witness panel, frags to 74 ft in front of structure, about 10-15% glass retained on film	Small dicing on floor almost to back of structure, no impact on witness panel, frags to 37 ft in front of structure, about 60% glass retained on film
Fragment Hazard to Occupants	Minor hazard to occupants within 10 ft behind window	No hazard to occupants	Minor hazard to occupants within 10 ft behind window	Minor hazard to occupants within 10 ft behind window
Condition	3	2	3-SHR	3-SHR

Test Notes:
1) Windows were mounted in heavy steel frames unless otherwise noted.
2) Window sizes for all steel framed windows were: pane = 48 x 66 inches; clear opening = 46 x 64 inches.
3) Window sizes for aluminum framed windows were: pane = 46-1/8 x 64-1/8 inches; clear opening = 45.5 inches x 63.5 inches.
4) AG = annealed glass, HSG = heat strengthened glass, TTG = thermally tempered glass.
5) Witness panels were located 116 inches behind window.
6) Percentages reported are percentage of all glass from a specimen unless otherwise noted.
7) The SHR stands for significant-hazard-reduction. This designation is used to distinguish a significantly reduced glass fragment hazard obtained with a protective window system versus a highly hazardous uncontrolled failure with no protective measure that is given the same GSA hazard condition. The SHR designation can be given for GSA conditions 3-5.

Pre Test

Post Test

Test 4, Window 1, 4.1 psi

- 1/4-in. mono AG, Ultra 600, 4 sided batten
- Glazing failed and film tore but was completely retained in frame
- A few fragments inside to back of structure, no impact on witness panel

Post Test

Pre Test

Post Test

Test 4, Window 2, 4.1 psi

- 1/4-in. mono TTG, Ultra 400, 4-sided wet glaze, aluminum frame
- Glazing failed and film was retained intact in frame with no openings

Post Test

Test 4, Window 3, 4.1 psi

- 1/4-in. mono AG, Ultra 400, 4 sided wet glaze, aluminum frame
- Glazing failed and film pulled from frame in top corner
- A few fragments inside 2/3 to back of structure

Test 4, Window 4, 4.1 psi

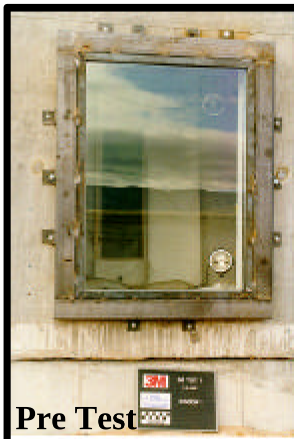
- 1/4-in. mono TTG, Ultra 400, 4-sided batten
- Glazing failed and film was retained in frame
- Small dicing on floor almost to back of structure

TEST 5 SUMMARY

Date:	16 January 1998
Nominal Charge Weight, lb ANFO:	600.0
Standoff Windows 1 and 4, ft:	122.2
Standoff Windows 2 and 3, ft:	121
Avg. Measured Peak Pressure, psi:	9.1
Avg. Measured Positive Impulse, psi-ms:	49.6
Time of Detonation:	11:30
Ambient Temperature, deg F:	49.0

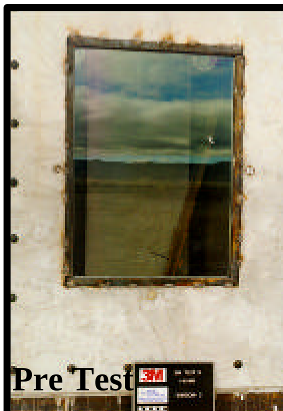
	Window 1	**Window 2**	**Window 3**	**Window 4**
Specimen Description	3/8-in. mono TTG, Ultra 400, 4-sided batten	1/2-in. mono TTG, Ultra 600, 4-sided batten	1/2-in. mono TTG, Ultra 400, 4-sided batten	3/8-in. mono TTG, Ultra 400, day-lite
Damage Description	Glazing failed and film tore across top and right edge but retained in frame	Glazing failed and film was retained intact in frame with no openings	Glazing failed and film tore along right edge and a hole developed on left of window, all film retained in frame	Glazing failed and left frame in one piece with no tearing of film, landed 46 inches in front of structure
Glass Fragment Locations	A few fragments inside contained in front 2/3 of structure, no impact on witness panel, frags to 51 ft in front of structure, about 40-50% glass retained on film	No fragments inside structure, frags to 34 ft in front of structure, about 5-10% glass retained on film	Several fragments inside, 20 fragment impact on witness panel– 7 below 2-ft height, 13 above 2-ft height, about 5% glass retained on film	A few fragments inside back to mid structure, few frags to 23 ft in front of structure, about 90-95% glass retained on film
Fragment Hazard to Occupants	Minor hazard to occupants within 10 ft behind window	No hazard to occupants	Moderate “hit or miss” hazard to persons within 10-15 ft behind window	Minor hazard to occupants within 10 ft behind window
Condition	3	2	5-SHR	3-SHR

Test Notes:
1) Windows were mounted in heavy steel frames unless otherwise noted.
2) Window sizes for all steel framed windows were: pane = 48 x 66 inches; clear opening = 46 x 64 inches.
3) Window sizes for aluminum framed windows were: pane = 46-1/8 x 64-1/8 inches; clear opening = 45.5 inches x 63.5 inches.
4) AG = annealed glass, HSG = heat strengthened glass, TTG = thermally tempered glass.
5) Witness panels were located 116 inches behind window.
6) Percentages reported are percentage of all glass from a specimen unless otherwise noted.
7) The SHR stands for significant-hazard-reduction. This designation is used to distinguish a significantly reduced glass fragment hazard obtained with a protective window system versus a highly hazardous uncontrolled failure with no protective measure that is given the same GSA hazard condition. The SHR designation can be given for GSA conditions 3-5.



Test 5, Window 1, 9.1 psi

- 3/8-in. mono TTG, Ultra 400, 4 sided batten
- Glazing failed and film tore across top and right edge but retained in frame
- A few fragments inside 2/3 to back of structure



Test 5, Window 2, 9.1 psi

- 1/2-in. mono TTG, Ultra 600, 4-sided batten
- Glazing failed and film was retained intact in frame with no openings

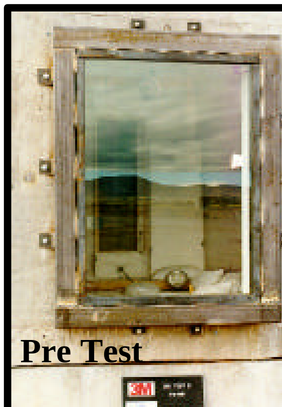

Pre Test


Post Test


Post Test

Test 5, Window 3, 9.1 psi

- 1/2-in. mono TTG, Ultra 400, 4 sided batten
- Glazing failed and film tore along left and right edge
- 20 fragment impact on witness panel


Pre Test


Post Test


Post Test

Test 5, Window 4, 9.1 psi

- 3/8-in. mono TTG, Ultra 400, day-lite
- Glazing failed and left frame in one piece with no tearing of film

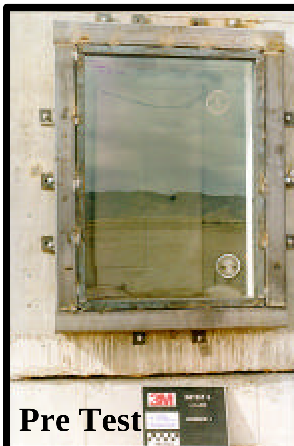
TEST 6 SUMMARY

Date:	19 January 1998
Nominal Charge Weight, lb ANFO:	600.0
Standoff Windows 1 and 4, ft:	122.2
Standoff Windows 2 and 3, ft:	121
Avg. Measured Peak Pressure, psi:	9.0
Avg. Measured Positive Impulse, psi-ms:	49.6
Time of Detonation:	12:30
Ambient Temperature, deg F:	50.8

	Window 1	Window 2	Window 3	Window 4
Specimen Description	1/4-in. mono TTG, Ultra 400, day-lite	1/4-in TTG + 1/2-inch air gap + 1/4-inch TTG, Ultra 400, 4-sided batten	1/4-in TTG + 1/2-inch air gap + 1/4-inch TTG, Ultra 600, 4-sided batten	1/4-in TTG + 1/2-inch air gap + 1/4-inch TTG, no film
Damage Description	Glazing failed, film tore but left frame in one piece and impacted witness panel	Glazing failed and film tore along right and bottom edge, film retained in frame	Glazing failed and film retained intact in frame with no openings	Glazing failed and most glass entered the structure at high velocity
Glass Fragment Locations	Window impact mark at 30-inch height, >100 impact on witness panel, few frags to 12 ft in front of structure, 70-80% glass retained on film	Few fragments inside structure, no impact on back wall, frags from window 2 & 3 undiscernible – scatter to 61 ft in front of structure, about 80% glass from inner lite retained on film	No glass inside structure, frags from window 2 & 3 undiscernible – scatter to 61 ft in front of structure, 20% glass from inner lite retained on film	130 impact on witness panel – 72 above 2-ft height, 58 below 2-ft height, less than 20% glass outside to 22 ft in front of structure
Fragment Hazard to Occupants	Significant hazard to persons within 10-15 ft behind window	Minor hazard to occupants within 10 ft behind window	No hazard to occupants	Significant hazard to persons within 10-15 ft behind window
Condition	5	3-SHR	2	5

Test Notes:

1) Windows were mounted in heavy steel frames unless otherwise noted.
2) Window sizes for all steel framed windows were: pane = 48 x 66 inches; clear opening = 46 x 64 inches.
3) Window sizes for aluminum framed windows were: pane = 46-1/8 x 64-1/8 inches; clear opening = 45.5 inches x 63.5 inches.
4) AG = annealed glass, HSG = heat strengthened glass, TTG = thermally tempered glass.
5) Witness panels were located 116 inches behind window.
6) Percentages reported are percentage of all glass from a specimen unless otherwise noted.
7) The SHR stands for significant-hazard-reduction. This designation is used to distinguish a significantly reduced glass fragment hazard obtained with a protective window system versus a highly hazardous uncontrolled failure with no protective measure that is given the same GSA hazard condition. The SHR designation can be given for GSA conditions 3-5.



Pre Test

Post Test

Post Test

Test 6, Window 1, 9.0 psi

- 1/4-in. mono TTG, Ultra 400, day lite
- Glazing failed, film tore but left frame in one piece and impacted witness panel

Post Test

Pre Test

Post Test

Post Test

Test 6, Window 2, 9.0 psi

- 1/4-in TTG + 1/4 inch air gap + 1/4 inch TTG, Ultra 400, 4-sided batten
- Glazing failed and film tore along right and bottom edge
- Few fragments inside structure, no impact on back wall

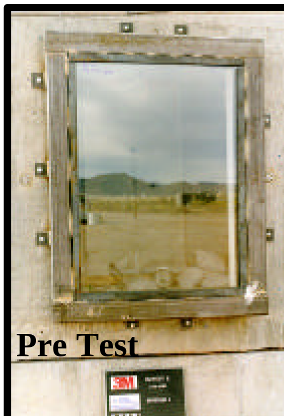

Pre Test


Post Test


Post Test

Test 6, Window 3, 9.0 psi

- 1/4-in TTG + 1/4 inch air gap + 1/4 inch TTG, Ultra 600, 4-sided batten
- Glazing failed and film retained intact in frame with no openings


Pre Test


Post Test


Post Test

Test 6, Window 4, 9.0 psi

- 1/4-in TTG + 1/4 inch air gap + 1/4 inch TTG, no film
- Glazing failed and most glass entered the structure at high velocity
- 130 fragment impact on witness panel

CONVERSION FACTORS
(NON-SI TO SI UNITS OF MEASUREMENT)

Non-SI units of measurement used in the report can be converted to SI units as follows:

Multiply:	By:	To Obtain:
degrees (deg)	0.01745329	radians (rad)
miles (U.S. statute)	1.609347	kilometers (km)
feet (ft)	0.3048	meters (m)
inches (in)	25.4	millimeters (mm)
mil	0.0254	millimeters (mm)
pounds (lb)	4.448222	newtons (N)
pounds (lb)	0.4535924	kilogram (kg)
kips per square inch (ksi)	6.894757	megapascals (mPa)
pounds per square inch (psi)	6894.757	pascals (N/m^2 or Pa)
pounds per square inch (psi)	6.894757	kilopascals (kPa)
pounds per square inch (psi)	0.006894757	megapascals (mPa)

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

When an explosion is detonated in an urban environment, window breakage is typically widespread and can occur over several city blocks. The window glass fragments generated by such an event are either driven into the buildings or drawn outside the buildings resulting in injury to building occupants and street pedestrians. For example, over 500 people in Oklahoma City sustained injuries (many due to window glass failure) and required medical attention due to the bombing of the A.P. Murrah Building in 1995.

To reduce the window glass fragment hazard generated by blast, several technologies have emerged, including security window films, laminated glass, blast curtains, blast louvers, etc. Security films, which are applied to the inner surface of the glazing, hold the glass together and use the plastic membrane response of the film to control the failure of the glazing. Blast testing has been performed on security window films, and they have been shown to be very effective at reducing hazards associated with failed glazings.

The US General Services Administration (GSA) oversees design and construction of new facilities and manages the existing real property inventory for a large portion of the US Government. After the Oklahoma City bombing, the President issued a directive for government agencies to take action toward protecting government facilities. In response to this presidential directive, the GSA published a security criteria document (GSA Security Criteria, Final Working Version, January 17, 1997 and subsequent revisions) which specifically addresses blast protection issues for both new and existing GSA facilities. Part of the criteria addresses window glazings and the associated hazard generated by blast. This portion of the criteria was based in part on a series of blast tests on windows performed by the GSA and other blast test data. The glazing criteria are performance based. The glass fragment hazard generated by windows is graded based on the post-blast location of glass fragments in a blast test. The GSA has indicated that manufacturers of glass fragment mitigating products must test their products to be considered for use in GSA Level C and D facilities.

3M commissioned Applied Research Associates, Inc. (ARA) to perform a series of six high explosive blast tests in order to evaluate the performance of their security window film. While this test series was aimed primarily at grading the 3M products against the GSA criteria, the test data will also provide useful information for many other government and civilian entities, both domestic and foreign, that are responsible for security planning of building facilities.

The tests were conducted at the Defense Special Weapons Agency's Chestnut Test Site on Kirtland Air Force Base in New Mexico during the period of January 12-19, 1998. The test procedure was designed in accordance with the same procedure used by the GSA. Each test used 600 lb of ANFO which is equivalent to 500 lb of TNT. The window sizes were the same as those tested by the GSA (4 ft by 5-1/2 ft). The windows were mounted in enclosed concrete reaction structures for testing. The standoff distance of the charge to the windows was varied to affect particular blast pressure levels on the windows.

The main goal for 3M in this test series was to show the benefit of their Ultra 400 product (4-mil thick film) and newly developed Ultra 600 (6-mil thick film) which were designed to offer significantly more tear resistance than typical commercial window films of comparable thickness. 3M intended to show with this test series that required levels of protection for GSA Level C and Level D buildings could be achieved with their Ultra 400 and Ultra 600 products.

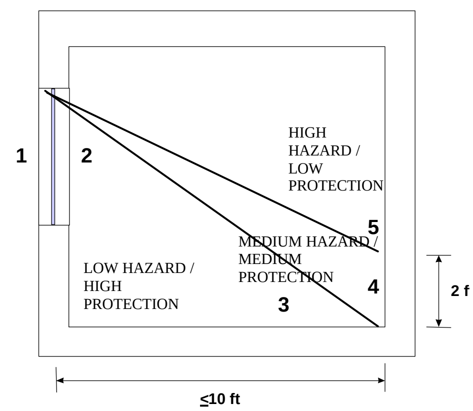
This test report documents the major findings from this test series.

1.2 OBJECTIVES

The primary objective of this test series was to evaluate the window glass fragment mitigation characteristics of 3M security film products in blast environments. The effect of various test specimen parameters was investigated to evaluate the effect of these variances on the performance of the films. The specimen parameters that were varied included: film type (thickness), film application/attachment, glass type, glass thickness, glass configuration (i.e., monolithic or insulated glass) and window frame type. The performances of the window systems were graded against the GSA Security Criteria.

1.3 GSA CRITERIA

Test results were related to the GSA Security Criteria. The GSA glass fragment hazard rating scheme is presented graphically and is described in Figure 1.1. The approach compares potential hazards based on the type and location of glass fragments interior and exterior to the test cubicle. These criteria indirectly reflect the velocity of fragments based on their distance from the window.



Side Elevation View of Test Structure

Condition	Description	Glass Fragments: Exterior to Structure	Glass Fragments: Interior to Structure	Hazard Level	Protection Level
1	Glass not cracked, fully survived and/or fully retained by frame and no glass fragments either inside or outside structure.	None	None	NA	Very high
2	Glass may be cracked but is retained by the frame.	Yes	No significant fragments. Dusting or very small fragments near sill or on floor acceptable.	Very Low	Very High
3	Glass failed and not fully retained in frame.	Yes	Yes - land on floor no more than 10 ft from window	Low	High
4	Glass failed and not fully retained in frame.	Yes	Yes - land on floor more than 10 ft from window and impact a vertical surface located not more than 10 ft behind the window no higher than 2 ft above floor level.	Medium	Medium
5	Glass fails catastrophically.	Yes	Yes - land on floor more than 10 ft from window and impact a vertical surface not more than 10 ft behind window above a height of 2 ft.	High	Low

Figure 1.1. GSA window glazing hazard rating scheme.

CHAPTER 2
TEST CONFIGURATION

2.1 TEST RANGE

The test series was performed at the Chestnut Test Site on Kirtland Air Force Base in New Mexico. This test site is owned and operated by the DSWA Field Command which is the US Government's lead agency for force protection.

2.2 TEST STRUCTURES AND TEST BED

Three concrete reaction structures were used for this test series. Reaction structures were enclosed and sealed to prevent airblast engulfment effects that occur in open frame blast tests. When a window or other specimen is blast tested in a open frame, the airblast engulfs the specimen before it can completely respond. The result is an airblast loading from both the front and the back. The net load driving the specimen is the difference between the load on the front of the specimen and the back of the specimen. This net differential load is much less than that which is obtained by using an enclosed reaction structure. To best simulate the loads that can be expected on typical buildings, the enclosed reaction structure is required.

Two reaction structures housed one window per test. A modular reaction structure was also used. The modular structure housed two window specimens per test. A median interior wall in this structure isolated infill airblast environments for each specimen. This prevented any potential engulfment effect that could occur if one window failed before the other window in this structure.

The three structures were placed in a semi-circle at 30 ft on center with windows facing in toward the charge. The modular structure was located in the center with the smaller boxes to either side. Window nomenclature and orientations are shown in Figure 2.1.

The charge standoff was varied from the structures to vary airblast environments on the window specimens. With multiple structures, when varying the standoff for close-in detonations, it is also necessary to change the rotations of the boxes to insure a normal impingement of the blast wave on the front face of each structure. The maximum reflected pressure level for these tests was 9 psi, and the minimum reflected pressure level was 4 psi. To affect these pressures on the structures for the charge size used in this series, standoff distances varied between about 121 ft and 190 ft. The angle the charge makes with the front of the structures does not vary much for these long standoff distances. Hence, it was not necessary to change rotation of the boxes for every test. For the previous GSA tests that used the same target blast levels, charge size and a similar test reaction structure arrangement, a "median" arrangement of the structures was used and no rotation of the structures was necessary between tests. The placement of these structures for this test series is as shown Figure 2.2.

The soil at the test site contains rocks. In order to reduce the potential for rock impact of the specimens, pits were dug at the ground zero locations and filled with clean dry sand. These pits were nominally 12 ft wide by 12 ft wide by 2 to 3 ft deep.

The structure depth for all three structures was nominally 10 ft inside from the window opening to the rear of the structure. Wood framed walls were erected in the rear of the structures for mounting of the rigid foam witness panels. These were located about 116 inches from the back of the windows in accordance with the GSA criteria (criteria dictates $\leq$10 ft). The witness panels were 4 ft wide by 8 ft high and were located behind the window openings. Butcher paper was attached to the rigid foam witness panel for survey of glass fragment impacts.

2.3 INSTRUMENTATION

The reaction structures were instrumented with exterior pressure gages (Figure 2.3) to monitor the reflected pressures near the window specimens. Two exterior pressure gages were used for each window for a total of eight exterior pressure gages. These were located as close as possible to either side of the window specimens mounted in the concrete wall near the vertical center of the window.

Interior pressure gages were mounted on the back wall (Figure 2.4) to monitor the infill pressures for each window. Infill pressures from all tests were very small and would not pose a hazard to occupants. All measured pressure data is plotted in Appendix B.

A high-speed video camera was located inside the structures behind each window and off to one side of the cubicle. The cameras used a Plexiglas screen to protect the lenses. In the modular structure the cameras were rigid mounted to the structure floor on steel tube stands. The cameras inside the small retrofitted structures were mounted on sandbags.

A high-speed film camera and a normal speed video camera were located about 750 ft to the south of the test bed range to capture exterior views of the explosion and the structures. See Figure 2.5 for all camera locations.

A temperature sensor was used to monitor the ambient temperature and variances of the glass temperature to ambient. Throughout the test series the glass temperature tended to be slightly lower than the ambient. In all cases ambient air and glass temperatures were within 4 degrees F of each other.

2.4 TEST CHARGE

The test charge for each test was 600 lb of ammonium nitrate and fuel oil which is equivalent to 500 lb of TNT. The charge was built in a 30-inch diameter cardboard Sonatube with two Pentolite boosters located in the center of the charge (Figures 2.6 and 2.7). The charge standoff distance was measured with a measuring tape and an iterative process was used to locate the charge the same distance from each window (Figure 2.8).

2.5 INSTALLATION DETAILS

Most windows were tested in non-responding steel frames that were similar in design to those used in the GSA's blast tests. For the steel framed windows, the pane dimension was 48 inches by 66 inches and the vision opening was 46 inches by 64 inches. Windows in typical 1-3/4-inch by 4-1/2-inch storefront aluminum frames were also tested. For the aluminum framed windows, the pane size was 46-1/8 inches by 64-1/8 inches and the vision opening was 45-1/2 inches by 63-1/2 inches.

Security window films can be applied in various configurations. Anchoring of the window film to the window frame provides benefit in controlling the window system after failure of the glazing. Several methods are available for film to window frame attachment. Two methods tested by 3M included an aluminum batten bar attachment and a wet glazed attachment. The aluminum batten bar is used to capture and hold down the film at the window edges. High strength tape adhesives are used to attach the film to the window frame and the batten bar. The batten bar is screwed to the window frame with quarter-inch hex head screws at 6 inches on center. Both two- and four-sided batten attachments were tested. The wet glazed application uses a high strength adhesive to attach the film to the window frame. 3M tested a four-sided wet glazed application in aluminum window frames. Day-lite film applications were also tested. Day-lite films are applied to the vision surface of the glass only and are not mechanically attached to the frame.

The window mounting details are shown in Figure 2.9. The through holes in the steel tube stop of the window frame were offset so that the tube could be reversed to give a 1-1/2-inch gap for insulated glass units (1-inch window plus two ¼-inch gaskets). Window details for a window mounted in a steel frame are shown in Figure 2.10 along with details of the batten film installation. Figure 2.11 shows the mounting detail of a typical aluminum frame with a wet glazed film attachment.

2.6 TEST MATRIX

A complex test matrix (Table 2.1) was designed in a joint effort between ARA and 3M in an attempt to get the most useful information from the limited number of specimens to be tested. Most windows were tested in heavy steel frames similar to ones used in the previous GSA tests. Windows were also tested in aluminum storefront window frames to evaluate the strength of the connection of both batten systems and the wet glazed film attachments to these type frames. Most testing was aimed at evaluation of typical 1/4-inch monolithic glass. One test included both 3/8- and 1/2-inch monolithic glass. Another test included 1-inch thick insulated glass units which consisted of two ¼-inch panes with a half-inch air gap between. Glass types tested included:

1) Annealed Glass (AG) – this is the most common glass type that is used in construction. It is also the weakest type glass and fails in large hazardous dagger-like fragments.
2) Heat Strengthened Glass (HSG) – this glass has about twice the compressive strength of regular AG but also fails in large hazardous shards.
3) Thermally Tempered Glass (TTG) – this glass has about four times the compressive strength of regular AG and is the same glass used by car manufacturers for side windows in automobiles. The TTG dices into small cube like pieces upon failure.

Pretest predictions included in Table 2.1 were made based on analytical models and extrapolations from previous test data.

Table 2.1. Test article matrix and pretest predictions.

Test # / standoff / Peak pressure*	Win. #	Test Articles	Expected Performance (GSA Rating)
1 standoff = 190 ft peak pressure = 4.0 psi	1 2 3 4	¼-in. mono. AG, Ultra 400 w/day-lite application ¼-in. mono. AG, Ultra 400 w/4-sided batten ¼-in. mono. AG, 7-mil film w/4-sided batten ¼-in. mono. AG	3 2-3 2-3 5
2 standoff = 190 ft peak pressure = 4.0 psi	1 2 3 4	¼-in. mono. HSG, Ultra 400 w/4-sided batten ¼-in. mono. TTG, Al frame, Ultra 400 w/4-sided batten ¼-in. mono. AG, Al frame, Ultra 400 w/4-sided batten ¼-in. mono. AG, Ultra 400 w/2-sided batten	2-3 2-3 2-3 2-3
3 standoff = 165 ft peak pressure = 5.0 psi	1 2 3 4	¼-in. mono. TTG, Ultra 400 w/4-sided batten ¼-in. mono. TTG, Ultra 600 w/4-sided batten ¼-in. mono. HSG, Ultra 600 w/4-sided batten ¼-in. mono. TTG, Ultra 400 w/day-lite application	2-3 2-3 2-3 3
4 standoff = 190 ft peak pressure = 4.0 psi	1 2 3 4	¼-in. mono. AG, Ultra 600 w/4-sided batten ¼-in. mono. TTG, Al frame, Ultra 400 w/4-sided wet glaze ¼-in. mono. AG, Al frame, Ultra 400 w/4-sided wet glaze ¼-in. mono. TTG, Ultra 400 w/4-sided batten	2-3 2-3 2-3 2-3
5 standoff = 121 ft peak pressure = 9.0 psi	1 2 3 4	3/8-in. mono. TTG, Ultra 400 w/4-sided batten ½-in. mono. TTG, Ultra 600 w/4-sided batten ½-in. mono. TTG, Ultra 600 w/4-sided batten 3/8-in. mono. TTG, Ultra 400 w/day-lite application	2-4 2-3 2-3 3-4
6 standoff = 121 ft peak pressure = 9.0 psi	1 2 3 4	¼-in. mono. TTG, Ultra 400 w/day-lite application 1-in. insulated TTG, Ultra 400 w/4-sided batten 1-in. insulated TTG, Ultra 600 w/4-sided batten 1-in. insulated TTG	3-5 2-3 2-3 5

* Standoff distance and peak pressure have been adjusted for altitudes of 5200 ft.

2.7 COMPLIANCE WITH ASTM TEST METHOD

The American Society for Testing and Materials (ASTM) issued a "Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings" (Designation: F 1642-96). This document addresses methods and requirements to be used when proof testing glazing systems for blast resistance characteristics. Where applicable and possible, these guidelines and requirements were followed. The following lists include guidelines that were followed from the ASTM and exceptions to these guidelines. A copy of the ASTM method is included in Appendix C of this report.

Guidelines Followed:

7.1 The test facility was an open-air arena. The open-air arena was sited on a clear and level terrain. The test facility was situated and of sufficient size to accommodate the amount of explosives. The potential environmental impact issues were determined and resolved prior to testing.

7.2 A high explosive was used. The charge was hemispherical and detonated at ground level.

7.3 A blast mat was omitted at the discretion of the test director. A sandpit was included.

7.4 The test frame was suitable for supporting the glazing systems. The area immediately behind the specimens was enclosed to prevent airblast pressure from wrapping behind the specimens.

7.5 Simple support subframe was not used in this test series.

7.6.2 The data acquisition system (DAS) used a digital recording system with a sufficient number of channels for the pressure transducers. The DAS operated at a sufficiently high frequency to record reliably the peak positive pressure. The DAS incorporated filters to preclude alias frequency effects from the data.

7.6.3 Photographic equipment was available to document the test.

8.1 Storage, handling, and detonation of high explosive material was conducted in accordance with applicable state and federal statutes by experienced professionals.

9.1 The test sponsor provided the test specimens.

9.2 The test sponsor was on site to insure proper handling and storage of test specimens.

9.3 A sticker was attached to each specimen with the manufacturer's model and serial numbers.

9.4 The test sponsor was on site to insure proper specimen orientation to the charge.

9.5 The test sponsor was on site to insure proper anchoring details for window specimens.

10.1.1 The reflected pressure transducers were installed flush with the test frame, facing the detonation point.

10.1.3 The pressure transducers were connected to the DAS and tested to verify proper operation.

10.2.1 The test specimens were installed in the test frame. The test frame was approximately a plane surface. No openings existed for infiltration of airblast pressures. The area immediately behind the specimen was enclosed to prevent airblast pressure wrapping behind the specimens.

10.4.1 A photographic record was made of the test specimen, the test frame and the test configuration prior to each test.

10.4.2 High-speed cameras recorded response of the specimens during the tests.

The following is a list of guidelines that were modified or not followed:

6.1 A minimum of three identical specimens were not tested at each blast level. Cost of testing made this unfeasible.

7.4 The frame system was not typical of field installations. A rigid frame was used for this test series so that the capacity of the glazing system alone could be determined. This same frame was used in the previous GSA tests. Aluminum window frames were also tested. These are typical of field installations although the connection of the aluminum frame into the structure was probably much stronger than a typical connection. The purpose in testing aluminum frames was to test the connection of the attachment methods to these frames.

7.6.1 Two reflected pressure transducers were used on each test frame. The method required a minimum of three reflected transducers on each test frame.

7.6.5 The aluminum witness panel immediately behind the specimen was replaced with a butcher paper panel on rigid foam at the back of the structure. The aluminum panel would have interfered with data obtained and the high-speed film. The aluminum witness panel 12 inches behind the specimen is not consistent with the glass hazard reduction approach to defining success or failure. The ASTM method uses full enclosure of the structure with no infiltration of pressure or glass fragments allowed. The aluminum panel was also eliminated in the GSA tests prior to this test series.

10.2.1 No free-field transducer was used. The value of such a measurement was unclear. This gage was also omitted in the GSA tests.

10.2.2 Orientation of structures to the charge was not perfectly perpendicular (we could not rotate the structures). Predictions were performed to minimize any variance.

10.3.1 Thickness measurements were taken only on one edge.

11.1.4-5 Glass temperature measurements were monitored prior to the test as close to the test time as safety requirements would allow.

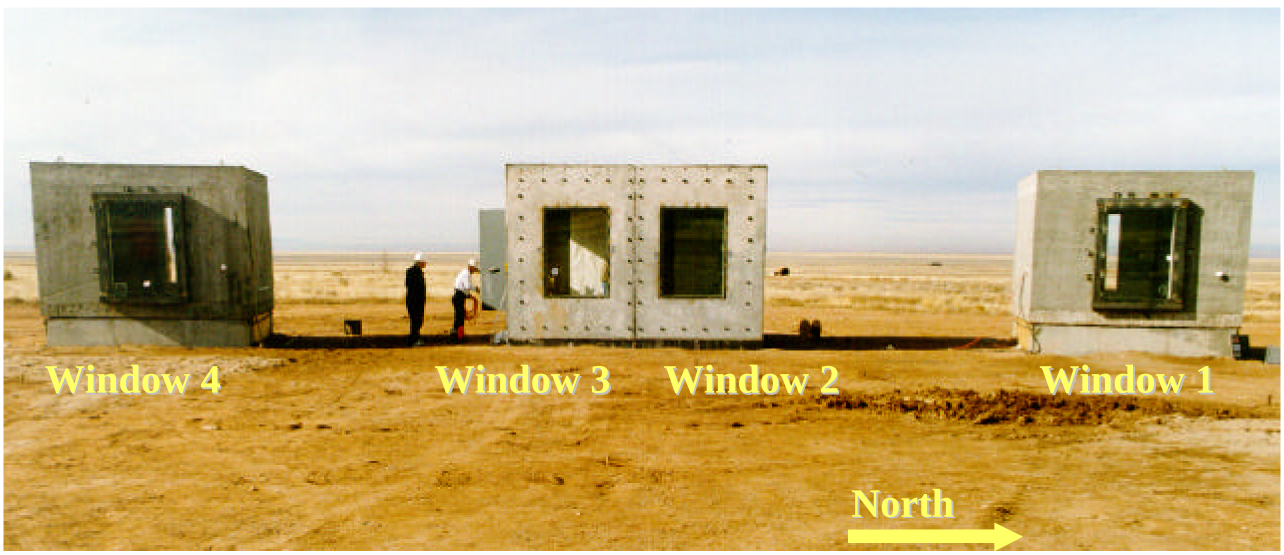


Figure 2.1. Structure orientation and window nomenclature.

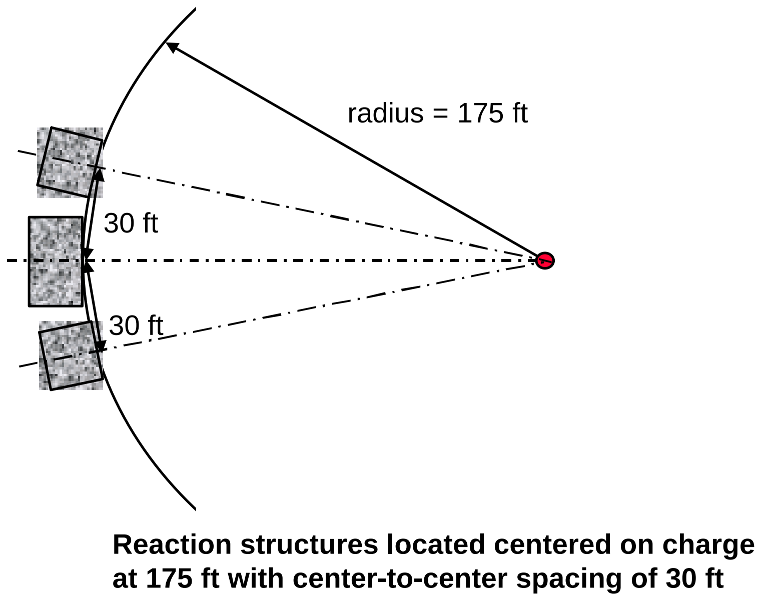


Figure 2.2. Radial orientation of structures (not drawn to scale).

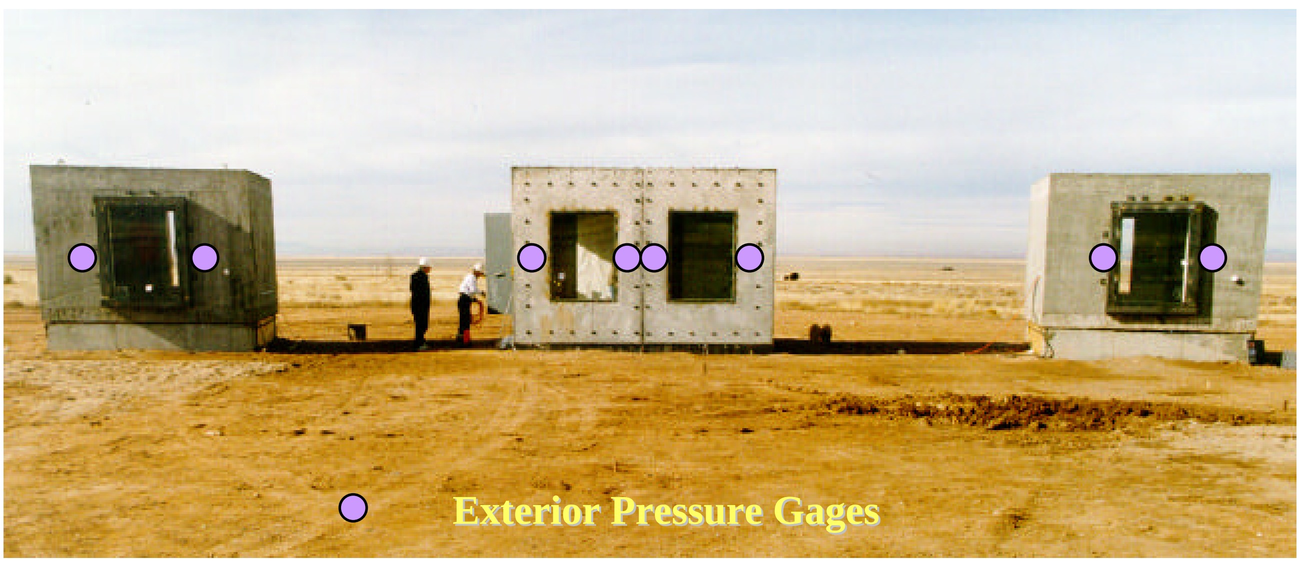


Figure 2.3. Exterior pressure gage locations.

Figure 2.4. Interior pressure gage locations.

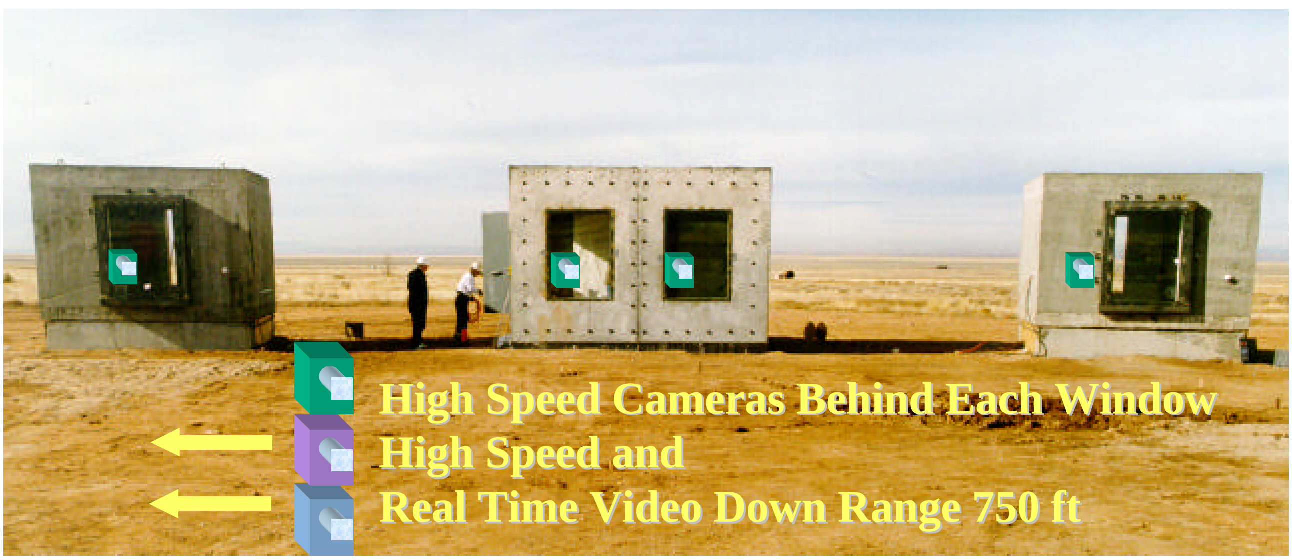


Figure 2.5. Camera locations.

Figure 2.6. Test charge(diameter = 30 inches, height = 26.7 inches).

Figure 2.7. Pentolite booster in the center of the charge.

Figure 2.8. Technicians measuring charge standoff distance.

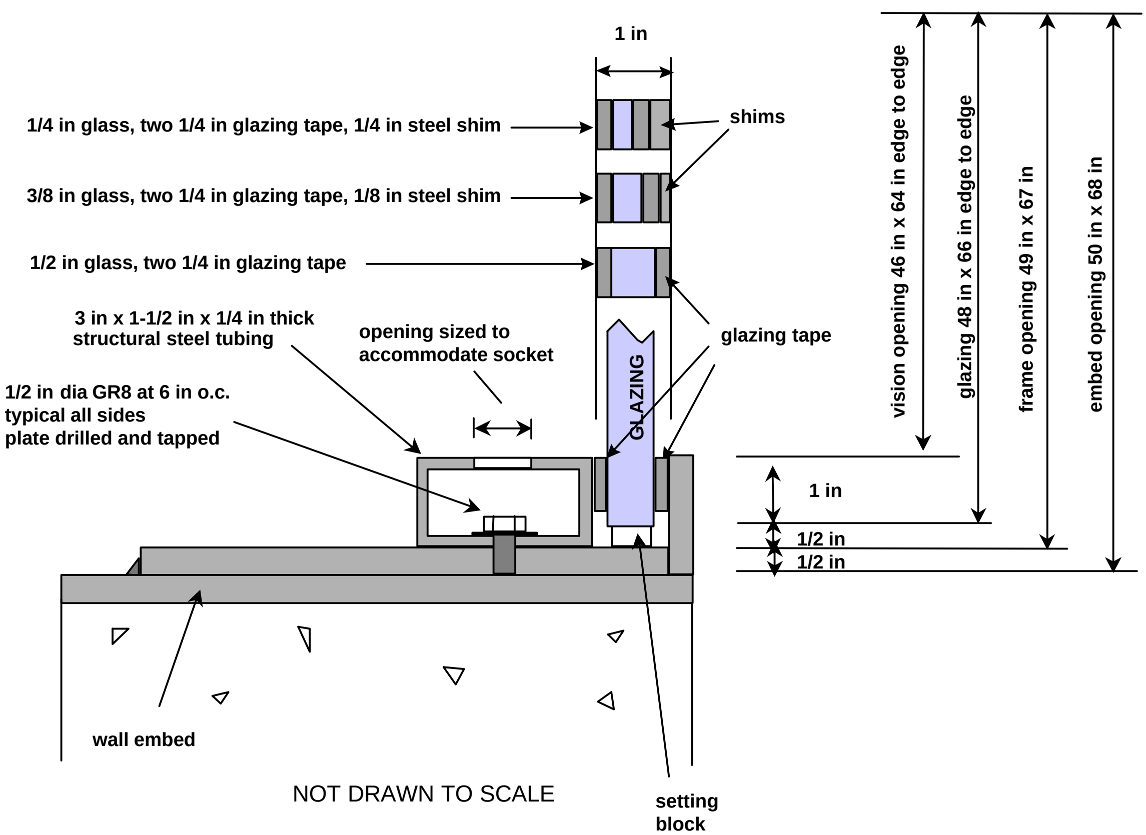


Figure 2.9. Glazing installation detail.

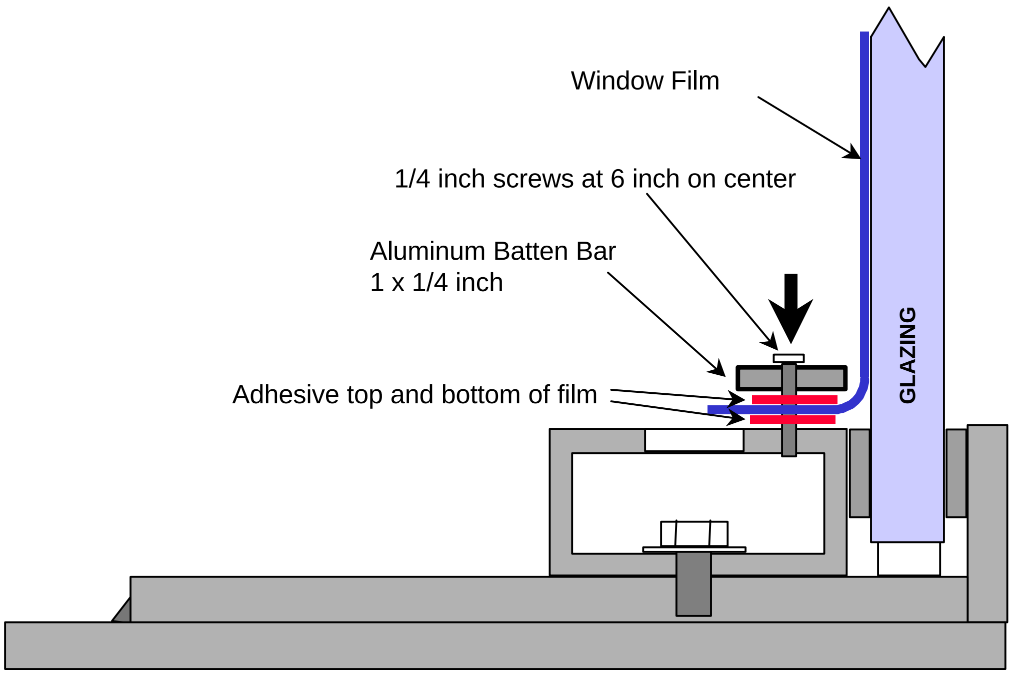


Figure 2.10. Film batten attachment detail.

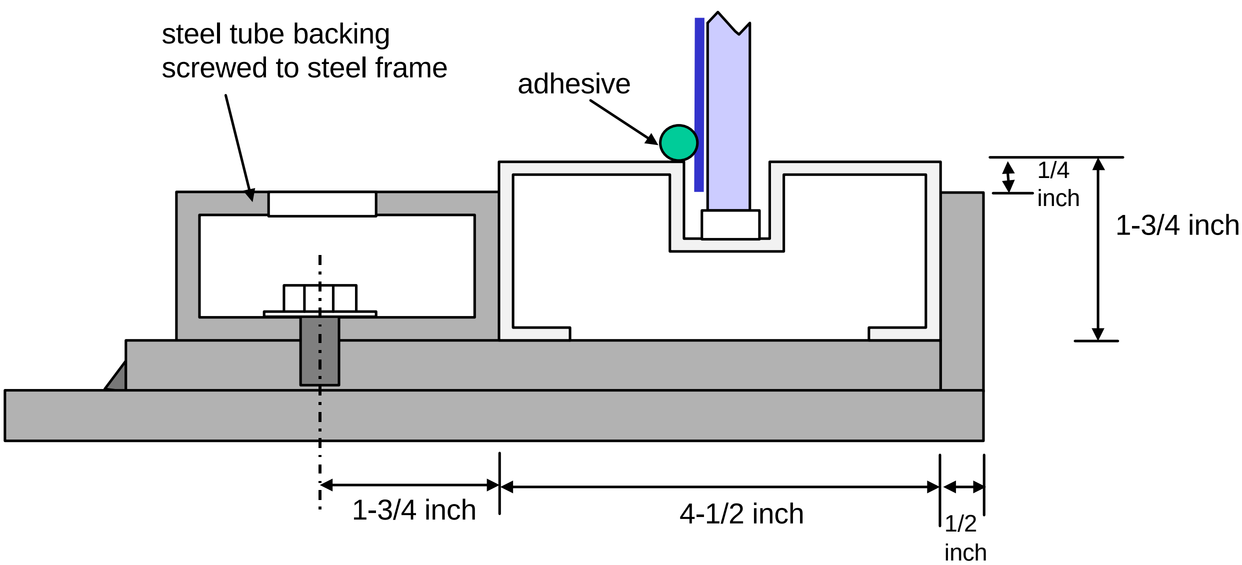


Figure 2.11. Aluminum frame mounting detail with a wet glazed film attachment.

CHAPTER 3

TEST 1

Test 1 was detonated on January 12 at 14:00. The charge was located at a standoff of 190 ft for a target pressure of 4.1 psi. A typical airblast waveform is shown in Figure 3.1, and the average airblast values from the exterior gages are given in Table 3.1. For this test two of the windows used batten attachments. The battens for these windows were held to the steel window frame with quarter-inch thumb screws as shown in Figure 3.2. This was the only test where these type screws were used. For all following days hex-head quarter-inch screws were used to secure the battens to the frames.

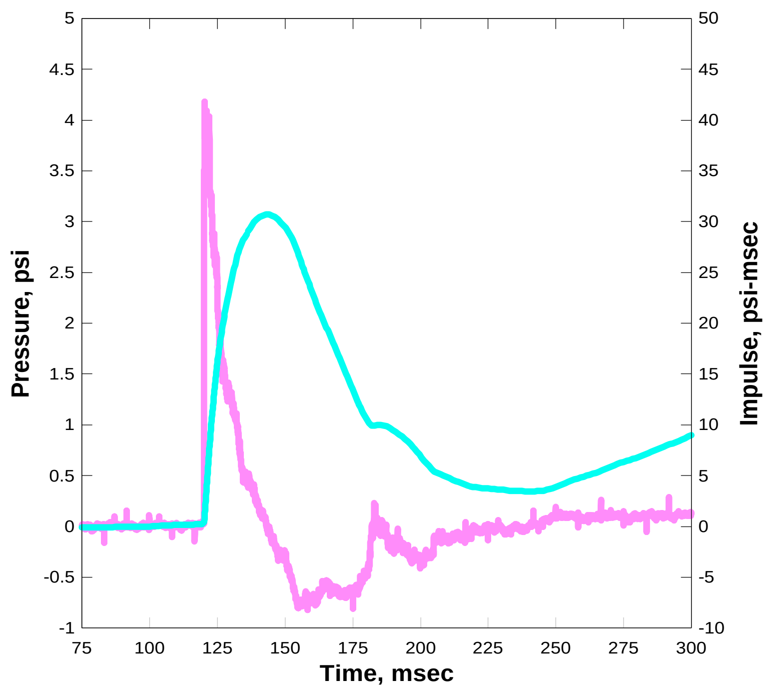


Figure 3.1. Typical airblast waveform from test 1.

Table 3.1. Average airblast values for test 1.

	Peak Positive Pressure (psi)	Peak Positive Impulse (psi-msec)	Peak Negative Pressure (psi)
Average	4.17	28.41	0.83
Standard Deviation	.24	2.91	0.11

3.1 TEST 1, WINDOW 1

Description: ¼-inch monolithic annealed glass, Ultra 400 4-mil film, day-lite application.

Rating: GSA Condition 3 (significant hazard reduction)

The glazing from window 1 broke and the film held nearly all of the glass together with no tears in the film. The film/glass left the window and was drawn out the front of the structure by the negative phase of the airblast pulse. It landed about 18 inches from the structure. Several large fragments were retained in the bite of the window frame. Glass fragments were strewn out to a distance of about 20 ft from the front edge of the structure. Only a few fragments entered the structure and these were either very fine fragments or small cube shaped fragments. There were no glass fragment impacts on the witness panel.

Several pretest photos are included in Figures A.10-A.16. Posttest photos of the window are included in Figure 3.3 and in Figures A.17-A.23.

3.2 TEST 1, WINDOW 2

Description: ¼-inch monolithic annealed glass, Ultra 400 4-mil film, 4-sided batten anchorage.

Rating: GSA Condition 3 (significant hazard reduction)

The glazing of window 2 failed. The film tore at both vertical edges and several inches along the head and sill. Nearly all film was retained in the frame with about 65% of the total window glass retained on the film. There was one large piece of film with glass attached 12 ft from the front of the structure. Several other fragments were strewn out to 26 ft from the front edge of the structure. Only a few very fine fragments and small cube shaped fragments entered the structure. There were no glass fragment impacts on the witness panel.

Several pretest photos are included in Figures A.24-A.26. Posttest photos of the window are included in Figures 3.4 and 3.5 and in Figures A.27-A.30.

3.3 TEST 1, WINDOW 3

Description: ¼-inch monolithic annealed glass, 7-mil film, 4-sided batten anchorage.

Rating: GSA Condition 3 (significant hazard reduction)

The glazing of window 3 failed. The film pulled out or tore from the batten attachment on the top and bottom corners of the left side of the window. The glass did not adhere to the 7-mil film well and most glass was strewn out in front of the structure out to a distance of 78 ft from the front edge of the structure. All film was retained in the frame with only about 5-10% of the total window glass retained on the film. Only a few small fragments entered the structure with no glass fragment impacts on the witness panel.

Several pretest photos are included in Figures A.31-A.33. Posttest photos of the window are included in Figures 3.6 and 3.7 and in Figures A.34-A.37.

3.4 TEST 1, WINDOW 4

Description: 1/4-inch monolithic annealed glass, control specimen with no film.

Rating: GSA Condition 5

The glazing of window 4 failed. About 95% of the fragments entered the structure at high velocities. The glass fragments were strewn across the floor of the reaction structure and many glass fragments impacted the witness panel. Ninety-eight total glass fragment impacts were surveyed on the witness panel with 82 below a 2-ft height (i.e., transition from GSA Condition 4 to GSA Condition 5) and 16 impact above a 2-ft height.

Several pretest photos are included in Figures A.38-A.41. Posttest photos of the window are included in Figures 3.8 and 3.9 and in Figures A.42-A.47.

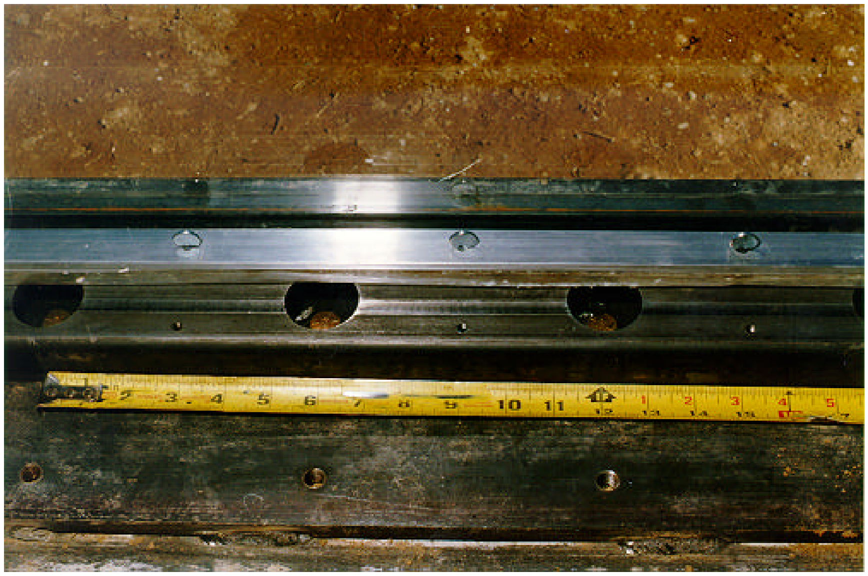


Figure 3.2. Thumb-screw attachment of batten for test 1, windows 2 and 3 (3M T1 pre 01.tif).

Figure 3.3. Exterior posttest view of window 1, test 1 (3M SD T1 post 05.tif).

Figure 3.4. Exterior posttest view of window 2, test 1(3M SD T1 post 20.tif).

Figure 3.5. Interior view of glass fragmentation from window 2, test 1 (3M SD T1 post 18.tif).

Figure 3.6. Exterior posttest view of window 3, test 1 (3M SD T1 post 36.tif).

Figure 3.7. Interior view of glass fragmentation from window 3, test 1 (3M SD T1 post 31.tif).

Figure 3.8. Exterior posttest view of window 4, test 1 (3M SD T1 post 48.tif).

Figure 3.9. Interior view of glass fragmentation from window 4, test 1 (3M SD T1 post 16.tif).

CHAPTER 4

TEST 2

Test 2 was detonated on January 13 at 12:30. The charge was located at a standoff of 190 ft for a target reflected pressure of 4.1 psi. A typical airblast waveform is shown in Figure 4.1, and the average airblast values from the exterior gages are given in Table 4.1.

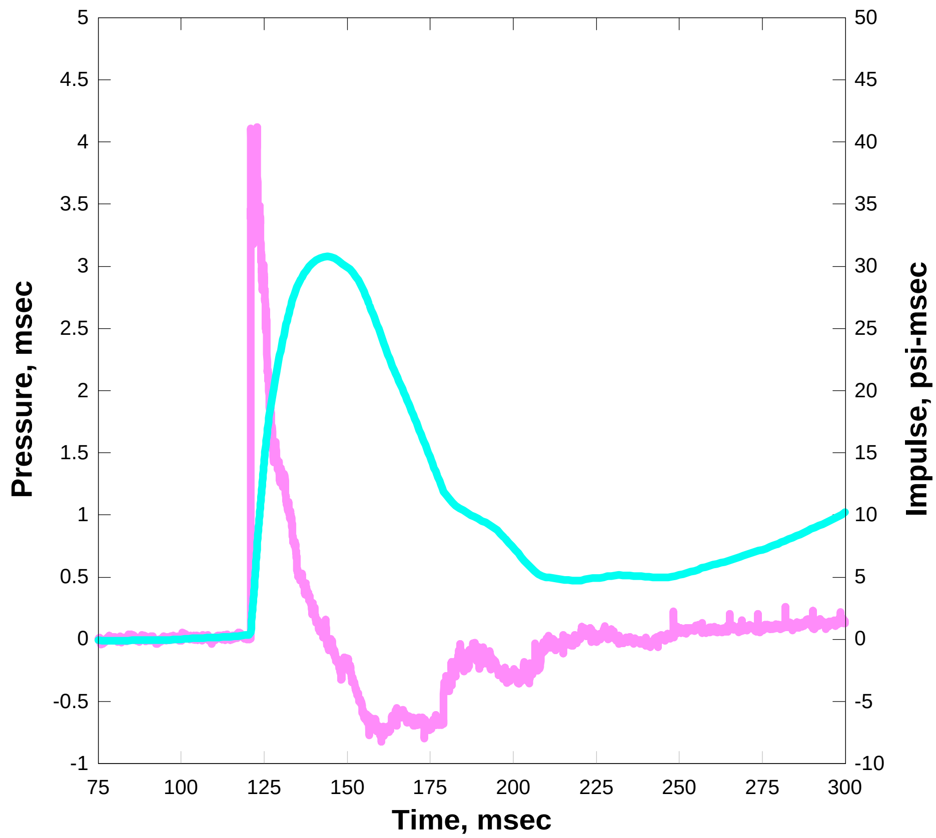


Figure 4.1. Typical airblast waveform from test 2.

Table 4.1. Average airblast values for test 2.

	Peak Positive Pressure (psi)	Peak Positive Impulse (psi-msec)	Peak Negative Pressure (psi)
Average	4.11	28.68	0.82
Standard Deviation	0.29	2.67	0.11

4.1 TEST 2, WINDOW 1

Description: **¼-inch monolithic heat strengthened glass, Ultra 400 4-mil film, 4-sided batten anchorage.**

Rating: **GSA Condition 3 (significant hazard reduction)**

The glazing of window 1 broke. The film tore along most of the right vertical edge and about two-thirds of the left edge. All film was retained in the frame with about 30% of the total window glass retained on the film. Most exterior glass fragments fell within about 40 ft from the structure, but a small number of small fragments were noted out to a distance of about 73 ft from the structure. Only a few fragments entered the structure, and there were no glass fragment impacts on the witness panel.

Several pretest photos are included in Figures A.50-A.53. Post test photos of the window are included in Figures 4.2 and 4.3 and in Figures A.54-A.57.

4.2 TEST 2, WINDOW 2

Description: **¼-inch monolithic thermally tempered glass, Ultra 400 4-mil film, 4-sided batten anchorage, aluminum storefront window frame.**

Rating: **GSA Condition 3 (significant hazard reduction)**

The glazing of window 2 failed. The film tore at the lower left corner. It was noted that the vertical and horizontal batten were not installed flush to one another in the lower left corner and this may have caused the tear. All film was retained in the frame with only about 20% of the total window glass retained on the film. The aluminum batten remained completely attached to the aluminum frame. Several fragments were strewn out to about 42 ft from the front edge of the structure. Only a few fragments entered the structure, and there were no glass fragment impacts on the witness panel.

The aluminum frame bent inwards at the sides significantly with a large permanent set. The aluminum frame was cradled in a steel window frame with a depth into the steel frame of 1-1/2 inches. The high-speed film from this window shows that the outer vertical edges of the aluminum frame bowed inward and out of the steel frame as much as 1-1/2 to 2 inches for a total maximum displacement of about 3 to 3-1/2 inches. The permanent gap as measured from outside the window was about 3/4 inch from the outer edge of the aluminum frame to the vision opening of the steel frame or about a 2-1/4-inch total permanent displacement.

Several pretest photos are included in Figures A.58-A.61. Posttest photos of the window are included in Figures 4.4 and 4.5 and in Figures A.62-A.65.

4.3 TEST 2, WINDOW 3

Description: ¼-inch monolithic annealed glass, Ultra 400 4-mil film, 4-sided batten anchorage, aluminum storefront window frame.

Rating: GSA Condition 5 (significant hazard reduction)

The glazing of window 3 failed. The film tore horizontally across the middle of the window. Most glass left the film on the rebound of the window system and landed in front of the structure out to a maximum distance of about 68 ft. Most film was retained in the frame with a large piece of film and glass found at about 15 ft from the front of the structure. Several fragments entered the structure, and seven fragment impact marks were surveyed on the witness panel.

The aluminum frame bent inwards at the sides with a permanent set. Similar to window 2, the aluminum window frame bowed in at the vertical edges and the outer edge of the aluminum frame came out of the steel frame about an inch based on the high-speed film footage. The maximum permanent set on this frame as measured from the outside was about 2 inches total on both vertical edges.

Several pretest photos are included in Figures A.66-A.67. Posttest photos of the window are included in Figures 4.6 and 4.7 and in Figures A.68-A.72.

4.4 TEST 2, WINDOW 4

Description: ¼-inch monolithic annealed glass, Ultra 400 4-mil film, 2-sided batten anchorage.

Rating: GSA Condition 3 (significant hazard reduction)

The glazing of window 4 failed and the film tore at both vertical edges. Most of the film with glass attached was drawn out by the negative phase of the blast and landed about 34 inches from the front of the structure. Most exterior glass fragments fell within about 22 ft from the front of the structure. Only a few fragments entered the structure and there were no glass fragment impacts on the witness panel.

Several pretest photos are included in Figures A.38-A.41. Posttest photos of the window are included in Figures 4.8 and 4.9 and in Figures A.42-A.47.

Figure 4.2. Exterior posttest view of window 1, test 2 (3M SD T2 post 45.tif).

Figure 4.3. Interior view of window 1 and fragmentation, test 2 (3M T2 post 19.tif).

Figure 4.4. Exterior posttest view of window 2, test 2 (3M SD T2 post 31.tif).

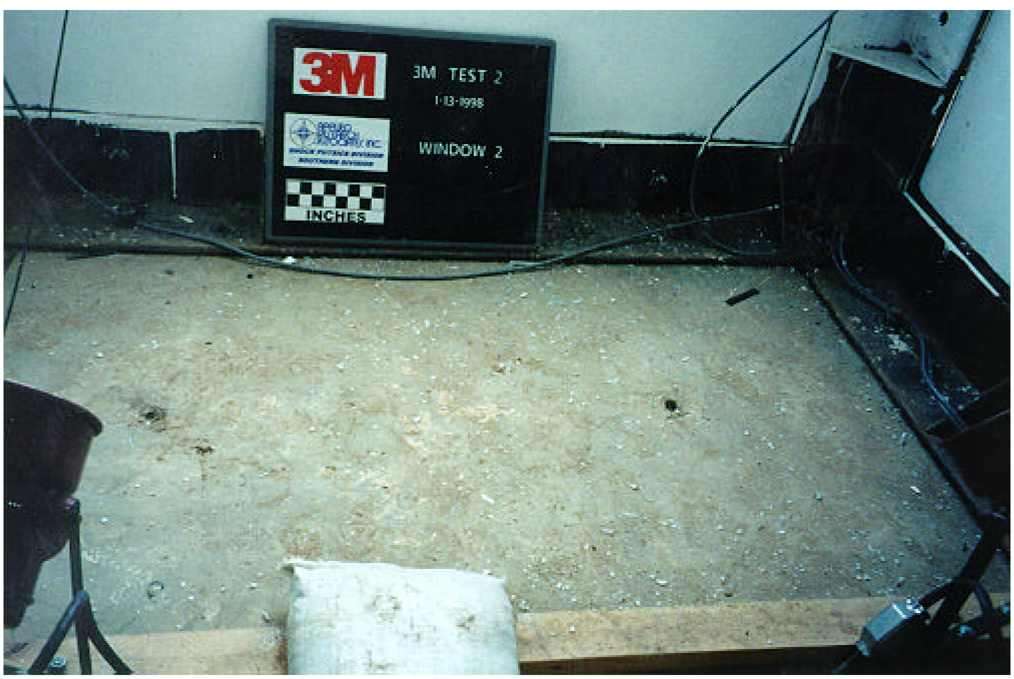


Figure 4.5. Interior view of glass fragmentation from window 2, test 2 (3M SD T2 post 12.tif).

Figure 4.6. Exterior posttest view of window 3, test 2 (3M SD T2 post 37.tif).

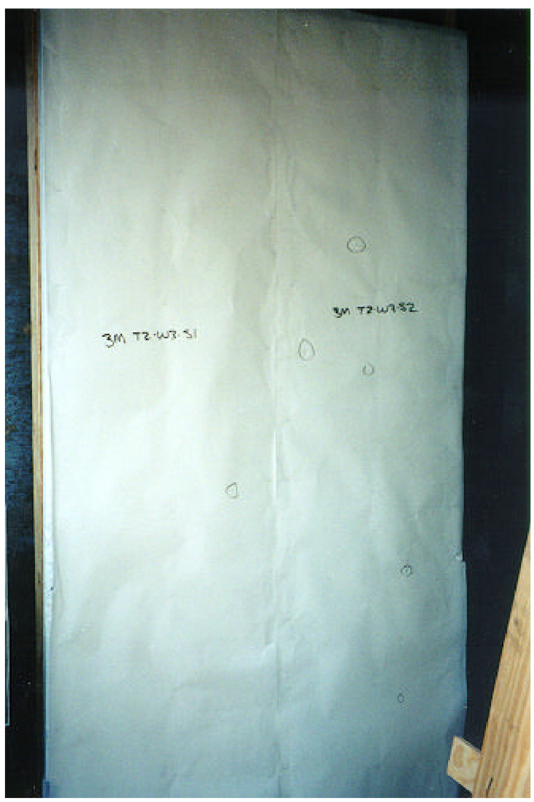


Figure 4.7. Interior view of witness panel impact from window 3, test 2. Impacts are circled (3M SD T2 post 06.tif).

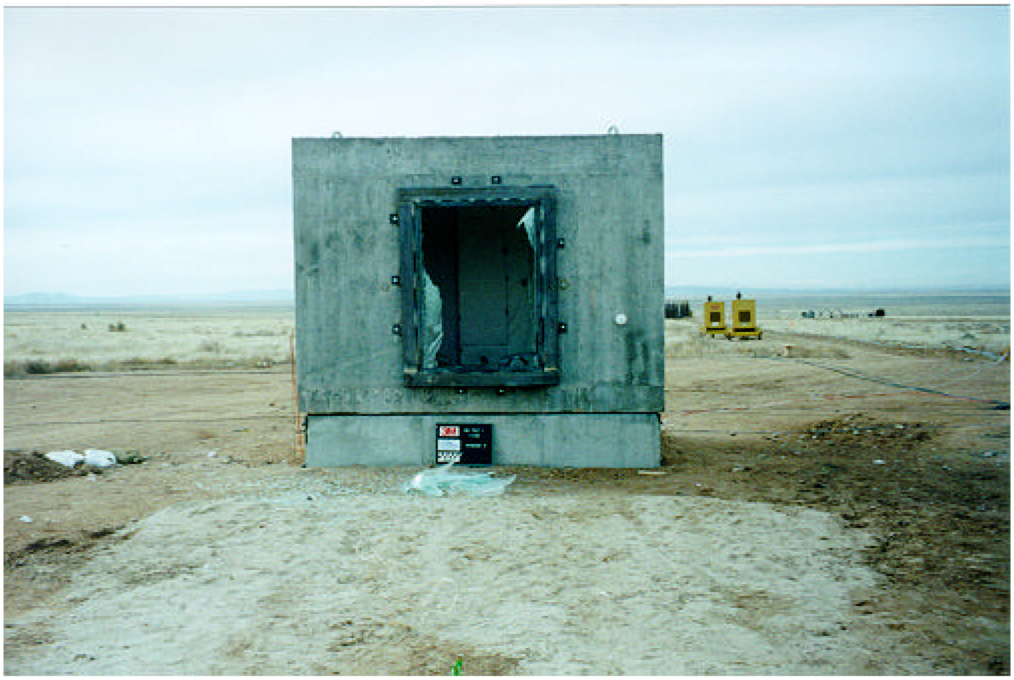


Figure 4.8. Exterior posttest view of window 4, test 2 (3M SD T2 post 43.tif).

Figure 4.9. Interior view of glass fragmentation from window 4, test 2 (3M T1 post 20.tif).

CHAPTER 5

TEST 3

Test 3 was detonated on January 14 at 12:00. The charge was located at a standoff of 165 ft for a target pressure of 5.1 psi. A typical airblast waveform is shown in Figure 5.1, and the average airblast values from the exterior gages are given in Table 5.1.

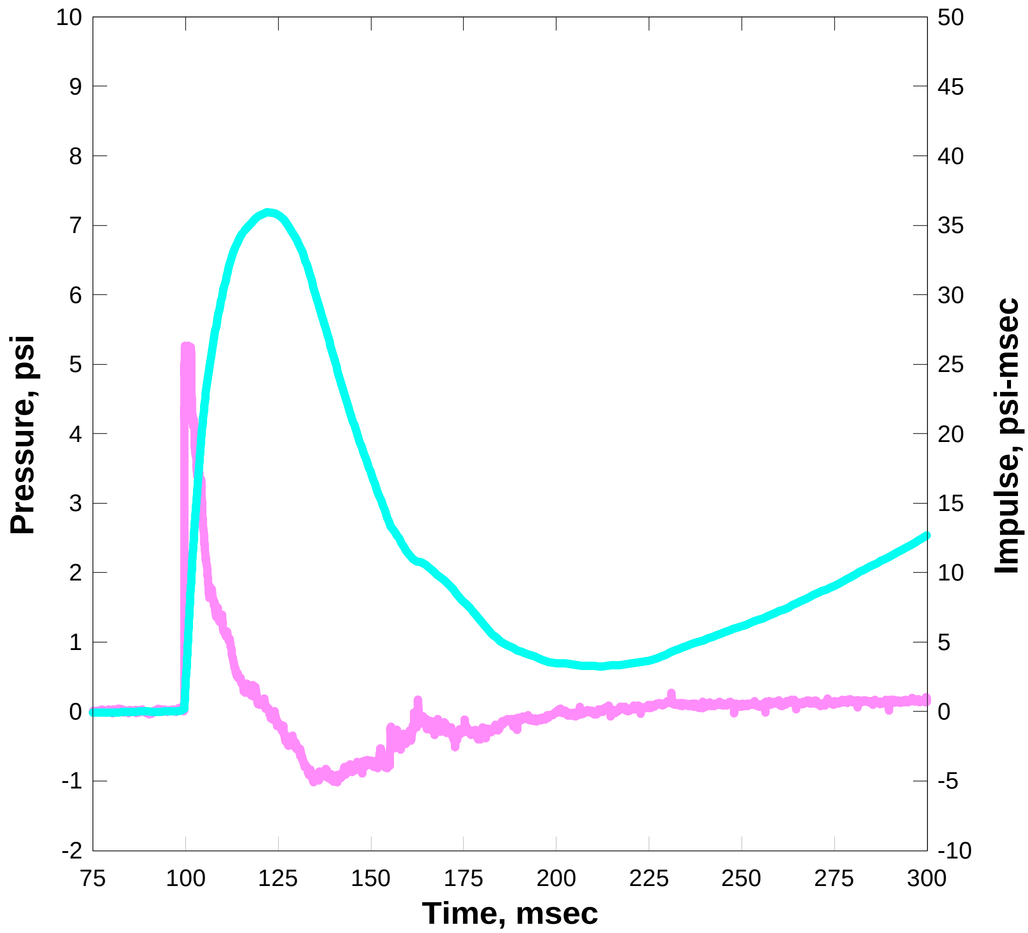


Figure 5.1. Typical airblast waveform from test 3.

Table 5.1. Average airblast values for test 3.

	Peak Positive Pressure (psi)	Peak Positive Impulse (psi-msec)	Peak Negative Pressure (psi)
Average	5.30	33.35	1.04
Standard Deviation	0.31	2.91	0.16

5.1 TEST 3, WINDOW 1

Description: ¼-inch monolithic thermally tempered glass, Ultra 400 4-mil film, 4-sided batten anchorage.

Rating: GSA Condition 3 (significant hazard reduction)

The glazing of window 1 broke. The film tore along most of the right vertical edge, along about one-third of the left edge and a few inches in from the top and bottom edges. All film was retained in the frame with a large portion of the film wadded at the sill. About 60% of the total window glass was retained on the film. Exterior glass fragments fell within about 56 ft from the structure. Only a few fragments entered the structure and were scattered to the back of the structure. There were no glass fragment impacts on the witness panel.

Several pretest photos are included in Figures A.82-A.85. Posttest photos of the window are included in Figures 5.2 and 5.3 and in Figures A.86-A.88.

5.2 TEST 3, WINDOW 2

Description: ¼-inch monolithic thermally tempered glass, Ultra 600 6-mil film, 4-sided batten anchorage.

Rating: GSA Condition 2

The glazing of window 2 failed. The film pulled out slightly from the batten on the right vertical edge of the window over about 10 inches. There was also a small tear in the film in the top left corner of the window. About half the glass was retained on the window film. Fragments that rebounded off the film landed within about 43 ft from the structure. Only some slight dusting of glass fragments was noticed inside near the sill.

Several pretest photos are included in Figures A.89-A.92. Posttest photos of the window are included in Figure 5/4 and in Figures A.93-A.96.

5.3 TEST 3, WINDOW 3

Description: **¼-inch monolithic heat strengthened glass, Ultra 600 6-mil film, 4-sided batten anchorage, aluminum storefront window frame.**

Rating: **GSA Condition 3 (significant hazard reduction)**

The glazing of window 3 failed and the film tore at the vertical edges. All film was retained in the frame. Most glass left the film on the rebound of the window system and landed in front of the structure. Many large chunks of glass were located far from the structure with the farthest at 89 ft from the structure. A few fragments entered the structure with a few located to the back of the structure on the floor. There were no glass fragment impact marks on the witness panel.

Several pretest photos are included in Figures A.97-A.98. Posttest photos of the window are included in Figures 5.5 and 5.6 and in Figures A.99-A.103.

5.4 TEST 3, WINDOW 4

Description: **¼-inch monolithic thermally tempered glass, Ultra 400 4-mil film, day-lite application.**

Rating: **GSA Condition 3**

The glazing of window 4 failed. The film, with most glass attached, left the window frame and landed inside the structure resting on the sill with one corner of the window protruding to the outside. About 90-95% of the glass was retained on the film. Exterior glass fragments were surveyed out to about 33 ft from the front of the structure. A few fragments entered the structure with a few located to the back of the structure on the floor. There were no glass fragment impact marks on the witness panel.

Several pretest photos are included in Figures A.104-A.107. Posttest photos of the window are included in Figures 5.7-5.9 and in Figures A.108-A.112.

Figure 5.2. Exterior posttest view of window 1, test 3 (3M SD T3 post 24.tif).

Figure 5.3. Interior view of window 1 and fragmentation, test 3 (3M T3 post 23.tif).

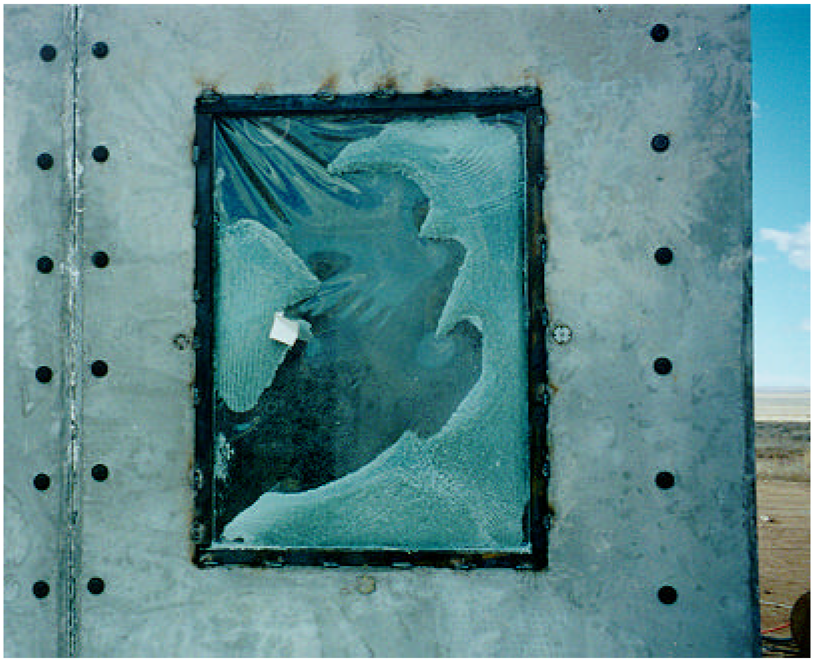


Figure 5.4. Exterior posttest view of window 2, test 3 (3M SD T3 post 19.tif).

Figure 5.5. Exterior posttest view of window 3, test 3 (3M SD T3 post 17.tif).

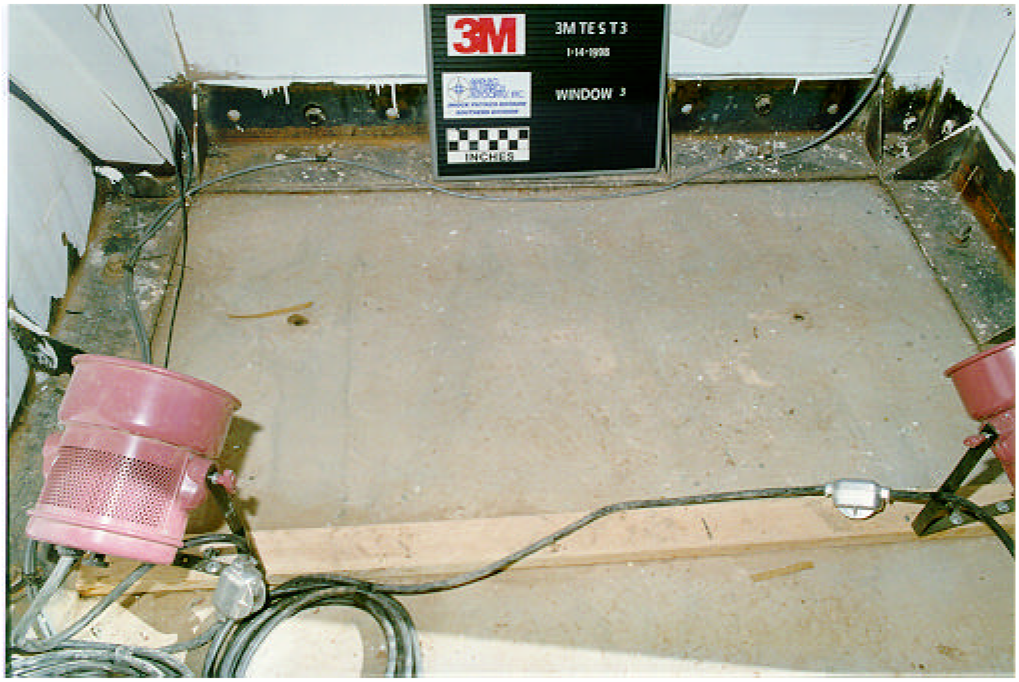


Figure 5.6. Interior view of window 3 and fragmentation, test 3 (3M T3 post 30.tif).

Figure 5.7. Exterior posttest view of window 4, test 3 (3M SD T3 post 14.tif).

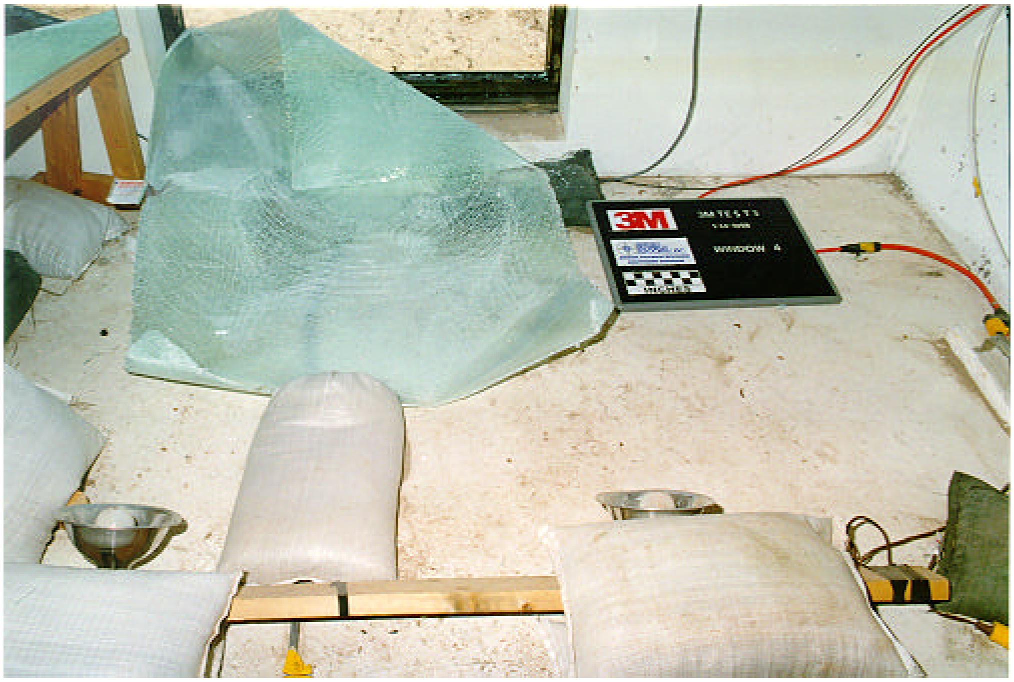


Figure 5.8. Interior view of window 4 and fragmentation, test 3 (3M T3 post 01.tif).

Figure 5.9. Exterior posttest view of window 4, test 3 (3M SD T3 post 12.tif).

CHAPTER 6

TEST 4

Test 4 was detonated on January 15 at 12:30. The charge was located at a standoff of 190 ft for a target pressure of 4.1 psi. A typical airblast waveform is shown in Figure 6.1, and the average airblast values from the exterior gages are given in Table 6.1.

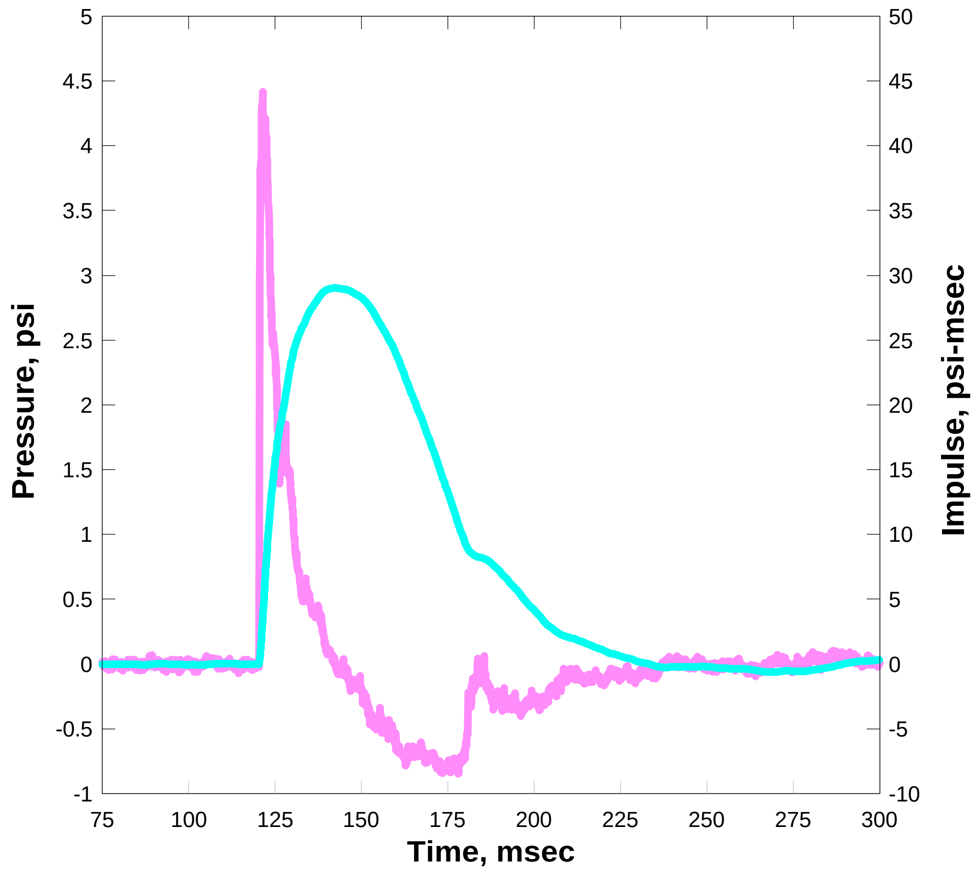


Figure 6.1. Typical airblast waveform from test 4.

Table 6.1. Average airblast values for test 4.

	Peak Positive Pressure (psi)	Peak Positive Impulse (psi-msec)	Peak Negative Pressure (psi)
Average	4.14	29.04	0.84
Standard Deviation	0.28	2.44	0.11

6.1 TEST 4, WINDOW 1

Description: **¼-inch monolithic annealed glass, Ultra 600 6-mil film, 4-sided batten anchorage.**

Rating: **GSA Condition 3**

The glazing of window 1 broke. The film tore in a "u-shape" in the middle of the window. All film was retained in the frame with about 70-80% of the window glass retained on the film. Fragments that rebounded off the film landed within about 44 ft from the structure. Several fragments entered the structure and were scattered to the back of the structure. There were no glass fragment impacts on the witness panel.

Several pretest photos are included in Figures A.115-A.118. Posttest photos of the window are included in Figures 6.1 and 6.2 and in Figures A.119-A.122.

6.2 TEST 4, WINDOW 2

Description: **¼-inch monolithic thermally tempered glass, Ultra 400 4-mil film, 4-sided wet glaze anchorage, aluminum storefront window frame.**

Rating: **GSA Condition 2**

The glazing of window 2 failed and the film remained intact in the window frame with no openings. About 30% of the glass was retained on the window film. Fragments that rebounded off the film landed within about 47 ft from the structure. No glass fragments entered the structure.

Similar to the aluminum window frames from test two, the aluminum frame for this window bowed with a permanent displacement. In fact, the aluminum frame of this window bowed at both the top and bottom whereas the aluminum frames in test two only bowed permanently at the vertical edges. Based on the high-speed video of window 2, the aluminum frame bowed out of the steel frame on the vertical edges of the window about 2-3 inches (3-1/2 to 4-1/2 total displacement) due to the rebound of the frame and the negative phase of the airblast. The permanent total displacement was about 1-3/4 inch on the left edge and about 1-9/16 inch on the right edge as measured from the outside of the window.

Several pretest photos are included in Figures A.123-A.126. Posttest photos of the window are included in Figures 6.3-6.4 and in Figures A.127-A.132.

6.3 TEST 4, WINDOW 3

Description: ¼-inch monolithic annealed glass, Ultra 400 4-mil film, 4-sided batten anchorage, aluminum storefront window frame.

Rating: GSA Condition 3 (significant hazard reduction)

The glazing of window 3 failed and the film was pulled from the window frame on the top left corner. All film was retained in the frame. About 85-90% of the total window glass left the film on the rebound of the window system and landed in front of the structure out to a distance of 74 ft from the front of the structure. A few fragments entered the structure and all landed within the first two-thirds of the distance to the rear of the structure. There were no glass fragment impact marks on the witness panel.

The high-speed film revealed significant displacements of the aluminum window frame during the rebound of the window and negative phase of the blast. Total permanent displacements of the frame on the vertical edges were about 2 inches on the left edge and about 1-7/8 inches on the right edge.

Several pretest photos are included in Figures A.133-A.135. Posttest photos of the window are included in Figures 6.5 and 6.6 and in Figures A.136-A.138.

6.4 TEST 4, WINDOW 4

Description: ¼-inch monolithic thermally tempered glass, Ultra 400 4-mil film, 4-sided batten anchorage.

Rating: GSA Condition 3 (significant hazard reduction)

The glazing of window 4 failed and the film remained in the frame. The film was pulled out of the batten on both vertical edges near the vertical center of the window. These pulled out sections measured 21 inches on the right edge and 23 inches on the left edge. About 60% of the glass was retained on the film. Exterior glass fragments were surveyed out to about 37 ft from the front of the structure. Only a few small fragments entered the structure. There were no glass fragment impact marks on the witness panel. The windows performance was a borderline GSA Condition 2 because the fragments inside were very small. However, these fine fragments were located to the rear the structure and, hence, the window was rated a Condition 3.

Several pretest photos are included in Figures A.139-A.142. Posttest photos of the window are included in Figures 6.7 and 6.8 and in Figures A.143-A.146.

Figure 6.1. Exterior posttest view of window 1, test 4 (3M T4 post 06.tif).

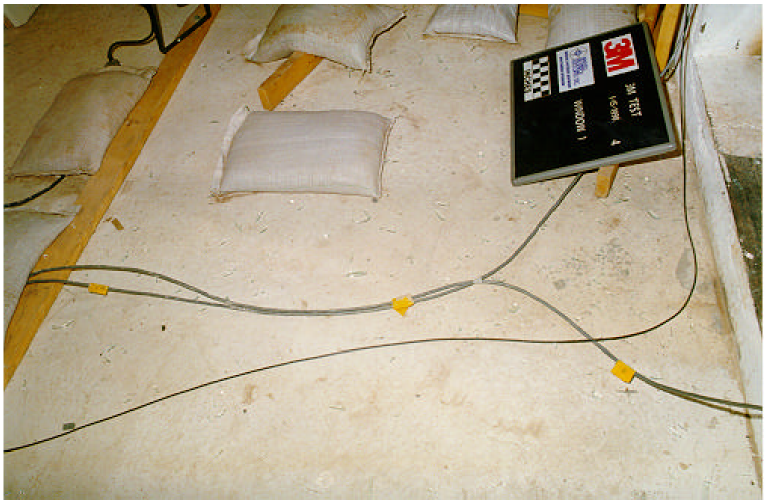


Figure 6.2. Interior view of fragmentation from window 1, test 4 (3M T4 post 20.tif).

Figure 6.3. Exterior posttest view of window 2, test 4 (3M T4 post 10.tif).

Figure 6.4. Interior view of window 2 frame deformation, test 4 (3M T4 post 14.tif).

Figure 6.5. Exterior posttest view of window 3, test 4 (3M T4 post 12.tif).

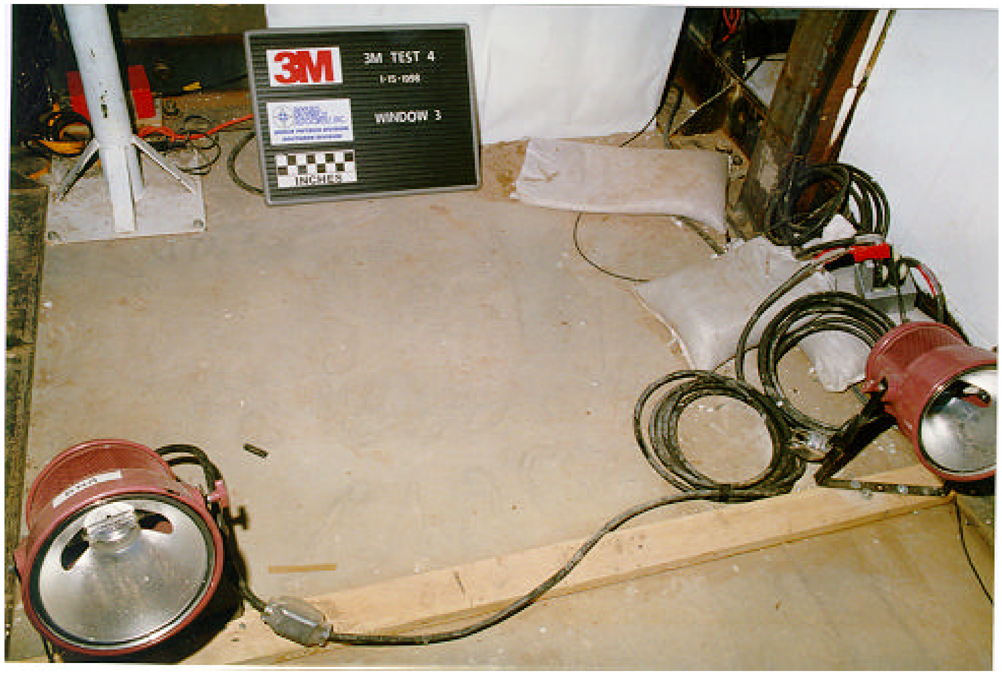


Figure 6.6. Interior view of fragmentation from window 3, test 4 (3M T4 post 27.tif).

Figure 6.7. Exterior posttest view of window 4, test 4 (3M T4 post 44.tif).

Figure 6.8. Interior view of window 4 fragmentation, test 4 (3M T4 post 45.tif).

CHAPTER 7

TEST 5

Test 5 was detonated on January 16 at 11:30. The charge was located so that the standoff to the modular structure was 121 ft and the standoff to the other two smaller structures was 122.2 ft. The target peak pressure at these two standoff distances was about 8.5 to 8.6 psi. A typical airblast waveform is shown in Figure 7.1, and the average airblast values from the exterior gages are given in Table 7.1.

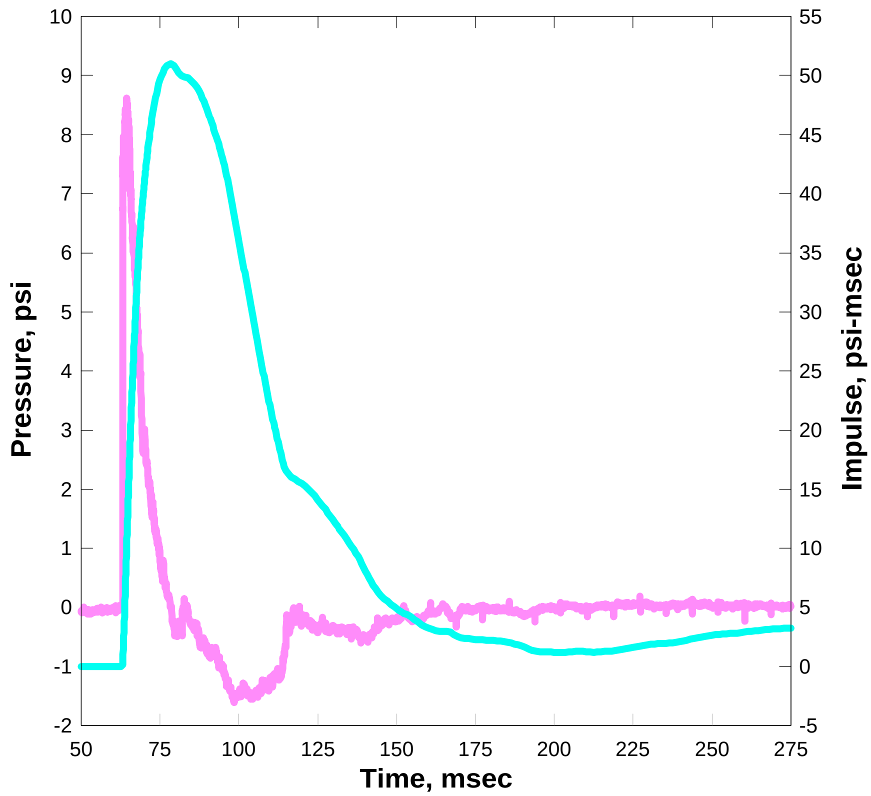


Figure 7.1. Typical airblast waveform from test 5.

Table 7.1. Average airblast values for test 5.

	Peak Positive Pressure (psi)	Peak Positive Impulse (psi-msec)	Peak Negative Pressure (psi)
Average	9.11	49.55	1.58
Standard Deviation	0.54	4.88	0.21

7.1 TEST 5, WINDOW 1

Description: 3/8-inch monolithic thermally tempered glass, Ultra 400 4-mil film, 4-sided batten anchorage.

Rating: GSA Condition 3

The glazing of window 1 broke. The film tore along the right vertical edge and across the top and bottom edges. All film was retained in the frame with about 40-50% of the window glass retained on the film. Fragments that rebounded off the film landed within about 51 ft from the structure. A few fragments entered the structure and all landed within the first two-thirds of the distance to the rear of the structure. There were no glass fragment impacts on the witness panel.

Several pretest photos are included in Figures A.148-A.151. Posttest photos of the window are included in Figures 7.2 and 7.3 and in Figures A.152-A.154.

7.2 TEST 5, WINDOW 2

Description: ½-inch monolithic thermally tempered glass, Ultra 600 6-mil film, 4-sided batten anchorage.

Rating: GSA Condition 2

The glazing of window 2 failed and the film remained intact in the window frame with no openings. Only about 5-10% the total window glass was retained on the window film. Fragments that rebounded off the film landed within about 34 ft from the structure. No glass fragments entered the structure.

Several pretest photos are included in Figures A.155-A.158. Posttest photos of the window are included in Figures 7.4 and 7.5 and in Figures A.159-A.161.

7.3 TEST 5, WINDOW 3

Description: ½-inch monolithic thermally tempered glass, Ultra 400 4-mil film, 4-sided batten anchorage.

Rating: GSA Condition 5 (significant hazard reduction)

The glazing of window 3 failed. The film was pulled from the batten along the right edge and a large tear also developed at the left edge. All film was retained in the frame. About 95% of the total window glass left the film on the rebound of the window system and landed in front of the structure out to a distance of 43 ft from the front of the structure. Several fragments entered the structure and about 20 impacted the witness panel (7 below a 2-ft height and 13 above a 2-ft height). The high-speed film showed that although the pullout of the film on the right edge occurred due to the initial blast pulse, the glass fragments did not enter the structure until the rebound and oscillation of the film. There was one impact tear near the center of the window that was about 2 inches by ¼ inch.

Several pretest photos are included in Figures A.162-A.164. Posttest photos of the window are included in Figures 7.6 and 7.7 and in Figures A.165-A.169.

7.4 TEST 5, WINDOW 4

Description: **3/8-inch monolithic thermally tempered glass, Ultra 400 4-mil film, day-lite application.**

Rating: **GSA Condition 3 (significant hazard reduction)**

The glazing of window 4 failed and the film with most glass attached left the window frame and landed 46 inches from the front of the structure. About 60% of the glass was retained on the film. Exterior glass fragments landed out to a distance of about 23 ft from the front of the structure. A few fragments entered the structure and these were contained within the first half of the structure. There were no glass fragment impact marks on the witness panel.

Several pretest photos are included in Figures A.170-A.173. Posttest photos of the window are included in Figures 7.8 and 7.9 and in Figures A.174-A.177.

Figure 7.2. Exterior posttest view of window 1, test 5 (3M T5 post 25.tif).

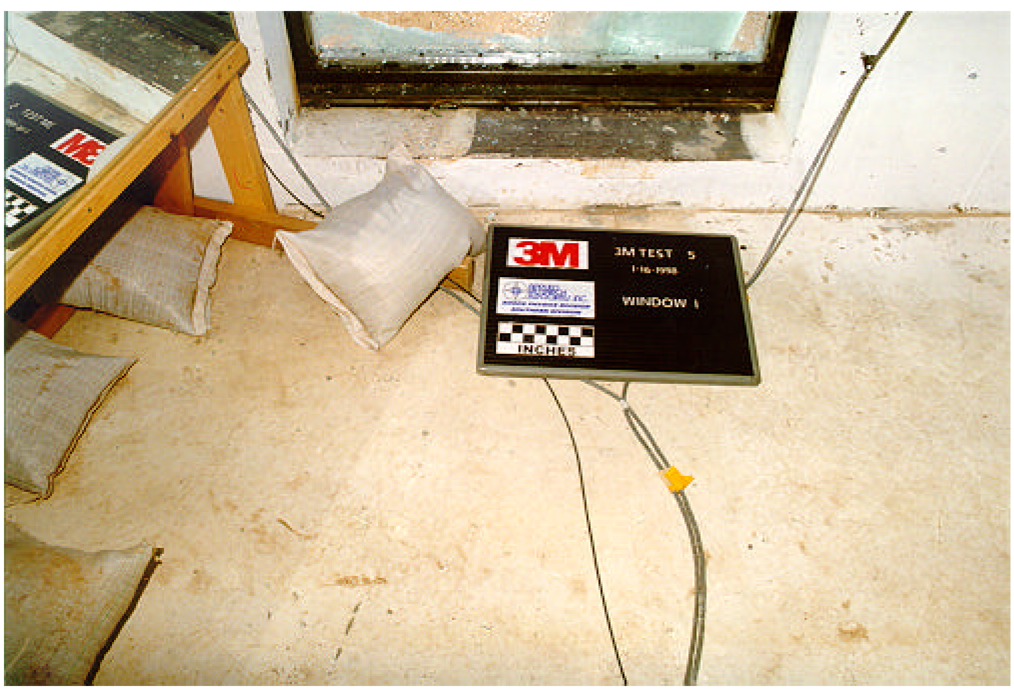


Figure 7.3. Interior view of fragmentation from window 1, test 5 (3M T5 post 07.tif).

Figure 7.4. Exterior posttest view of window 2, test 5 (3M T5 post 28.tif).

Figure 7.5. Interior view of window 2 frame deformation, test 5 (3M T5 post 06.tif).

Figure 7.6. Exterior posttest view of window 3, test 5 (3M T5 post 32.tif).

Figure 7.7. Interior view of fragmentation from window 3, test 5 (3M T5 post 03.tif).

Figure 7.8. Exterior posttest view of window 4, test 5 (3M T5 post 37.tif).

Figure 7.9. Interior view of window 4 fragmentation, test 5 (3M T5 post 47.tif).

CHAPTER 8

TEST 6

Test 6 was detonated on January 19 at 12:30. The charge was located so that the standoff to the modular structure was 121 ft and the standoff to the other two smaller structures was 122.2 ft. The target peak pressure at these two standoff distances was about 8.5 to 8.6 psi. A typical airblast waveform is shown in Figure 8.1, and the average airblast values from the exterior gages are given in Table 8.1.

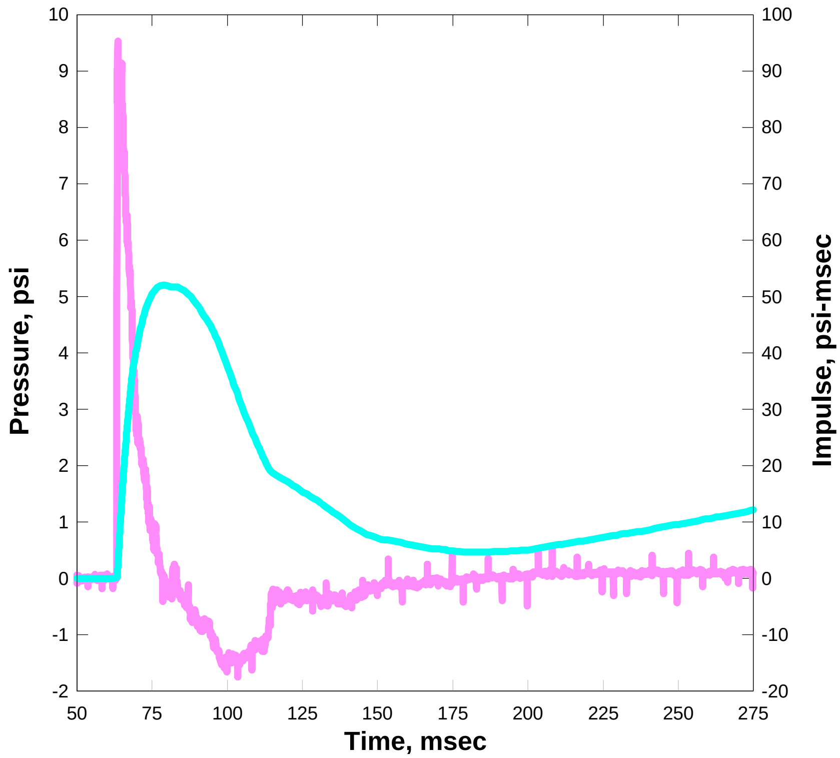


Figure 8.1. Typical airblast waveform from test 6.

Table 8.1. Average airblast values for test 6.

	Peak Positive Pressure (psi)	Peak Positive Impulse (psi-msec)	Peak Negative Pressure (psi)
Average	9.02	49.75	1.55
Standard Deviation	0.47	5.08	0.25

8.1 TEST 6, WINDOW 1

Description: ¼-inch monolithic thermally tempered glass, Ultra 400 4-mil film, day-lite application.

Rating: GSA Condition 5

The glazing of window 1 broke. The film left the frame in one piece with most glass attached. The film/glass entered the structure and impacted the witness panel. Where the film/glass impacted the witness panel, most of the impact mark was below the 2-ft height on the witness panel and the mark reached above the 2-ft height for only a few inches. Many other glass fragment impact marks were noted on the witness panel. Only a few glass fragments left the front of the structure and landed within about 12 ft from the structure.

Several pretest photos are included in Figures A.180-A.182. Posttest photos of the window are included in Figures 8.2 and 8.3 and in Figures A.183-A.187.

8.2 TEST 6, WINDOW 2

Description: ¼-inch thermally tempered glass + ½-inch air gap + ¼-inch thermally tempered glass, Ultra 400 4-mil film, 4-sided batten anchorage.

Rating: GSA Condition 3 (significant hazard reduction)

Both lites of window 2 failed and the film tore along the right edge and across the bottom edge and all film was retained in the frame. About 80% of the glass from the inner lite was retained on the film. The glass fragment scatter in front of the modular structure for windows 2 and 3 fell within 61 ft from the structure. Which window created which fragments was difficult to determine as both windows used the same glass type and thickness. Only a few glass fragments entered the structure and no glass fragments impacted the witness panel.

Several pretest photos are included in Figures A.189-A.191. Posttest photos of the window are included in Figures 8.4 and 8.5 and in Figures A.192-A.194.

8.3 TEST 6, WINDOW 3

Description: **¼-inch thermally tempered glass + ½-inch air gap + ¼-inch thermally tempered glass, Ultra 600 6-mil film, 4-sided batten anchorage.**

Rating: **GSA Condition 2**

Both lites from window 3 failed and the film was completely retained in the frame with no openings. No glass entered the structure. Only about 20% of the glass from the inner lite was retained on the film. The glass fragment scatter in front of the modular structure for windows 2 and 3 fell within 61 ft from the structure.

Several pretest photos are included in Figures A.195-A.197. Posttest photos of the window are included in Figure 8.6 and in Figures A.198-A.202.

8.4 TEST 6, WINDOW 4

Description: **¼-inch thermally tempered glass + ½-inch air gap + ¼-inch thermally tempered glass, control specimen with no film.**

Rating: **GSA Condition 5**

The glazing of window 4 failed and most glass entered the structure at high velocities. Less than 20% of the glass left the front of the structure and this glass was contained within 22 ft from the front of the structure. Glass was scattered throughout the inside of the structure and much of the glass impacted the rear witness panel. About 130 impact marks were surveyed on the witness panel; 72 impacts were surveyed above a 2-ft height on the witness panel and 58 impact marks were surveyed below the 2-ft height.

Several pretest photos are included in Figures A.203-A.206. Posttest photos of the window are included in Figures 8.7-8.9 and in Figures A.207-A.212.

Figure 8.2. Interior posttest view of window 1 fragmentation near the front of the structure, test 6 (3M T6 post 19.tif).

Figure 8.3. Interior posttest view of window 1 fragmentation near the rear of the structure, test 6 (3M T6 post 21.tif).

Figure 8.4. Exterior posttest view of window 2, test 6 (3M T6 post 01.tif).

Figure 8.5. Interior view of window 2 glass fragmentation, test 6 (3M T6 post 33.tif).

Figure 8.6. Exterior posttest view of window 3, test 6 (3M T6 post 04.tif).

Figure 8.7. Exterior posttest view of window 4, test 6 (3M T6 post 07.tif).

Figure 8.8. Interior view of window 4 glass fragmentation, test 6 (3M T6 post 27.tif).

Figure 8.9. Interior view of window 4 glass fragmentation, test 6 (3M T6 post 29.tif).

CHAPTER 9

RESULTS SUMMARIES AND MAJOR FINDINGS

9.1 IMPLICATION OF RESULTS AND GSA SECURITY REQUIREMENTS

The GSA Security Criteria for window response requires that windows meet a certain level of performance for a particular design threat. This is true for GSA buildings with security classifications of Levels C and D. Level A and Level B buildings, which are lower in security classification than C and D buildings, require no specific performance criteria though use of certain window types in Level A and B buildings is prohibited. Level E GSA buildings are very high security buildings and the generalized criteria do not give guidance for these buildings.

The airblast loading that is used in the window design for GSA Level C and Level D buildings is based on a particular threat size at the worse case threat scenario location based on available perimeter standoff. Realistic limits are placed on the maximum design loads with the assumption that some damage and potential injury are acceptable. For Level C buildings, any portion of the building that is predicted to experience blast pressures of ½ psi or higher due to the design threat at the site perimeter must be designed to the maximum predicted load. For Level D buildings the design is to correspond to the actual predicted blast environment.

For GSA Level C Buildings the maximum required design load is a triangular blast load that instantaneously rises to 4 psi and decays linearly to zero over a duration of 13.9 milliseconds (msec). The performance required for GSA Level C buildings is a Condition 4 or lower. The impulse that this blast load generates is 27.8 psi-msec. The impulse generated during testing at 4 psi was nominally 28-30 psi-msec. Thus, window specimens that performed to a Condition 4 or better at 4 psi from this test series can be considered for use in GSA Level C Buildings. This is true for windows that are the size of those tested or smaller. Framing conditions specific to a particular project must be addressed separately.

For GSA Level D buildings the maximum required design load is a triangular blast load that instantaneously rises to 10 psi and decays linearly to zero over a duration of about 17.9 msec. All windows that performed to a Condition 3 or better can be considered for use on Level D buildings <u>up to the maximum pressure and impulse level at which they were tested</u>. This is true for windows that are the size of those tested or smaller. Framing conditions specific to a particular project must be addressed separately.

9.2 CONSOLIDATED RESULTS

The results of the tests were consolidated into several tables. Each table shows results for a particular glass type and thickness for the various configurations tested.

Table 9.1 shows results for ¼-inch thick annealed glass specimens. The test article designation gives the test number then the window number. For example "3M-1-4" indicates 3M Test 1 Window 4. Six of the seven ¼-inch thick monolithic annealed glass windows tested with security window films achieved a GSA Condition 3 at 4 psi.

Table 9.1. Summary of results for ¼-inch thick monolithic annealed glass windows.

¼ inch AG Specimens	**Summary**							
Test Article	3M-1-4	3M-1-1	3M-1-2	3M-1-3	3M-2-3	3M-2-4	3M-4-1	3M-4-3
Security Film	No film	Ultra 400	Ultra 400	3M 7 mil	Ultra 400	Ultra 400	Ultra 600	Ultra 400
Attachment	N/A	day-lite	4-sided batten	4-sided batten	4-sided batten	2-sided batten	4-sided batten	wet glazed
Window Frame	steel	steel	steel	steel	aluminum	steel	steel	aluminum
Nom. Peak pressure, psi	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Condition	5	3-SHR	3-SHR	3-SHR	5-SHR	3-SHR	3	3-SHR

Table 9.2 gives results for the ¼-inch thick monolithic HSG windows that were tested. Both window systems performed quite well and provided significant glass fragment hazard mitigation at the respective blast pressure levels at which they were tested.

Table 9.3 gives results for the ¼-inch thick monolithic TTG windows that were tested. The protected TTG windows performed very well in providing glass fragment mitigation up to blast pressures as high as 5 psi.

Table 9.4 gives results for 3/8-inch thick monolithic TTG windows and Table 9.5 gives results for ½-inch thick monolithic TTG windows. Three of these four windows performed very well at providing protection to building occupants from glass fragmentation at significantly high blast environments. Similarly, Table 9.6 shows significant fragment mitigation performance for filmed windows versus unprotected for the 1-inch insulated TTG units.

Table 9.2. Summary of results for ¼-inch thick monolithic heat strengthened glass windows.

¼ inch HSG Specimens	**Summary**	
Test Article	3M-2-1	3M-3-3
Security Film	Ultra 400	Ultra 600
Attachment	4-sided batten	4-sided batten
Window Frame	steel	steel
Nom. Peak pressure, psi	4.0	5.0
Condition	3-SHR	3-SHR

Table 9.3. Summary of results for ¼-inch thick monolithic thermally tempered glass windows.

¼ inch TTG Specimens	Summary						
Test Article	3M-2-2	3M-4-2	3M-4-4	3M-3-1	3M-3-2	3M-3-4	3M-6-1
Security Film	Ultra 400	Ultra 400	Ultra 400	Ultra 400	Ultra 600	Ultra 400	Ultra 400
Attachment	4-sided batten	wet glazed	4-sided batten	4-sided batten	4-sided batten	day-lite	day-lite
Window Frame	aluminum	aluminum	steel	steel	steel	steel	steel
Nom. Peak pressure, psi	4.0	4.0	4.0	5.0	5.0	5.0	9.0
Condition	3-SHR	2	3-SHR	3-SHR	2	3	5

Table 9.4. Summary of results for 3/8-inch thick monolithic thermally tempered glass windows.

3/8 inch TTG Specimens	Summary	
Test Article	3M-5-1	3M-5-4
Security Film	Ultra 400	Ultra 400
Attachment	4-sided batten	day-lite
Window Frame	steel	steel
Nom. Peak pressure, psi	9.0	9.0
Condition	3	3-SHR

Table 9.5. Summary of results for 1/2-inch thick monolithic thermally tempered glass windows.

1/2 inch TTG Specimens	Summary	
Test Article	3M-5-2	3M-5-3
Security Film	Ultra 600	Ultra 400
Attachment	4-sided batten	4-sided batten
Window Frame	steel	steel
Nom. Peak pressure, psi	9.0	9.0
Condition	2	5-SHR

Table 9.6. Summary of results for 1/2-inch thick monolithic thermally tempered glass windows.

1 inch insulated TTG, ¼” TTG + ½” airgap + ¼” TTG	Summary		
Test Article	3M-6-4	3M-6-2	3M-6-3
Security Film	no film	Ultra 400	Ultra 600
Attachment	N/A	4-sided batten	4-sided batten
Window Frame	steel	steel	steel
Nom. Peak pressure, psi	9.0	9.0	9.0
Condition	5	3-SHR	2

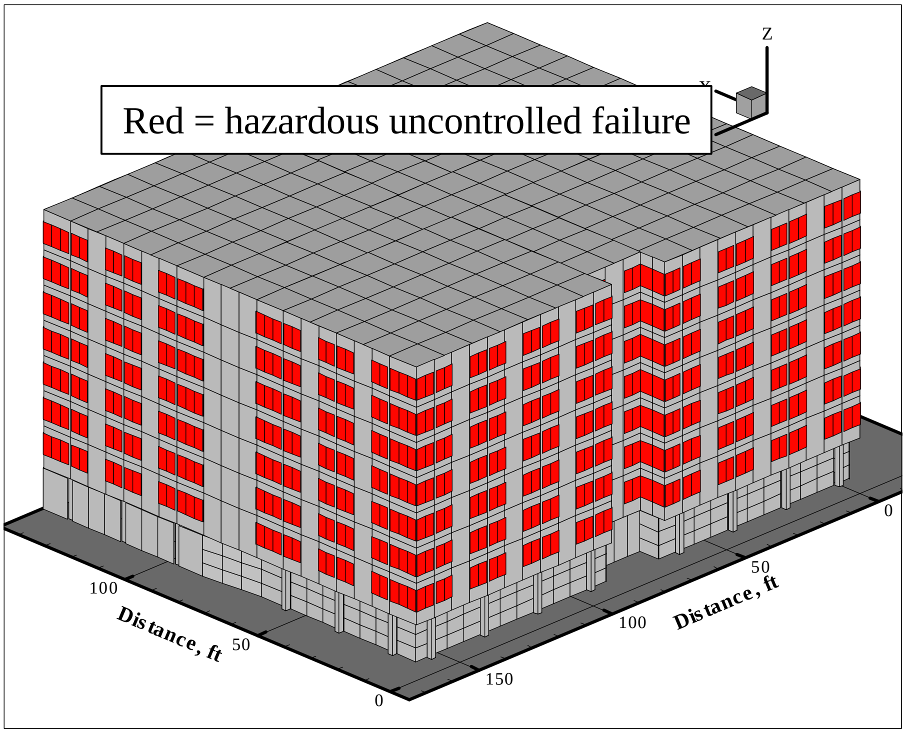
9.3 EXAMPLE CASE STUDY

In order to demonstrate the glass fragment mitigation benefits of the security film products tested and what these test results mean in a potential real life terrorist event, damage prediction comparison calculations were made for glazing damage to a typical GSA office building. A special purpose computer program, ***Anti-Terrorism (AT) Assessor***, was used for the damage comparison analysis. This program was developed by ARA for predicting damage to building components due to exterior blast threats. Geometric depictions of building facilities are modeled in a 3-dimensional environment. The code is equipped with airblast prediction models based on formulations given in a military design manual (TM5-855). The predicted airblast is compared against pressure-impulse failure relationships for the given component models and a damage prediction estimate is made.

The building used for the comparison is about 140 ft by 160 ft in plan and is 8 stories high. In the damage prediction figures, damage is displayed and color-coded for windows on floors 2-8 only. All other windows and structural elements are displayed as a light gray color. The window used for the comparison is the same 4-ft by 5-1/2-ft by ¼-inch thick monolithic annealed glass window that was tested. The charge weight used is a 100-lb TNT charge located at the curbside 20 ft from the front edge of the building. The comparison is made between an unprotected window with no security film and a window with security film. In the top calculation in Figure 9.1, a model for the capacity of a plain monolithic window is used to predict window breakage. Hazardous breakage of the windows is indicated with the color red, and it can be seen that, for this scenario, hazardous uncontrolled breakage of all windows in the building is predicted. The bottom calculation shows the potential benefit of using security films based on test results. For this calculation all window glass is also predicted to be broken but controlled in varying extents. In areas of the building that are color coded green, glazing failure is predicted to be significantly controlled. All specimens from Table 9.1 that performed to a Condition 3 are predicted to perform to a Condition 3 in the green colored regions. For this scenario the security film applications would have likely mitigated more than about three-fourths of the glass fragment hazards to building occupants. In the regions colored orange, the failure is predicted to be somewhat controlled, but the blast loads may be high enough to cause Condition 4 or worse with the film retrofit. It is important to note that the analysis assumes the exterior walls and the connection of the window frame into the supporting structure is adequate to survive the blast.

9.4 MAJOR FINDINGS

This test series showed that the 3M Ultra series of security window films provide significant benefit in mitigating window glass fragment environments in blast. Though the GSA criteria explicitly calls out 7-mil or thicker security films as preferable, the 4-mil and 6-mil 3M films performed to required levels for many of the configurations tested. In general, the 6-mil Ultra 600 product performed significantly better than the 4-mil Ultra 400 film. This trend was noted by observing the overall response of the window systems. In three cases, the thicker film received a better GSA Condition rating with otherwise identical window system configurations. Both products performed well up to blast pressures as high as 9 psi. Many configurations tested performed to the required level of protection for GSA Level C buildings at the maximum design load. A few others performed to the required level of protection for Level D buildings up to 9 psi and for an impulse of about 50 psi-msec. Another major finding of this test series is that the mechanical batten system and the wet glazed systems provide an adequate attachment to aluminum frames for the conditions evaluated. It is likely that the connection of the aluminum frame into the exterior wall would be the weakest part of a typical aluminum framed window system. This must be handled carefully so that a balanced window system is developed.



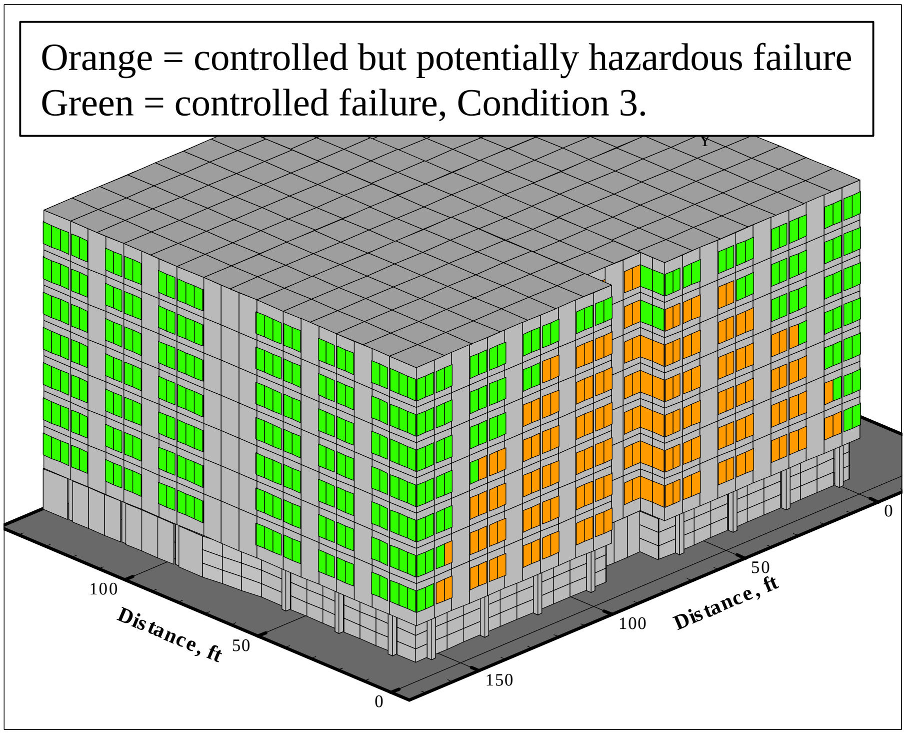


Figure 9.1. Damage comparison calculations: top calculation = no film; bottom calculation = film retrofits.

Appendix A

Figure A.1. The steel frame of the modular reaction structure (viewed from the east face) (3M PREP 15.tif).

Figure A.2. The steel frame of the modular reaction structure (3M PREP 13.tif).

Figure A.3. Placement of the South Bay Structure roof panel (3M PREP 20.tif, 3M PREP 19.tif, 3M PREP 17.tif).

Figure A.4. Views of a crane lifting the South Bay Structure front panel (3M PREP 16.tif, 3M PREP 01.tif).

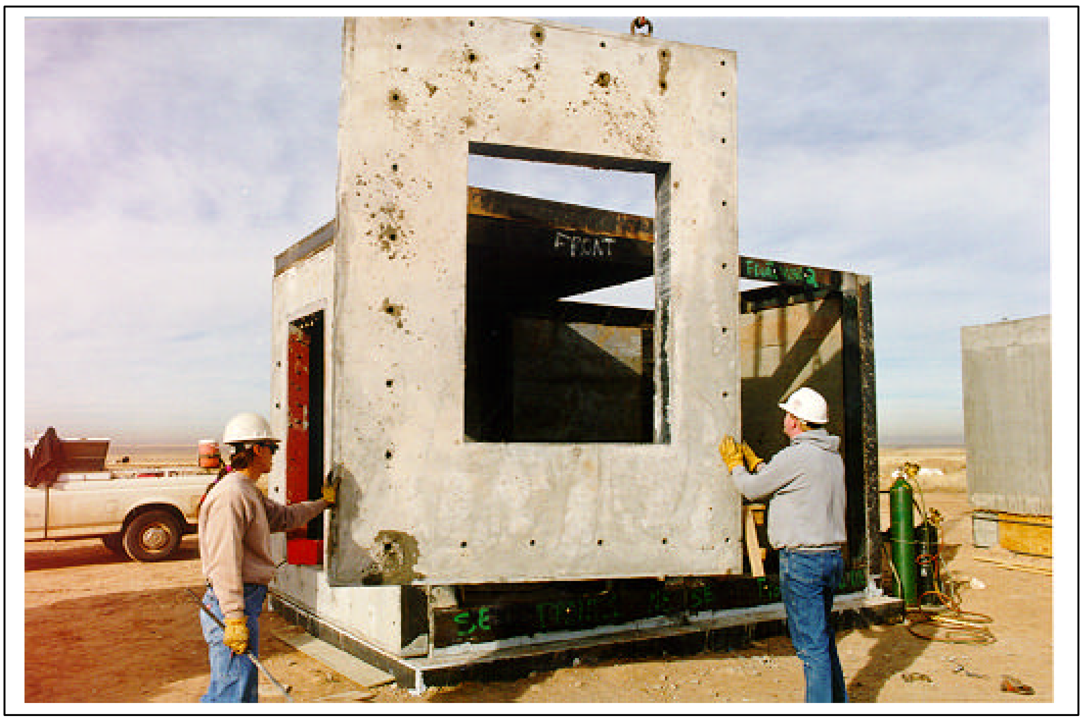


Figure A.5. Placement of the South Bay Structure front panel into the modular structure steel frame (3M PREP 03.tif, 3M PREP 04.tif).

Figure A.6. View of a technician welding the window frame to the embed (3M PREP 12.tif).

Figure A.7. Picture of the completely constructed reaction structure (3M PREP 29.tif).

Figure A.8. Test 1. Pretest view of the test bed (3M T1 PRE 14.tif).

Figure A.9. Test 1. Posttest view of the test bed (3M T1 POST 01.tif).

Figure A.10. Test 1. Pretest, exterior view of window 1 (3m sd T1 pre07.tif).

Figure A.11. Test 1. Pretest, exterior view of window 1 (3M T1 F26.tif).

Figure A.12. Test 1. Pretest, interior view of window 1 (3m sd T1 pre20.tif).

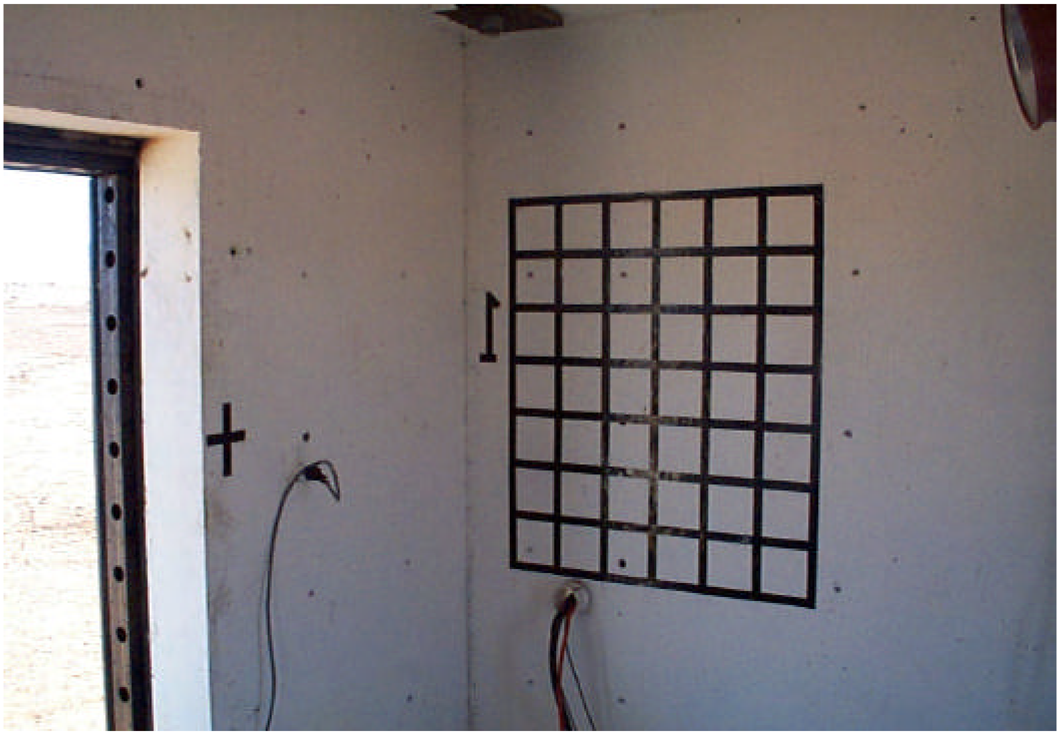


Figure A.13. Test 1. Pretest, interior view of window 1 (test1_02.jpg).

Figure A.14. Test 1. Pretest, interior view of window 1 (test1_03.jpg).

Figure A.15 . Test 1. Pretest, interior view of window 1 (test1_04.jpg).

Figure A.16. Test 1. Pretest, interior view of window 1 (test1_07.jpg).

Figure A.17. Test 1. Posttest, exterior view of window 1 (3m sd T1 post37.tif).

Figure A.18. Test 1. Posttest, exterior view of window 1 (3M T1 F46.tif).

Figure A.19. Test 1. Posttest view of the security film and attached glazing from window 1 (3M T1 POST 05.tif).

Figure A.20. Test 1. Posttest view of the security film and attached glazing from window 1 (3M T1 F51.tif).

Figure A.21. Test 1. Posttest, interior view of window 1 (3m sd T1 post08.tif).

Figure A.22. Test 1. Posttest view of the North Structure floor (3m sd T1 post21.tif).

Figure A.23. Test 1. Posttest view of the interior of the North Structure (3M T1 F53.tif).

Figure A.24 Test 1. Pretest, exterior view of windows 2 and 3 (3m T1 F14.tif).

Figure A.25. Test 1. Pretest, exterior views of window 2 (3m sd T1 pre09.tif, 3m sd T1 pre08.tif).

Figure A.26. Test 1. Pretest, exterior view of window 2 (3M T1 PRE 08.tif).

Figure A.27. Test 1. Posttest, exterior view of windows 2 and 3 (3M T1 F22.tif).

Figure A.28. Test 1. Posttest, exterior views of window 2 (3M T1 POST 07.tif, 3m sd t1 post25.tif).

Figure A.29. Test 1. Posttest, exterior views of window 2 (3M T1 F17.tif, 3M T1 F18.tif).

Figure A.30. Test 1. Posttest, exterior view of windows 2 and 3 (test1_27.jpg).

Figure A.31 Test 1. Pretest exterior views of window 3 (3M T1 PRE 06.tif, 3M T1 PRE 07.tif).

Figure A.32. Test 1. Pretest, interior views of window 3 (3m sd T1 pre02.tif, 3M T1 PRE 18.tif).

Figure A.33. Test 1. Pretest, interior view of window 3. Close up view of the batten system (3m sd T1 pre05.tif).

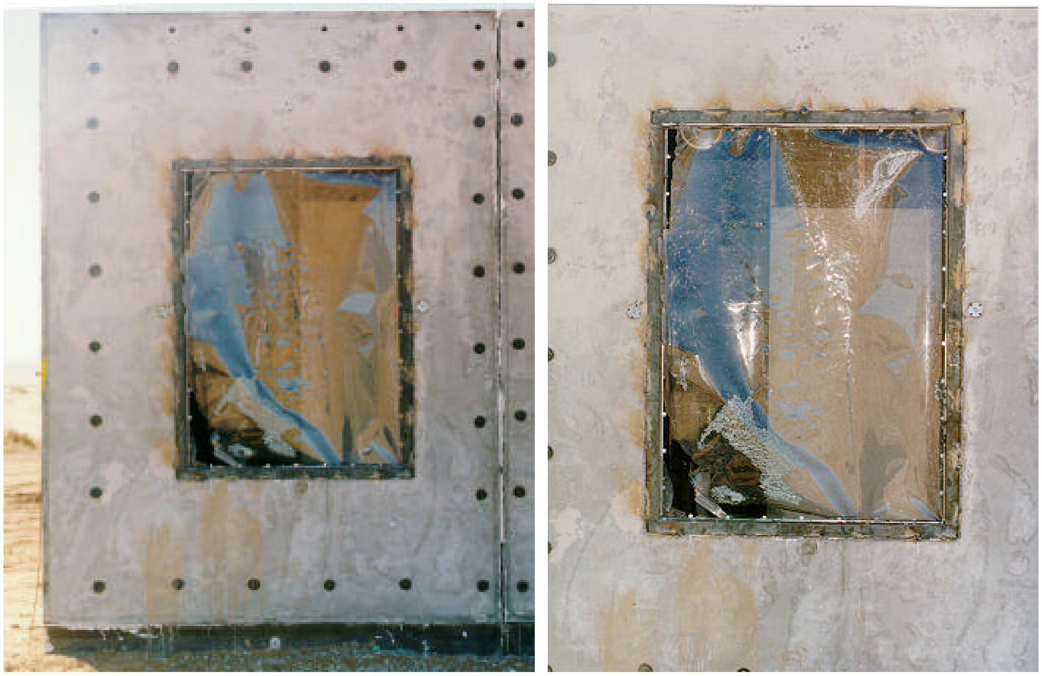


Figure A.34. Test 1. Posttest, exterior views of window 3 (3M T1 POST 10a.tif, 3M T1 POST 08.tif).

Figure A.35. Test 1. Posttest, exterior view of Window 3. View of top left corner (3M T1 POST 08a.tif).

Figure A.36. Test 1. Posttest, exterior view of window 3. View of bottom left corner (3M T1 POST 08b.tif).

Figure A.37. Test 1. Posttest, interior view of window 2 (3M T1 F55.tif).

Figure A.38 Test 1. Pretest, exterior view of window 4 (3M T1 F32.tif).

Figure A.39. Test 1. Pretest, exterior views of window 4 (3M T1 PRE 05.tif, 3M T1 F09.tif).

Figure A.40. Test 1. Pretest, interior view of window 4 (3m sd T1 pre15.tif).

Figure A.41. Test 1. Pretest, interior views of window 4 (test1_10.jpg, test1_12.jpg).

Figure A.42. Test 1. Posttest, exterior view of window 4 (3M T1 F61.tif).

Figure A.43. Test 1. Posttest, exterior views of window 4 (3M T1 POST 11.tif, 3M T1 F58.tif).

Figure A.44. Test 1. Posttest, interior view of window 4 (test1_41.jpg).

Figure A.45. Test 1. Posttest view of glass debris on the South Structure floor (test1_42.jpg).

Figure A.46. Test 1. Posttest view of glass debris on the South Structure floor (test1_47.jpg).

Figure A.47. Test 1. Posttest view of the witness panel located behind window 4 (test1_45.jpg).

Figure A.48. Test 2. Pretest view of the test bed (3M T2 PRE 23.tif).

Figure A.49. Test 2. Posttest view of the test bed (3M T2 PRE 23.tif).

Figure A.50. Test 2. Pretest, exterior view of window 1 (3m sd T2 pre13.tif).

Figure A.51. Test 2. Pretest, exterior view of window 1 (3m sd T2 pre11.tif).

Figure A.52. Test 2. Pretest, exterior view of window 1 (3m sd T2 pre10.tif).

Figure A.53. Test 2. Pretest, interior view of window 1 (3M T2 PRE 12.tif).

Figure A.54. Test 2. Posttest, exterior view of window 1 (3m sd T2 post28.tif).

Figure A.55.Test 2. Posttest, exterior view of window 1 (3m sd T2 post27).

Figure A.56. Test 2. Posttest, exterior view of window 1 (3M T2 POST 10.tif).

Figure A.57. Test 2. Posttest interior view of window 1 (3M T2 POST 12 .tif).

Figure A.58. Test 2. Pretest, exterior view of windows 2 and 3 (3M T2 PRE 18.tif).

Figure A.59. Test 2. Pretest exterior views of window 2 (3M T2 PRE 19.tif, 3M T2 PRE 20.tif).

Figure A.60. Test 2. Pretest, interior view of window 2 (3M T2 PRE 08.tif).

Figure A.61 Test 2. Pretest, interior view of window 2. Close-up view of the batten system (3M T2 PRE 09.tif).

Figure A.62. Test 2. Posttest, exterior view of windows 2 and 3 (3M T2 POST 01.tif).

Figure A.63. Test 2. Posttest, exterior view of window 2 (3M T2 POST 17.tif).

Figure A.64. Test 2. Posttest, exterior view of windows 2 and 3 (3m sd T2 post30 .jpg).

Figure A.65. Test 2. Posttest, interior view of window 2 (3M T2 POST 23.tif).

Figure A.66. Test 2. Pretest, exterior view of window 3 (3M T2 PRE 17.tif).

Figure A.67. Test 2. Pretest, interior views of window 3. Close-up view of the batten system shown on right (3M T2 PRE 05.tif, 3M T2 PRE 03.tif).

Figure A.68. Test 2. Posttest, exterior view of window 3 (3M T2 POST 15.tif).

Figure A.69. Test 2. Posttest, exterior views of window 3 (3M T2 POST 34.tif, 3M T2 POST 35.tif).

Figure A.70. Test 2. Posttest, exterior views of window 3 (3M T2 POST 37.tif, 3M T2 POST 38.tif).

Figure A.71. Test 2. Posttest, interior view of window 3 (3M T2 POST 26.tif).

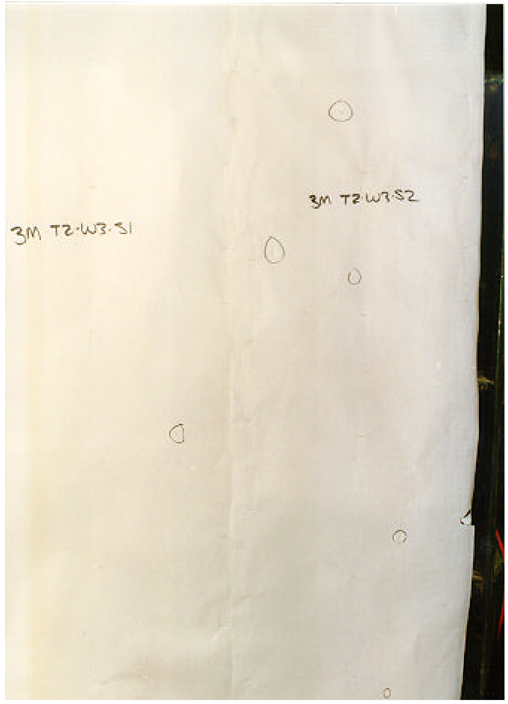


Figure A.72. Test 2. Posttest, interior view of the witness panel behind window 3 (3M T2 POST 33.tif).

Figure A.73. Test 2. Pretest, exterior view of window 4 (3M T2 PRE 28.tif).

Figure A.74. Test 2. Pretest, exterior view of window 4 (3M T2 PRE 13.tif).

Figure A.75. Test 2. Pretest, interior view of window 4 (3M T2 PRE 02.tif).

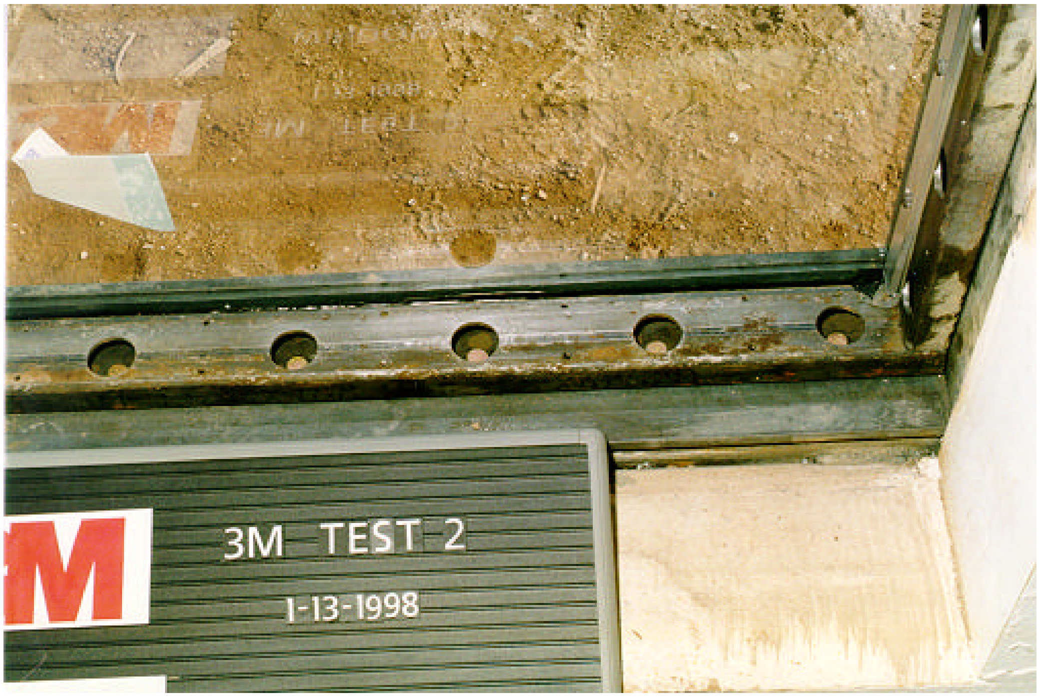


Figure A.76. Test 2. Pretest, interior view of window 4. Close-up view of the batten system (3M T2 PRE 01.tif).

Figure A.77. Test 2. Posttest, exterior view of window 4 (3M T2 POST 02.tif).

Figure A.78. Test 2. Posttest, exterior views of window 4 (3M T2 POST 04.tif, 3M T2 POST 03.tif).

Figure A.79. Test 2. Posttest, interior view of window 4 (3M T2 POST 21.tif).

Figure A.80. Test 2. Posttest view of the glass debris on the South Structure floor (3M T2 POST 22.tif).

Figure A.81. Test 3. Posttest view of the test bed (3m sd T3 post27.tif).

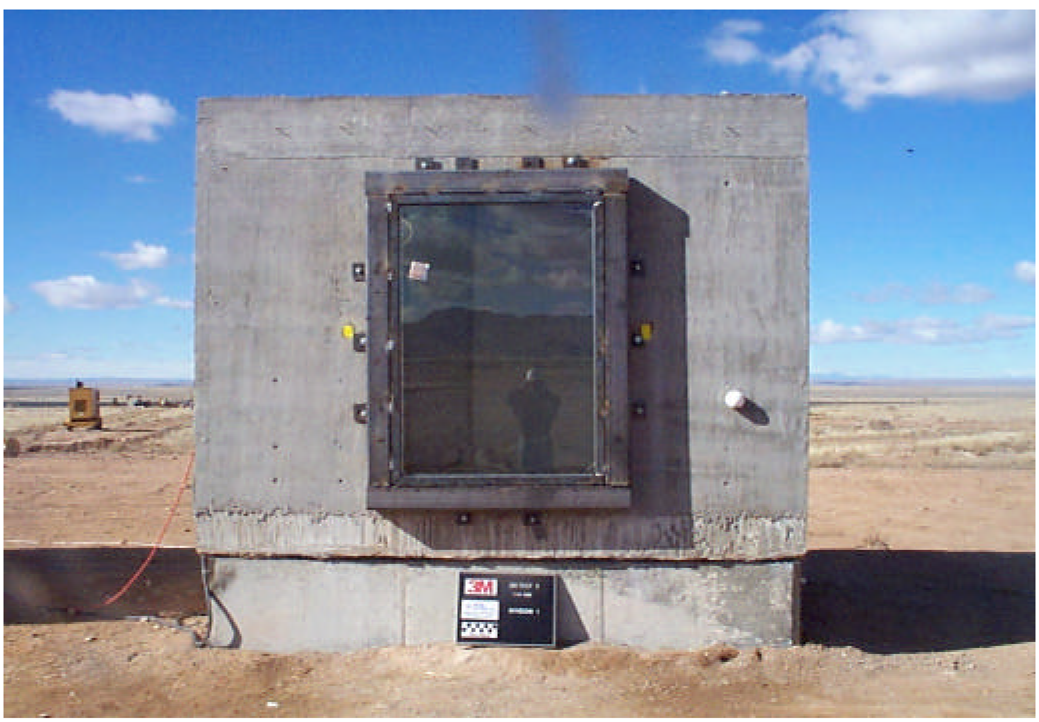


Figure A.82. Test 3. Pretest, exterior view of window 1 (test3_14.jpg).

Figure A.83. Test 3. Pretest, exterior view of window 1 (test3_15.jpg).

Figure A.84. Test 3. Pretest, interior view of window 1 (3M T3 PRE 01.tif).

Figure A.85. Test 3. Pretest interior view of window 1. Close-up view of the batten system (3M T3 PRE 02.tif).

Figure A.86. Test 3. Posttest, exterior view of window 1 (test3_22.jpg).

Figure A.87. Test 3. Posttest, exterior view of window 1 (test3_23.jpg).

Figure A.88. Test 3. Posttest, interior view of window 1 (3M T3 POST 22.tif).

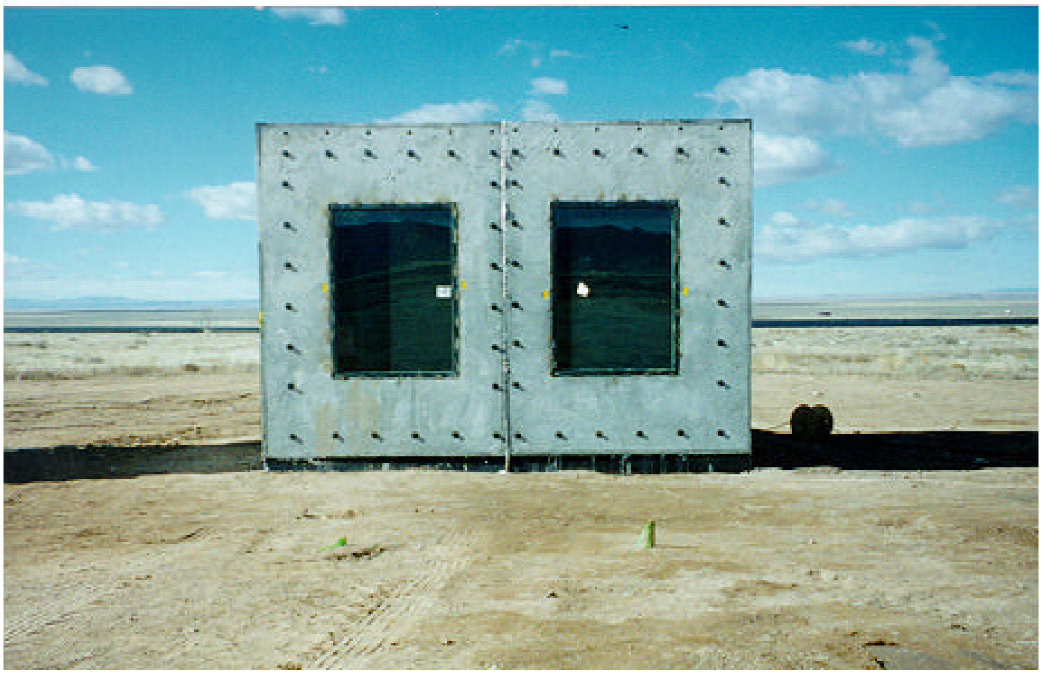


Figure A.89. Test 3. Pretest, exterior view of windows 2 and 3 (3m sd T3 pre01.tif).

Figure A.90. Test 3. Pretest, exterior view of window 2 (test3_13.jpg).

Figure A.91. Test 3. Pretest, interior view of window 2 (3M T3 PRE 04.tif).

Figure A.92. Test 3. Pretest, interior view of window 1. Close-up view of the batten system (3M T3 PRE 05.tif).

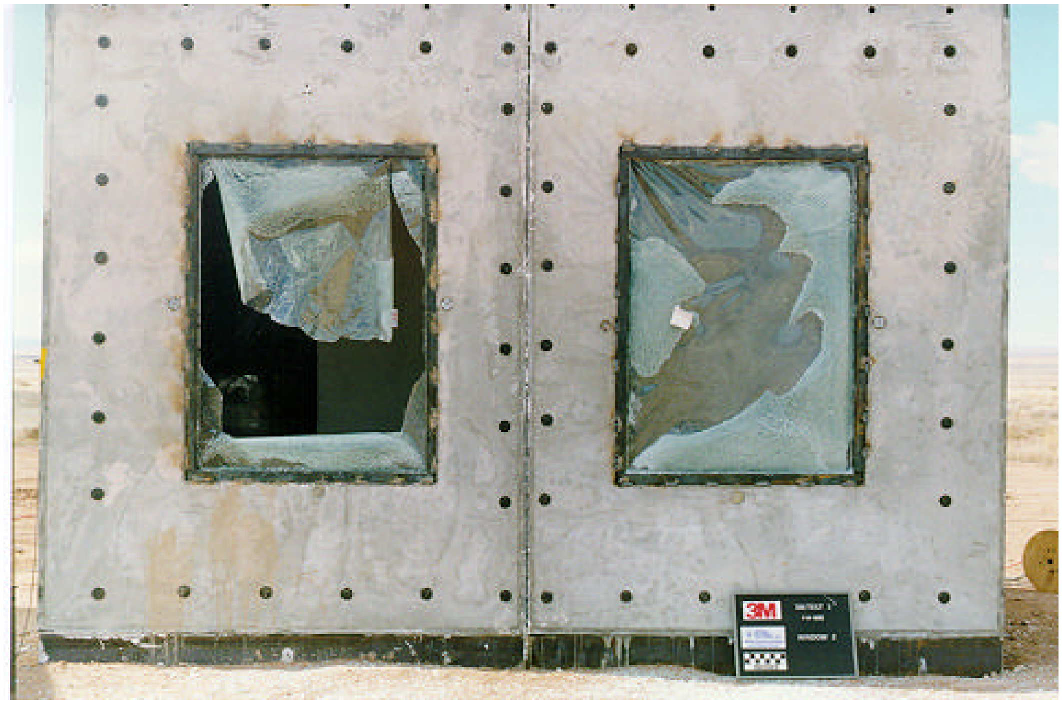


Figure A.93. Test 3. Posttest, exterior view of windows 2 and 3 (3M T3 POST 09.tif).

Figure A.94. Test 3. Posttest, exterior view of window 2 (3M T3 POST 10.jpg).

Figure A.95. Test 3. Posttest, interior view of window 2 (3M T3 POST 25.tif).

Figure A.96. Test 3. Posttest, interior view of window 2. Close-up view of a tear in the security film along the vertical edge (3M T3 POST 27.tif).

Figure A.97. Test 3. Pretest, exterior view of window 3 (3m sd T3 pre02.tif).

Figure A.98. Test 3. Pretest, interior views of window 3. Close-up view of the batten system shown on right (3M T3 PRE 07.tif, 3M T3 PRE 08.tif).

Figure A.99. Test 3. Posttest, exterior view of window 3 (3M T3 POST 11.tif).

Figure A.100. Test 3. Posttest, interior views of window 3 (3M T3 POST 29.tif, 3M T3 POST 31.tif).

Figure A.101. Test 3. Posttest, interior view of window 3 (top half) (3m sd T3 post01.tif).

Figure A.102. Test 3. Posttest, interior view of window 3 (bottom half) (3m sd T3 post02.tif).

Figure A.103. Test 3. Posttest, exterior view of windows 2 and 3. Picture depicting the glass fragment spray in front of the reaction structures (3M T3 POST 20.tif).

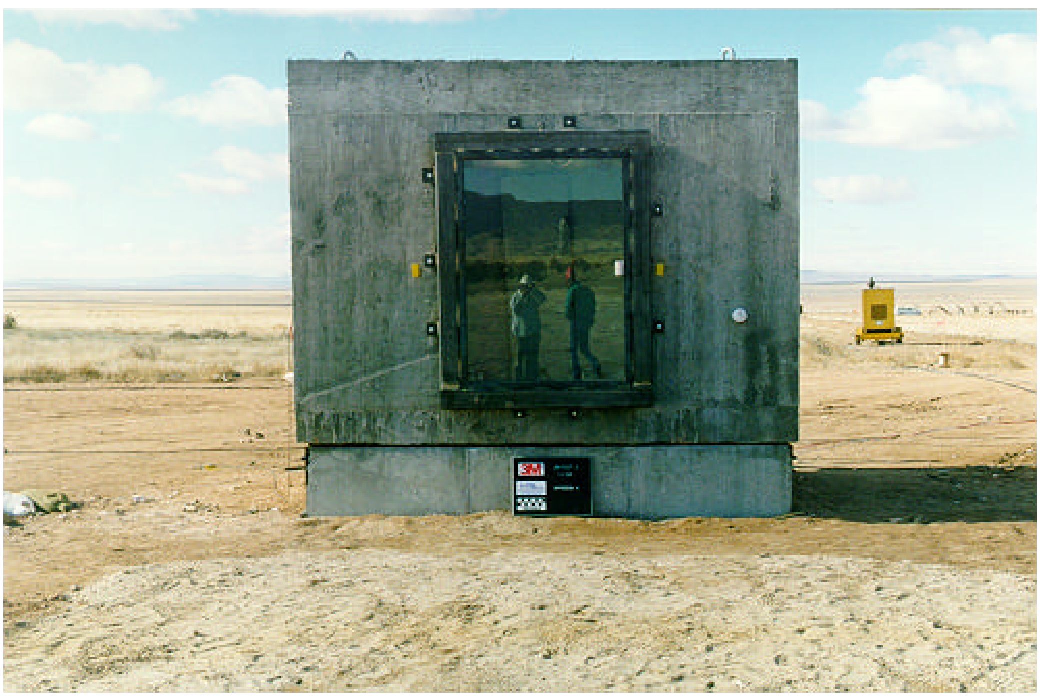


Figure A.104. Test 3. Pretest, exterior view of window 4 (3M T3 PRE 12.tif).

Figure A.105. Test 3. Pretest, exterior view of window 4 (3M T3 PRE 14.tif).

Figure A.106. Test 3. Pretest, interior view of window 4 (3M T3 PRE 09.tif).

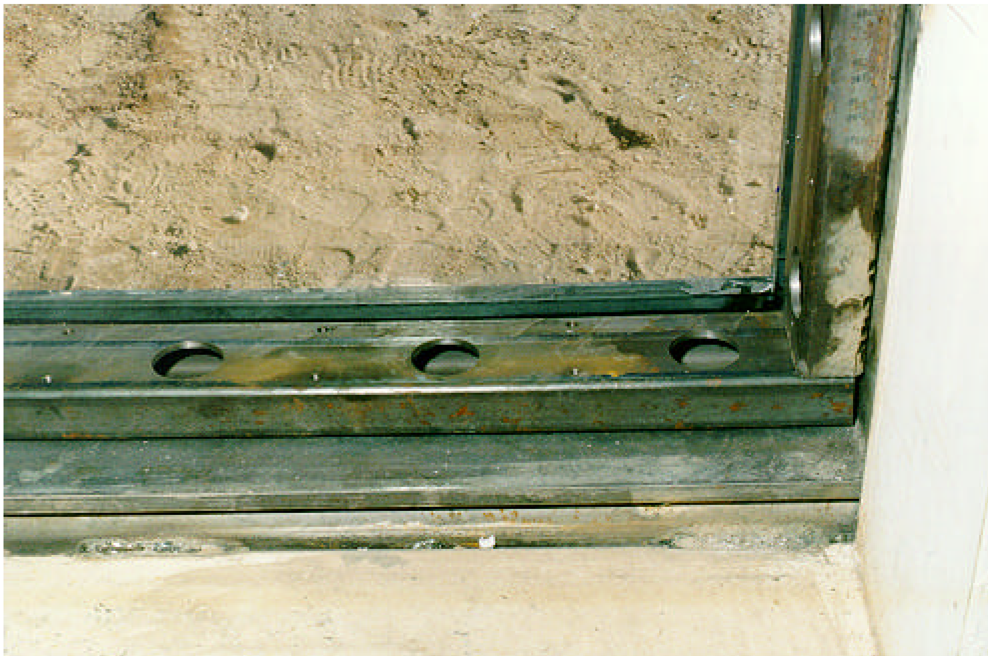


Figure A.107. Test 3. Pretest, interior view of window 4. Picture showing daylight application (3M T3 PRE 10.tif).

Figure A.108. Test 3. Posttest, exterior view of window 4 (3M T3 POST 13.tif).

Figure A.109. Test 3. Posttest, exterior view of window 4 (3M T3 POST 16.tif).

Figure A.110. Test 3. Posttest, interior view of window 4 (3m sd T3 post03.tif).

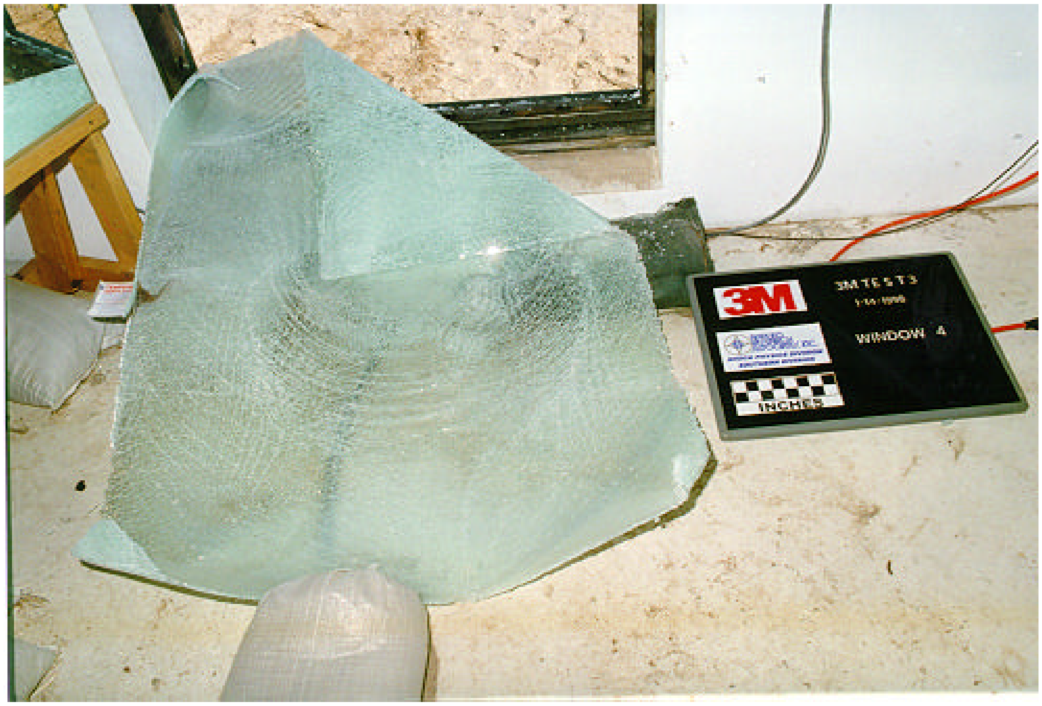


Figure A.111. Test 3. Posttest, interior view of window 4 (3M T3 POST 33.tif).

Figure A.112. Test 3. Pretest, interior view of window 4 (3M T3 POST 02.tif).

Figure A.113. Test 4. Pretest view of the test bed (3M T4 PRE 25.tif).

Figure A.114. Test 4. Posttest view of the test bed (3M T4 POST 03.tif).

Figure A.115. Test 4. Pretest, exterior view of window 1 (3M T4 PRE 19.tif).

Figure A.116. Test 4. Pretest, exterior view of window 1 (3M T4 PRE 18.tif).

Figure A.117. Test 4. Pretest, interior view of window 1 (3M T4 PRE 01.tif).

Figure A.118. Test 4. Pretest, interior view of window 1. Close-up view of the batten system (3M T4 PRE 02.tif).

Figure A.119. Test 4. Posttest, exterior view of window 1 (3M T4 POST 07.tif).

Figure A.120. Test 4. Posttest, exterior view of window 1 (3M T4 POST 05.tif).

Figure A.121. Test 4. Posttest, interior view of window 1 (3M T4 POST 18.tif).

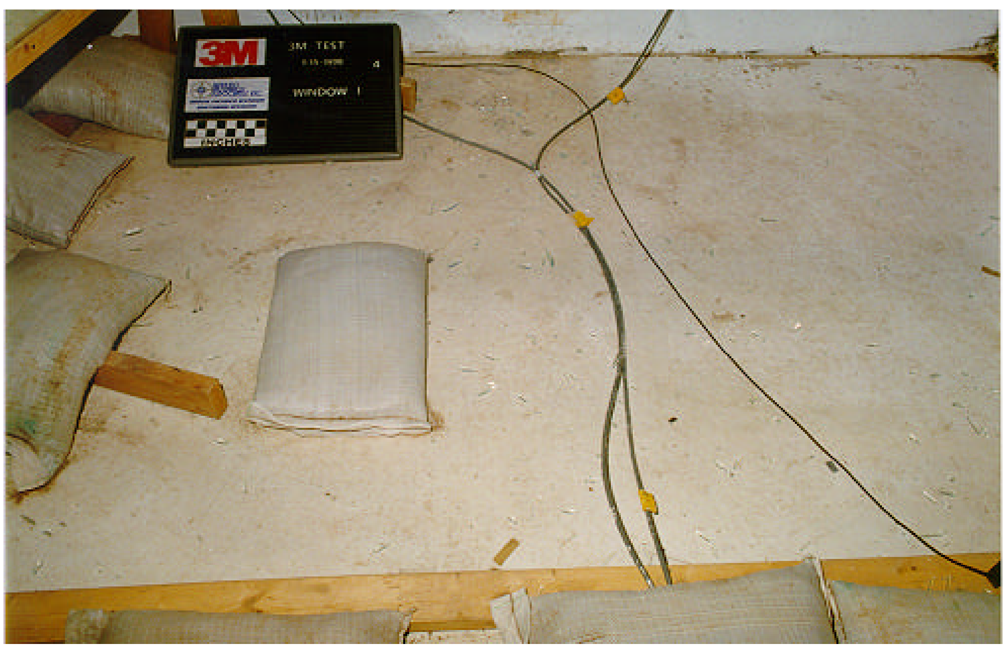


Figure A.122. Test 4. Posttest view of the North Structure floor (3M T4 POST 19.tif).

Figure A.123. Test 4. Pretest, exterior view of windows 2 and 3 (3M T4 PRE 15.tif).

Figure A.124. Test 4. Pretest, exterior view of window 2 (3M T4 PRE 17.tif).

Figure A.125. Test 4, pretest interior view of window 2 (3M T4 PRE 03.tif).

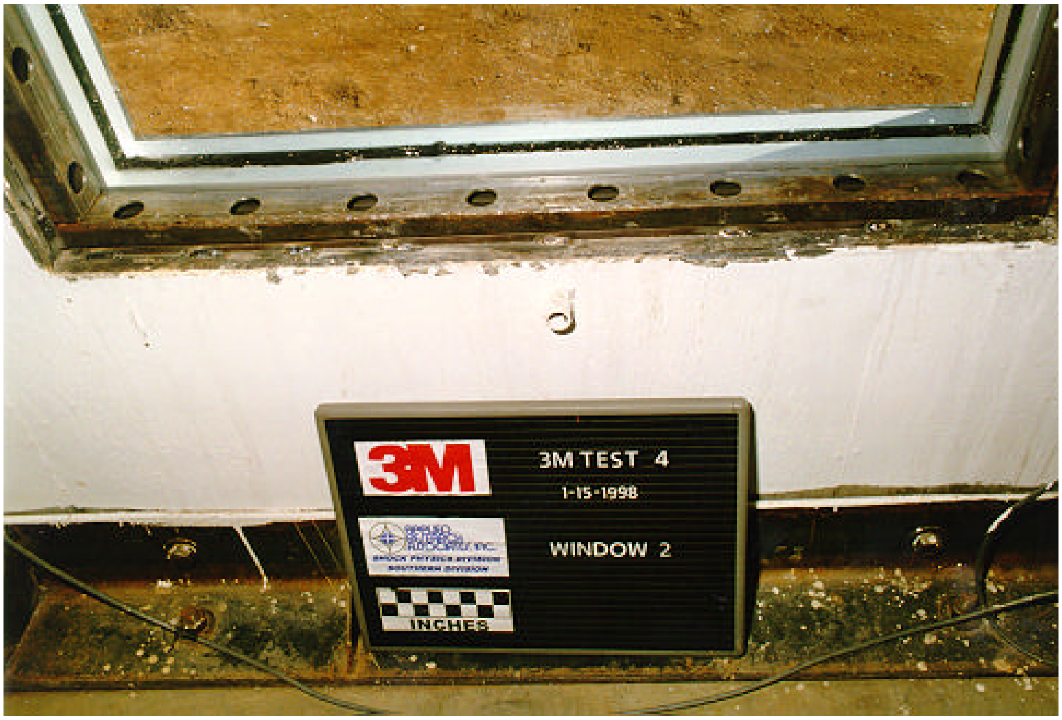


Figure A.126. Test 4, pretest interior view of window 2. Picture showing wet glazed application (3M T4 PRE 05.tif).

Figure A.127. Test 4. Posttest, exterior view of windows 2 and 3 (3M T4 POST 09.tif).

Figure A.128. Test 4. Posttest, exterior view of window 2 (3M T4 POST 11.tif).

Figure A.129. Test 4. Posttest, interior view of window 2 (3M T4 POST 13.tif).

Figure A.130. Test 4. Posttest, interior views of window 2. Pictures of the aluminum frame displacement along the vertical edges (3M T4 POST 16.tif).

Figure A.131. Test 4. Posttest, interior view of window 2. Picture of the aluminum frame displacement along the top edge (3m sd T4 post02.tif).

Figure A.132. Test 4. Posttest, interior view of window 2. Picture of the aluminum frame displacement along the bottom edge (3m sd T4 post02.tif).

Figure A.133. Test 4. Pretest, exterior view of window 3 (3M T4 PRE 14.tif).

Figure A.134. Test 4. Pretest, interior view of window 3 (3M T4 PRE 06.tif).

Figure A.135. Test 4. Pretest, interior view of window 3. Close-up view of the batten system (3M T4 PRE 07.tif).

Figure A.136. Test 4. Posttest, exterior view of window 3 (3M T4 POST 41.tif, 3M T4 POST 33.tif).

Figure A.137. Test 4. Posttest interior view of window 3 (3M T4 POST 30.tif).

Figure A.138. Test 4. Posttest, interior views of window 3. Pictures of the aluminum frame displacement along the vertical edges (3m sd T4 post04.tif, 3m sd T4 post03.tif).

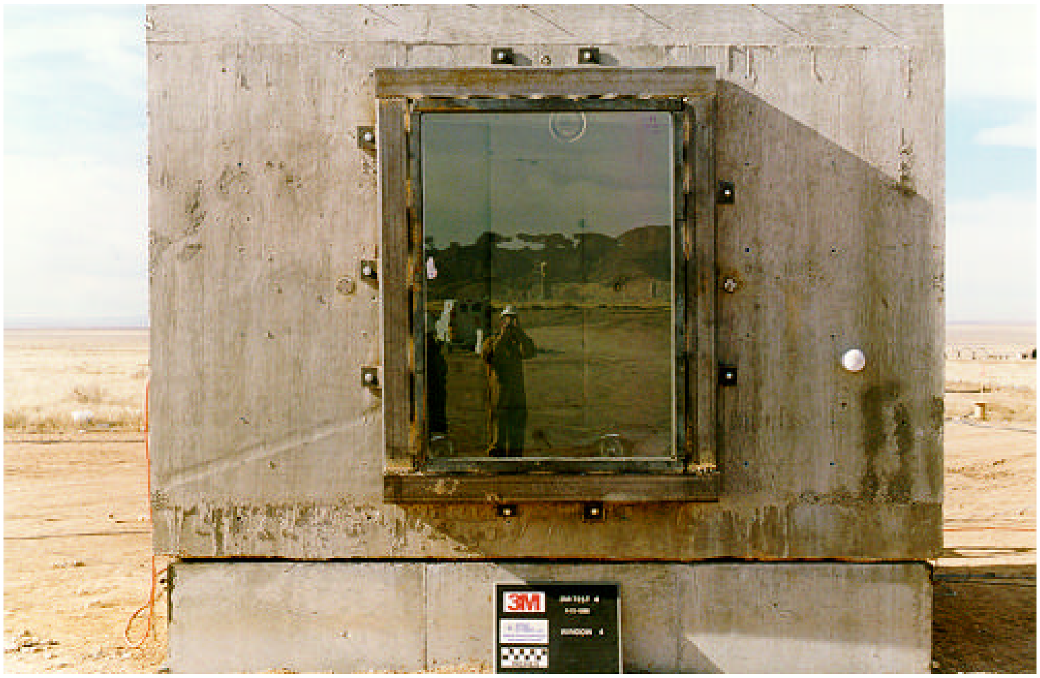


Figure A.139. Test 4. Pretest, exterior view of window 4 (3M T4 PRE 11.tif).

Figure A.140. Test 4. Pretest, exterior view of window 4 (3M T4 PRE 10.tif).

Figure A.141 Test 4. Pretest, interior view of window 4 (3M T4 PRE 08.tif).

Figure A.142. Test 4. Pretest, interior view of window 4. Close-up view of batten system (3M T4 PRE 09.tif).

Figure A.143. Test 4. Posttest, exterior view of window 4 (3M T4 POST 43.tif).

Figure A.144. Test 4. Posttest, exterior view of window 4 (3M T4 POST 32.tif).

Figure A.145. Test 4. Posttest, interior view of window 4 (3M T4 POST 31.tif).

Figure A.146. Test 4. Posttest, interior view of window 4 (3M T4 POST 46.tif).

Figure A.147. Test 5. Posttest view of the test bed (3M T5 POST 20.tif).

Figure A.148. Test 5. Pretest, exterior view of window 1 (3M T5 PRE 20.tif).

Figure A.149. Test 5. Pretest, exterior view of window 1 (3M T5 PRE 18.tif).

Figure A.150. Test 5. Pretest, interior view of window 1 (3M T5 PRE 05.tif).

Figure A.151. Test 5. Pretest, interior view of Window 1. Close-up view of the batten system (3M T5 PRE 07.tif).

Figure A.152. Test 5. Posttest, exterior view of window 1 (3M T5 POST 24. tif).

Figure A.153. Test 5. Posttest, exterior view of window 1 (3M T5 POST 26.tif).

Figure A.154. Test 5. Posttest, interior view of window 1 (3M T5 POST 06.tif).

Figure A.155. Test 5. Pretest, exterior view of windows 2 and 3 (3M T5 PRE 13.tif).

Figure A.156. Test 5. Pretest, exterior view of window 2 (3M T5 PRE 15.tif).

Figure A.157. Test 5. Pretest, interior view of window 2 (3M T5 PRE 01.tif).

Figure A.158. Test 5. Pretest, interior view of window 2. Close-up view of the batten system (3M T5 PRE 03.tif).

Figure A.159. Test 5. Posttest, exterior view of windows 2 and 3 (3M T5 POST 33. tif).

Figure A.160. Test 5. Posttest, exterior view of window 2 (3M T5 POST 29.tif).

Figure A.161. Test 5. Posttest, interior view of window 2 (3M T5 POST 04.tif).

Figure A.162. Test 5. Pretest, exterior view of window 3 (3M T5 PRE 12.tif).

Figure A.163. Test 5, pretest interior view of window 3 (3M T5 PRE 02.tif).

Figure A.164. Test 5, pretest interior view of window 3 (3M T5 PRE 04.tif).

Figure A.165. Test 5. Posttest, exterior view of window 3 (3M T5 POST 31.tif).

Figure A.166. Test 5. Posttest, interior view of window 3 (3M T5 POST 45. tif).

Figure A.167. Test 5. Posttest, interior views of window 3 (3M T5 POST 48.tif, 3M T5 POST 49.tif).

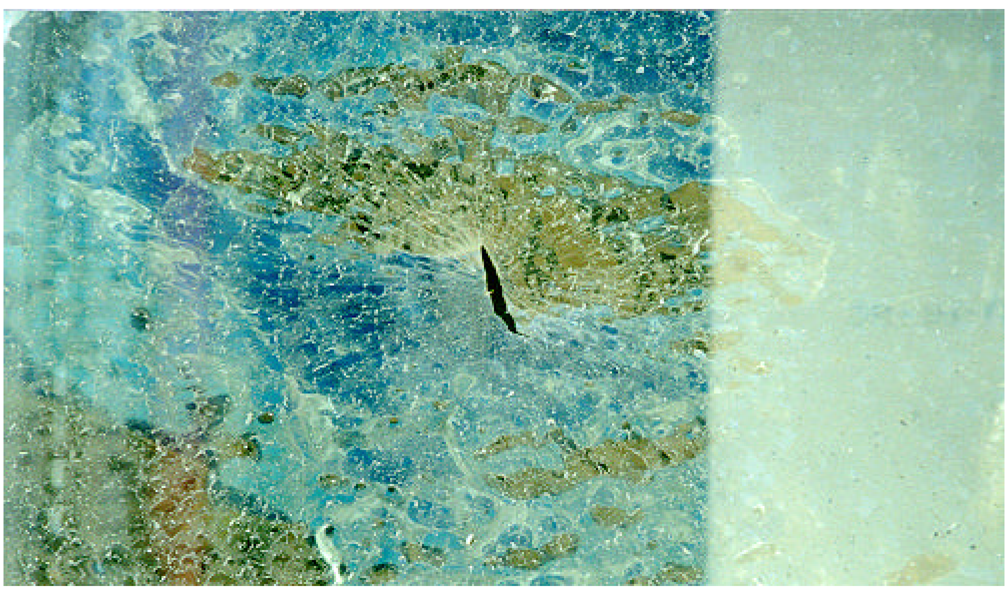


Figure A.168. Test 5. Posttest, exterior view of window 3. Picture of an apparent projectile penetration (3M sd T5 post01.tif).

Figure A.169. Test 5. Possible projectile found near the front of the structure containing window 3 (3M sd T5 post02.tif).

Figure A.170. Test 5. Pretest, exterior view of window 4 (3M T5 PRE 11.tif).

Figure A.171. Test 5. Pretest, exterior view of window 4 (3M T5 PRE 09.tif).

Figure A.172. Test 5. Pretest, interior view of window 4 (3M T5 PRE 06.tif).

Figure A.173. Test 5. Pretest, interior view of window 4 (3M T5 PRE 08.tif).

Figure A.174. Test 5. Posttest, exterior view of window 4 (3M T5 POST 37. tif).

Figure A.175. Test 5. Posttest, exterior view of window 4 (3M T5 POST 38.tif).

Figure A.176. Test 5. Posttest, interior views of window 4 (3M T5 POST 43.tif, 3M T5 POST 45.tif).

Figure A.177. Test 5. Posttest, exterior view of window 4 (3M sd T5 post03.tif).

Figure A.178. Test 6. Pretest view of the test bed (3M T6 PRE 23.tif).

Figure A.179. Test 6. Posttest view of the test bed (3M T6 POST 09.tif).

Figure A.180. Test 6. Pretest exterior view of window 1 (3M T6 PRE 20).

Figure A.181. Test 6. Pretest, exterior view of window 1 (3M T6 PRE 20.tif).

Figure A.182. Test 6. Pretest, interior view of window 1 (3M T6 PRE 05.tif).

Figure A.183. Test 6. Posttest, exterior view of window 1 (3M T6 POST 10.tif).

Figure A.184. Test 6. Posttest, exterior view of window 1 (3M T6 POST 12. tif).

Figure A.185. Test 6. Posttest, interior view of window 1 (3M sd T6 post01.tif).

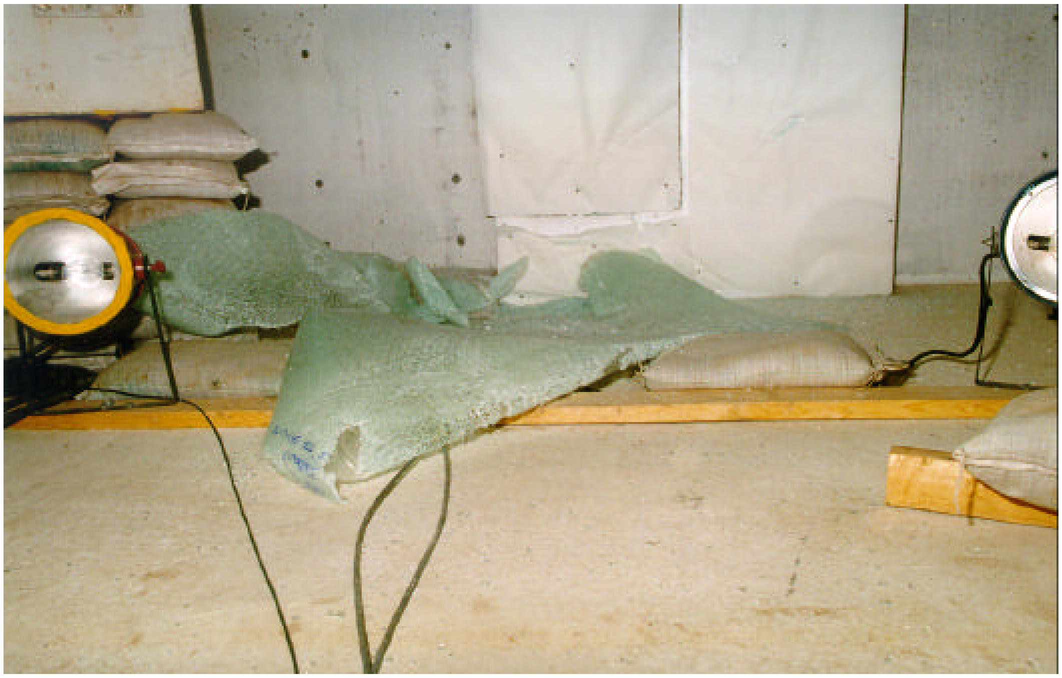


Figure A.186. Test 6. Posttest view of the back wall and floor of the North Structure (3M T6 POST 14.tif).

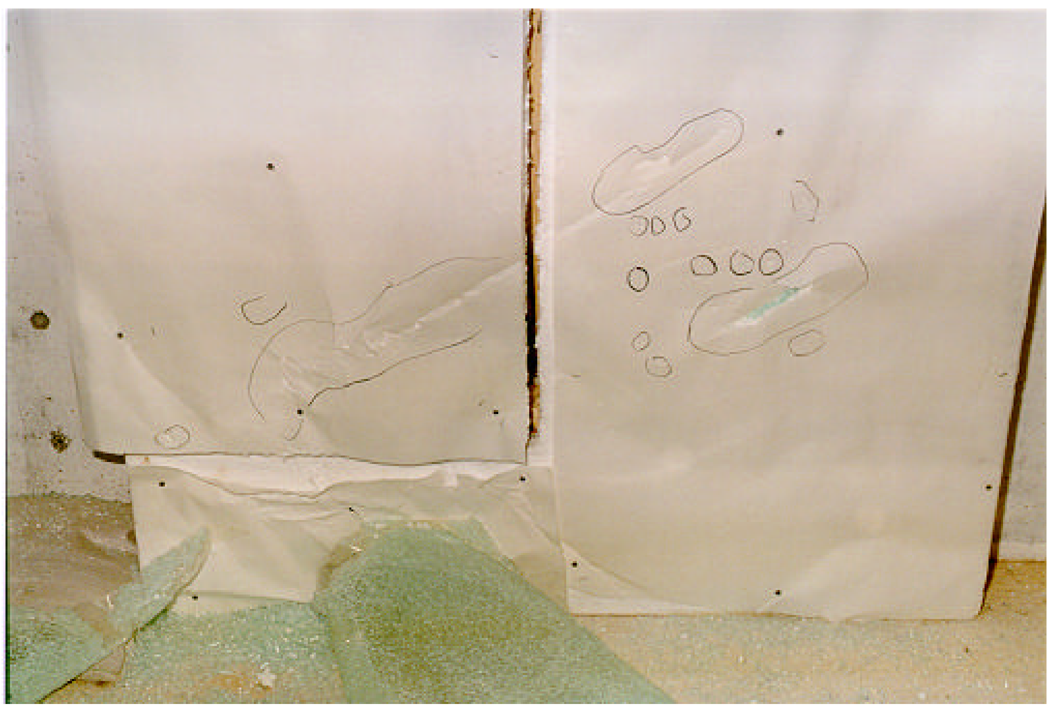


Figure A.187. Test 6. Posttest view of the witness panel located behind window 1 (3M T6 POST 22.tif).

Figure A.188. Test 6. Pretest, exterior view of windows 2 and 3 (3M T6 PRE 22.tif).

Figure A.189. Test 6. Pretest, exterior view of window 2 (3M T6 PRE 18.tif).

Figure A.190. Test 6. Pretest, interior view of window 2 (3M T6 PRE 06.tif).

Figure A.191. Test 6. Pretest interior view of window 2. Close-up view of the batten system (3M T6 PRE 07.tif).

Figure A.192. Test 6. Posttest, exterior view of windows 2 and 3 (3M T6 POST 05. tif).

Figure A.193. Test 6. Posttest, exterior view of window 2 (3M T6 POST 02.tif).

Figure A.194. Test 6. Posttest, interior views of window 2 (3M T6 POST 30.tif).

Figure A.195. Test 6. Pretest, exterior view of window 3 (3M T6 PRE 16.tif).

Figure A.196. Test 6. Pretest, interior view of window 3 (3M T6 PRE 08.tif).

Figure A.197. Test 6. Pretest, interior view of window 3. Close-up view of the batten system (3M T6 PRE 09.tif).

Figure A.198. Test 6. Posttest, exterior view of window 3 (3M T6 POST 03.tif).

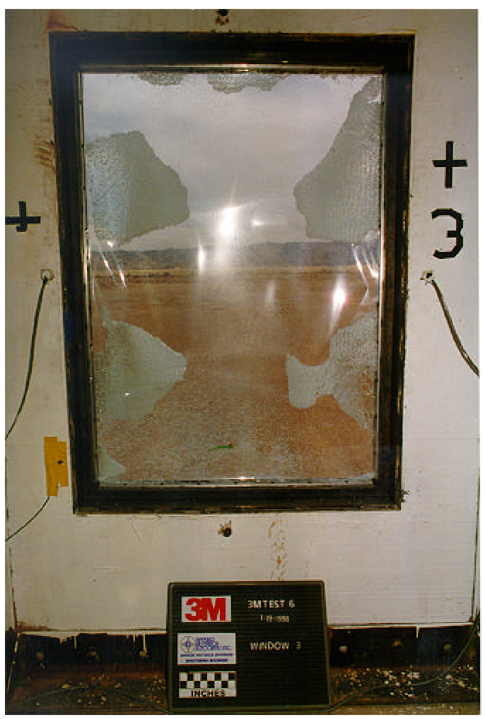


Figure A.199. Test 6. Posttest, interior view of window 3 (3M T6 POST 35. tif).

Figure A.200. Test 6. Posttest, interior view of window 3 (3M T6 POST 36.tif).

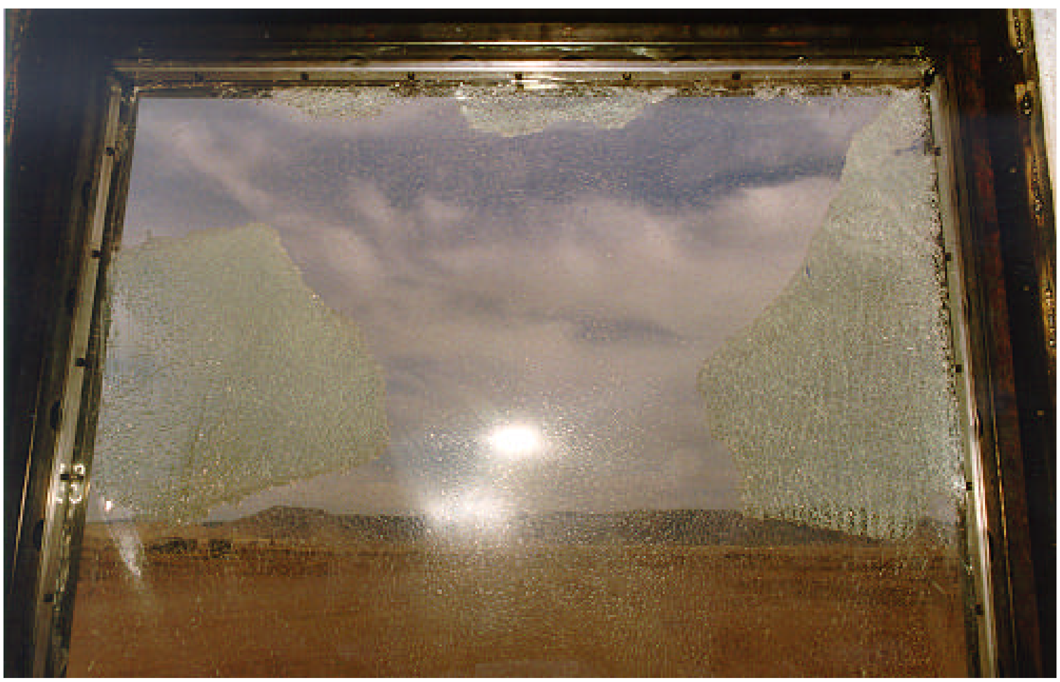


Figure A.201. Test 6. Posttest, interior view of window 3 (view of top half) (3M T6 POST 38.tif).

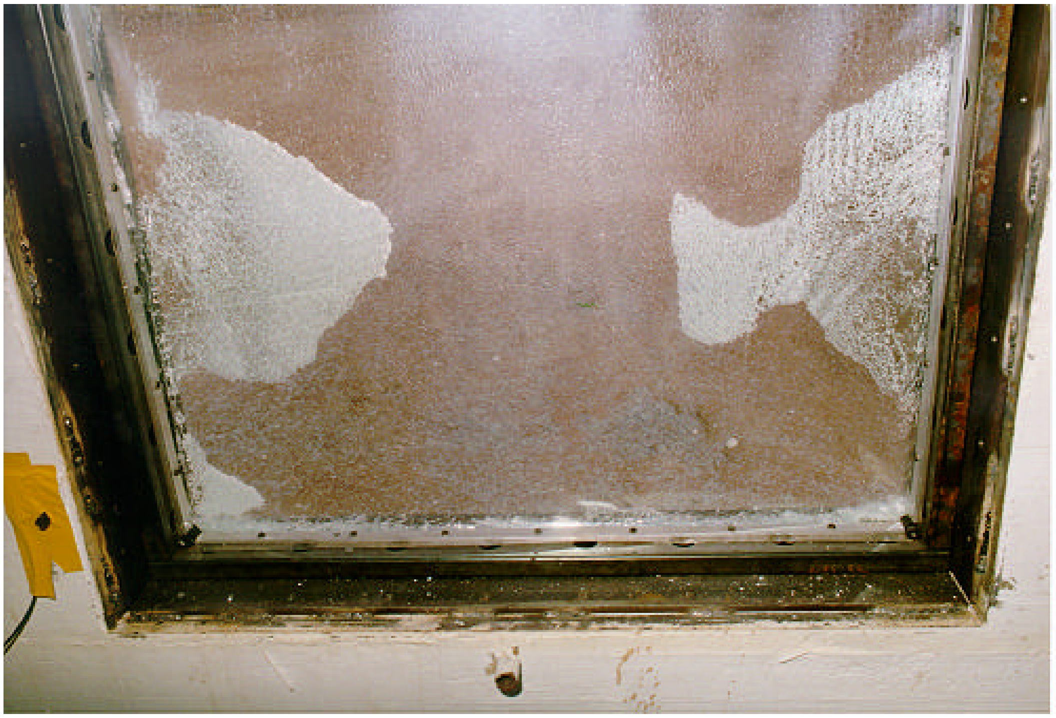


Figure A.202. Test 6. Posttest, interior view of window 3 (view of bottom half) (3M T6 POST 37.tif).

Figure A.203. Test 6. Pretest, exterior view of window 4 (3M T6 PRE 12.tif).

Figure A.204. Test 6. Pretest, exterior view of window 4 (3M T6 PRE 14.tif).

Figure A.205. Test 6. Pretest, interior view of window 4 (3M T6 PRE 10.tif).

Figure A.206. Test 6. Pretest, interior view of window 4 (3M T6 PRE 11.tif).

Figure A.207. Test 6. Posttest, exterior view of window 4 (3M T6 POST 06. tif).

Figure A.208. Test 6. Posttest, exterior view of window 4 (3M T6 POST 16.tif).

Figure A.209. Test 6. Posttest, exterior view of window 4 (3M T6 POST 17.tif).

Figure A.210. Test 6. Posttest, interior view of window 4 (3M T6 POST 23.tif).

Figure A.211. Test 6. Posttest view of the South Structure floor (3M T6 POST 24.tif).

Figure A.212. Test 6. Posttest view of the South Structure floor (3M T6 POST 26.tif).

Appendix B

Pressure gauges were installed in all of the reaction structures in order to measure the pressure levels that the window systems experienced in each explosive test. There were a total of 12 gauges used during this series. Figure B.1 shows the location of each gauge.

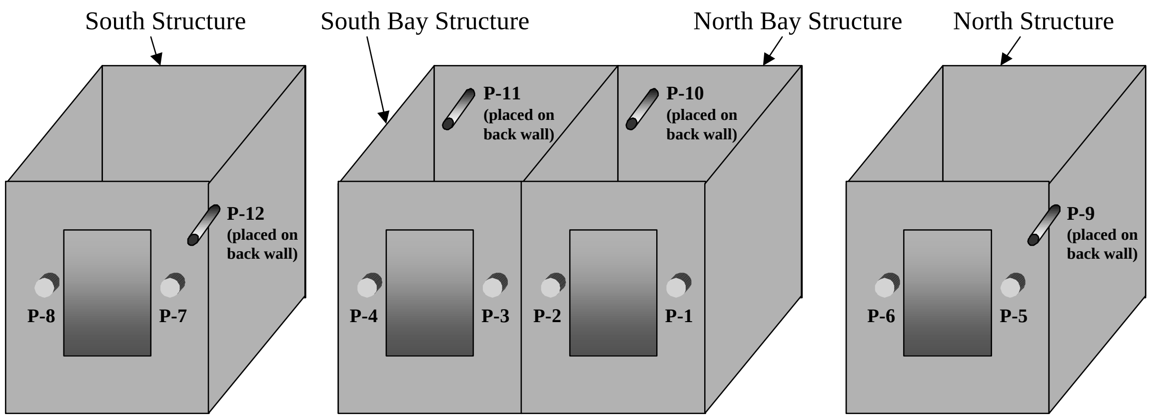


Figure B.1. Illustration of pressure gauge locations.

The table below (Table B.1) summarizes the peak pressures and impulses. Waveforms for each of the gauges (for each test) follow this. It should be noted that when attempting to determine the peak pressure and impulses, obvious noise (spikes) in the waveforms were ignored.

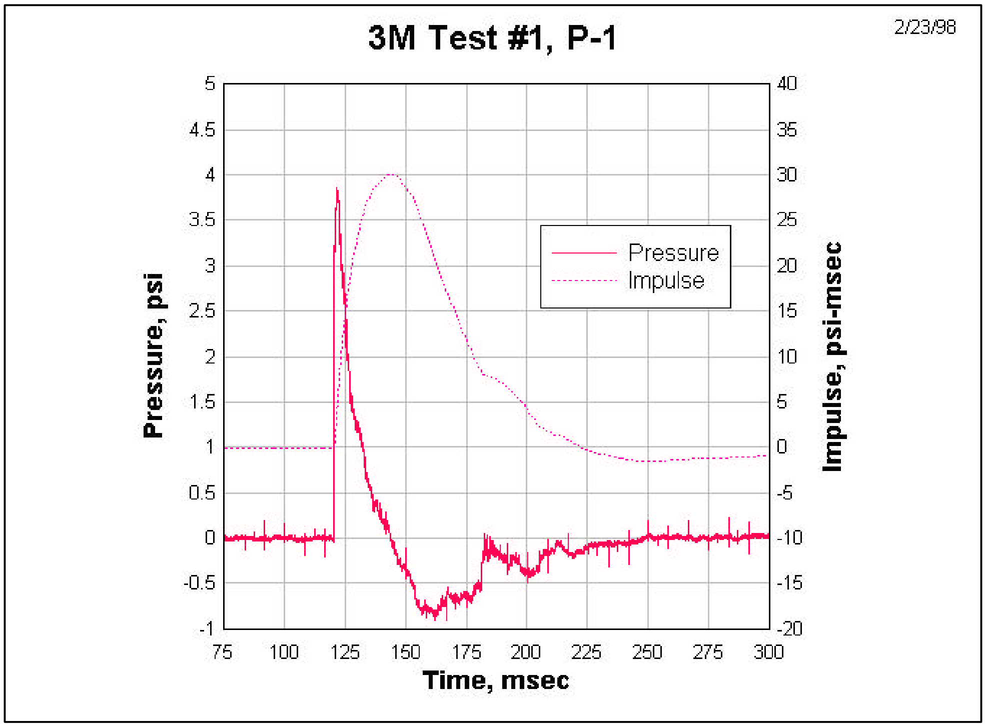
Table B.1. Summary of the peak pressures and impulses.

Test Number	Gauge Number*/ Average/ Standard Deviation	Peak Positive Pressure (psi)	Peak Positive Impulse (psi-msec)	Peak Negative Pressure (psi)
1	1	3.86	30.08	0.85
	2	3.88	30.02	0.99
	3	4.22	30.59	0.93
	4	4.28	30.72	0.79
	5	4.2	28.2	0.84
	6	4.63	29.5	0.9
	7	4.08	22.51	0.64
	8	4.22	25.62	0.72
	Average	4.17	28.41	0.83
	Standard Deviation	.24	2.91	.11

Test Number	Gauge Number*/ Average/ Standard Deviation	Peak Positive Pressure (psi)	Peak Positive Impulse (psi-msec)	Peak Negative Pressure (psi)
2	1	3.80	29.89	0.87
	2	3.76	30.00	0.93
	3	4.13	30.64	0.91
	4	4.13	30.81	0.77
	5	4.44	28.90	0.91
	6	4.56	29.89	0.80
	7	3.89	23.18	0.64
	8	4.2	26.12	0.71
	Average	4.11	28.68	0.82
	Standard Deviation	0.29	2.67	0.11
3	1	4.80	32.83	1.10
	2	5.00	35.60	1.28
	3	5.21	35.79	1.24
	4	5.27	35.96	1.04
	5	5.35	32.93	0.89
	6	5.72	35.05	1.03
	7	5.37	27.68	0.81
	8	5.65	30.92	0.94
	Average	5.30	33.35	1.04
	Standard Deviation	0.31	2.91	0.16
4	1	3.76	29.90	0.88
	2	3.77	30.18	0.98
	3	4.11	30.53	0.96
	4	4.15	31.42	0.83
	5	4.42	29.04	0.85
	6	4.56	30.39	0.81
	7	4.13	24.00	0.68
	8	4.24	26.88	0.70
	9	0.04	0.43	0.05
	10	0.05	0.79	0.04
	11	0.05	0.87	0.04
	12	0.04	0.60	0.03
	Average External Gauge	4.14	29.04	0.84
	Standard Deviation External Gauge	0.28	2.44	0.11
	Average Internal Gauge	0.05	0.67	0.04
	Standard Deviation Internal Gauge	0.01	0.20	0.01

Test Number	Gauge Number*/ Average/ Standard Deviation	Peak Positive Pressure (psi)	Peak Positive Impulse (psi-msec)	Peak Negative Pressure (psi)
5	1	8.62	51.01	1.62
	2	8.41	55.04	1.85
	3	9.19	54.83	1.88
	4	9.50	51.52	1.57
	5	8.76	48.03	1.49
	6	10.02	50.44	1.59
	7	9.53	40.78	1.30
	8	8.90	44.76	1.37
	9	0.05	0.53	0.06
	10	0.04	0.58	0.04
	11	0.05	0.74	0.06
	12	0.05	1.02	0.08
	Average External Gauge	9.11	49.55	1.58
	Standard Deviation External Gauge	0.54	4.88	0.21
	Average Internal Gauge	0.05	0.72	0.06
	Standard Deviation Internal Gauge	0.01	0.22	0.02
6	1	8.51	51.54	1.61
	2	8.37	55.40	1.85
	3	8.77	54.85	1.83
	4	9.17	52.05	1.59
	5	8.95	48.29	1.42
	6	9.77	50.57	1.63
	7	9.10	40.43	1.17
	8	9.48	44.83	1.27
	9	0.07	1.09	0.12
	10	0.05	0.69	0.04
	11	0.05	0.71	0.04
	12	0.05	0.62	0.18
	Average External Gauge	9.02	49.75	1.55
	Standard Deviation External Gauge	0.47	5.08	0.25
	Average Internal Gauge	0.06	0.78	0.10
	Standard Deviation Internal Gauge	0.01	0.21	0.07

*Pressure Gauges 1 thru 8 are located on the on the exterior of the structures. Pressure gauges 9 thru 12 are located on the interior of the structures. For reference see Figure B.1.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Impulse, psi-msec
Time, msec
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1.5
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0
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-1
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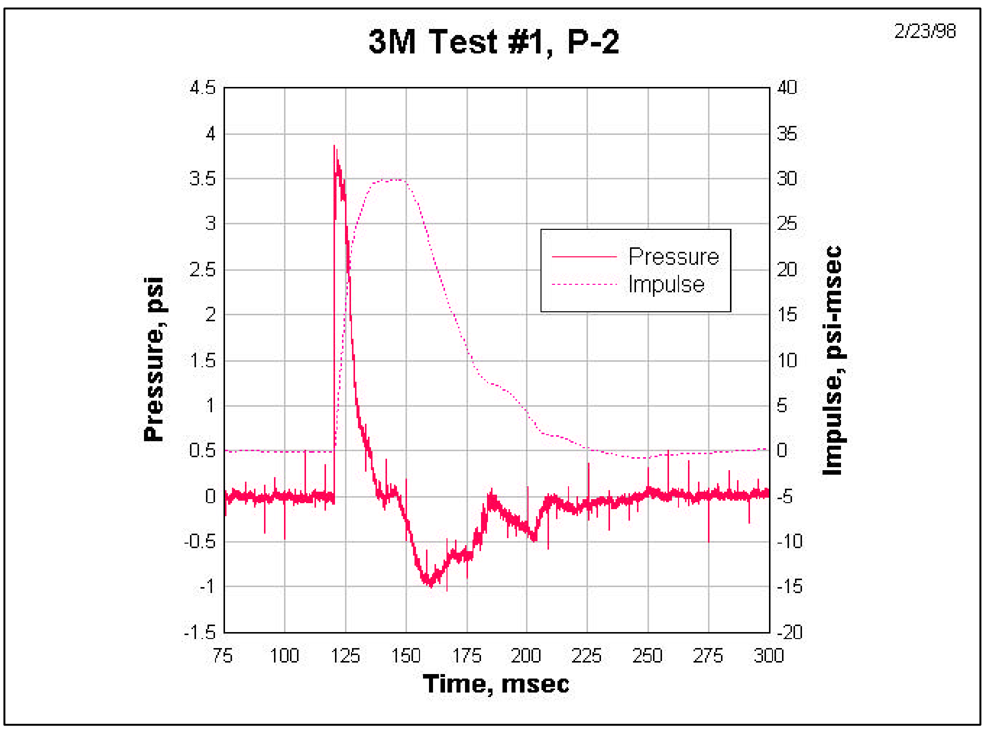
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Impulse, psi-msec
Time, msec
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2.5
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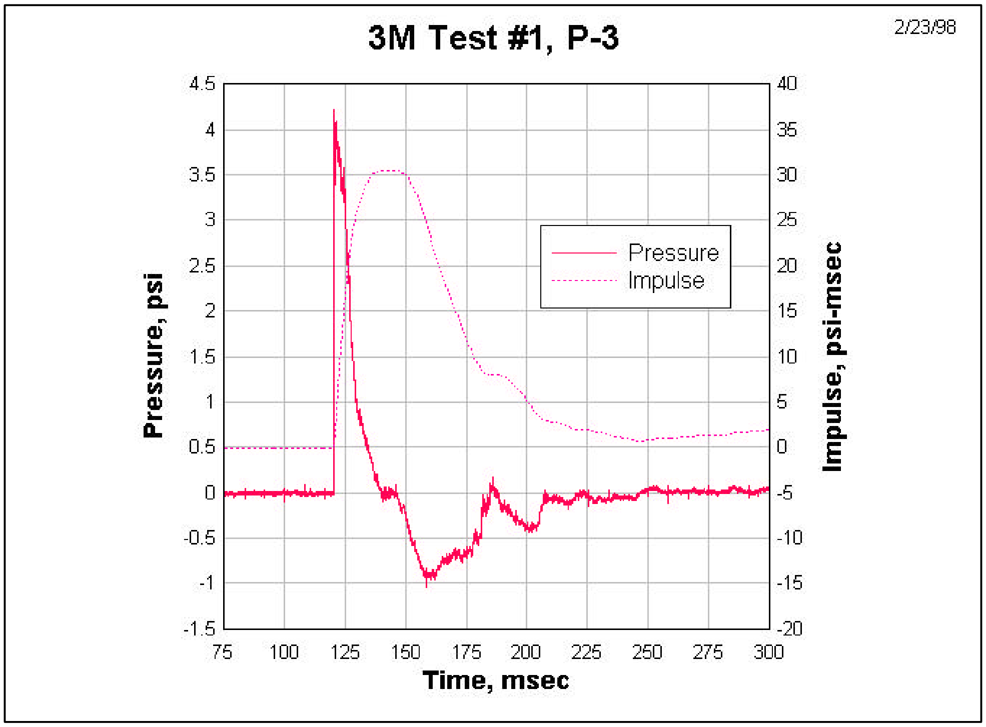
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2.5
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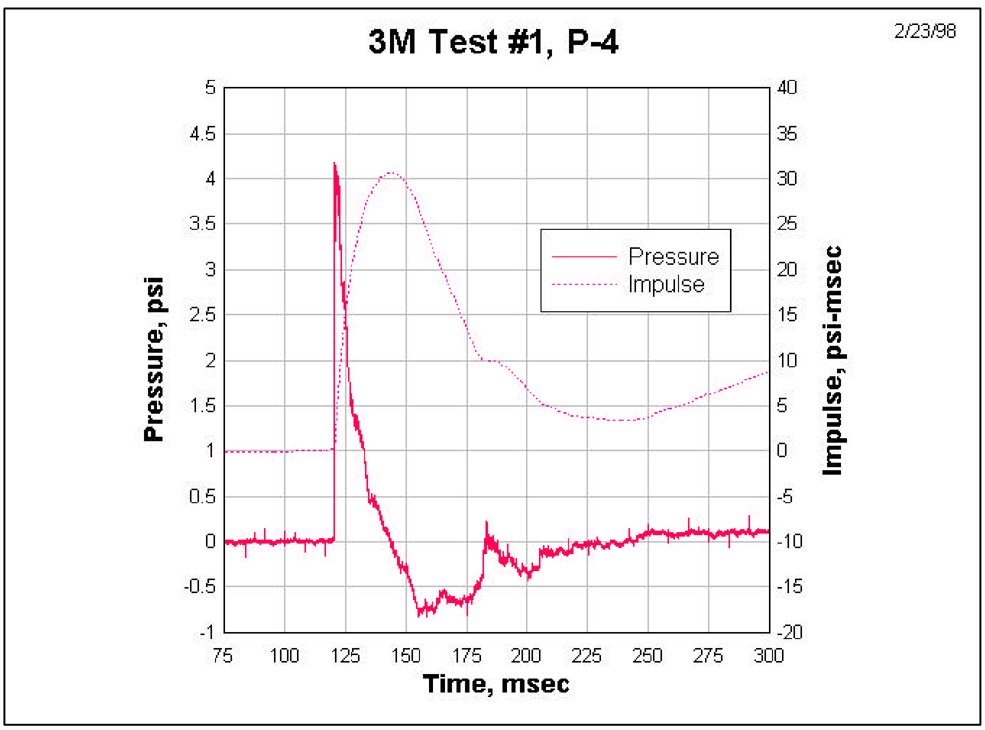
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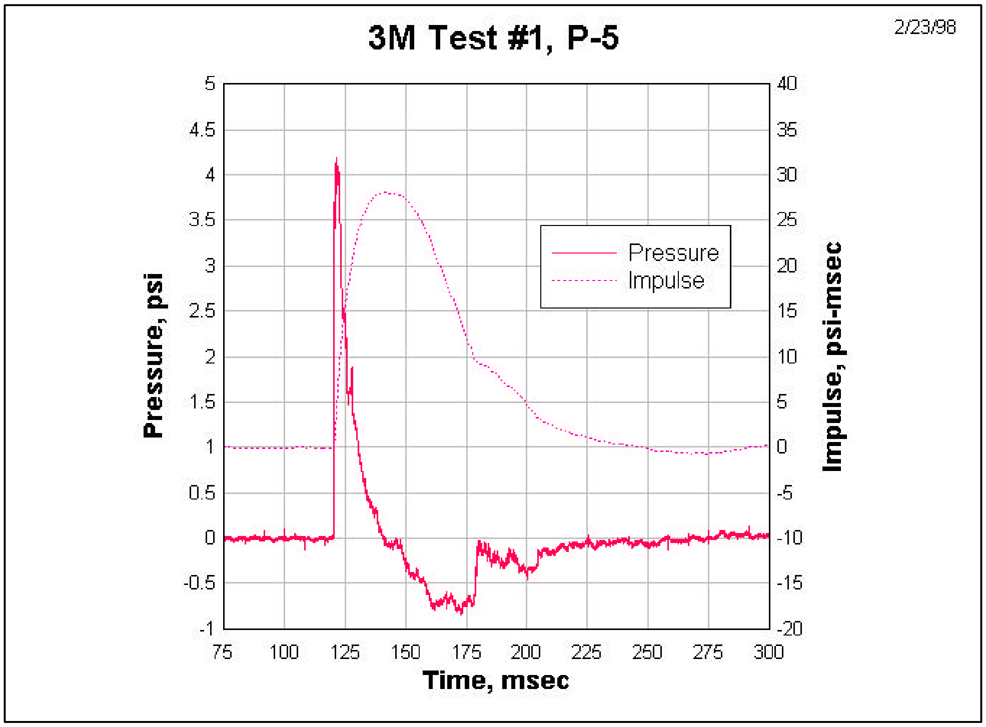
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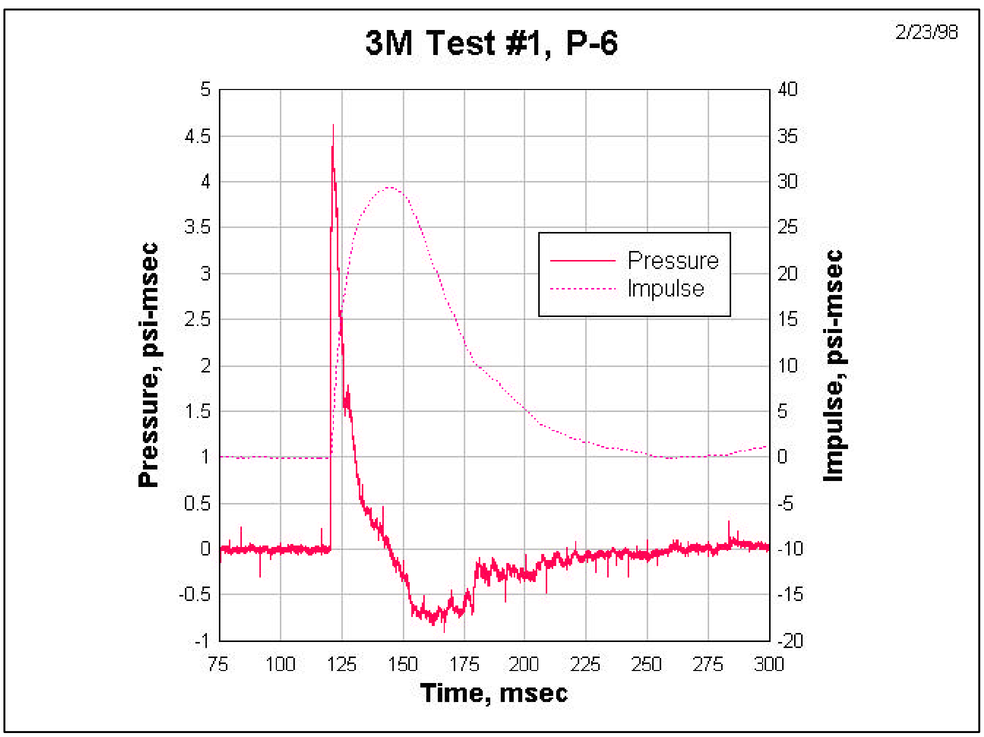
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Impulse, psi-msec
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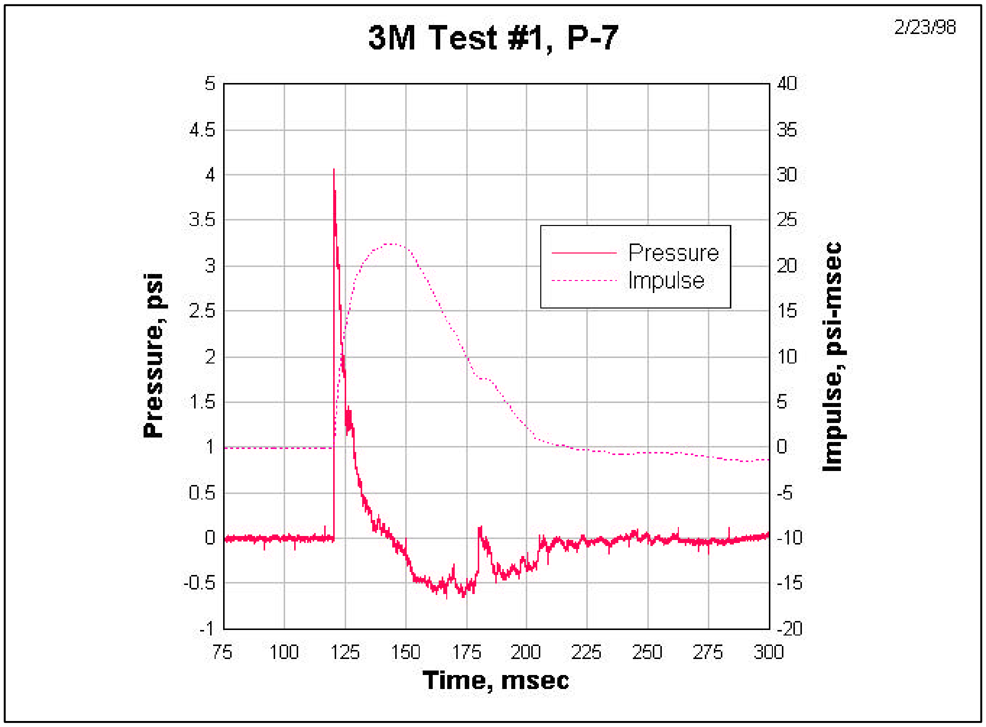
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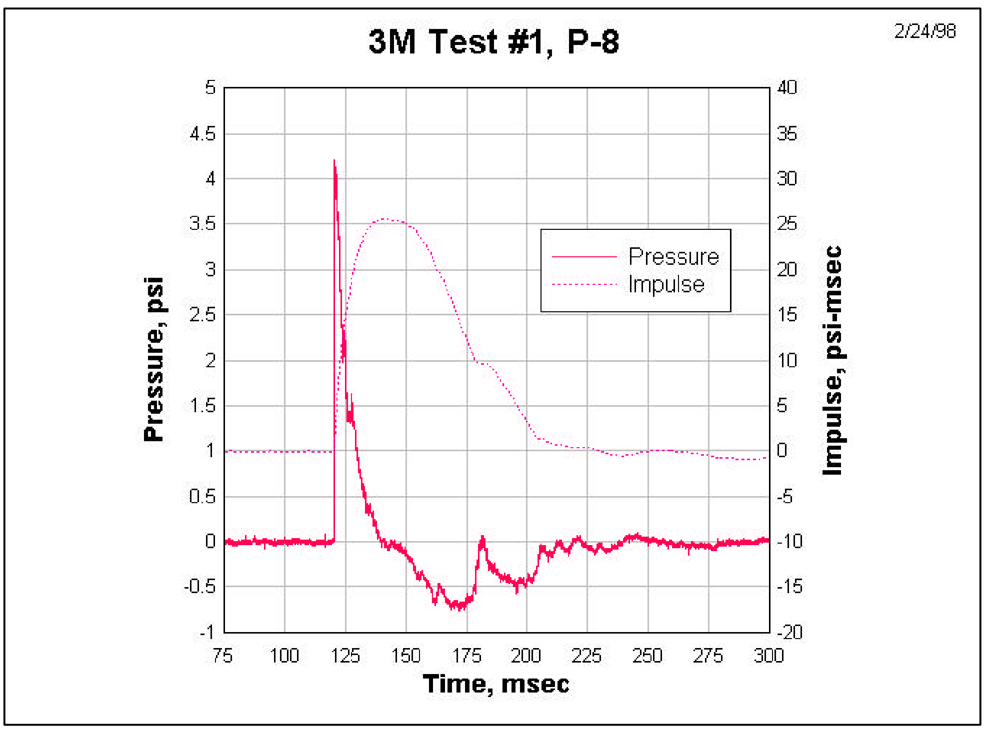
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100
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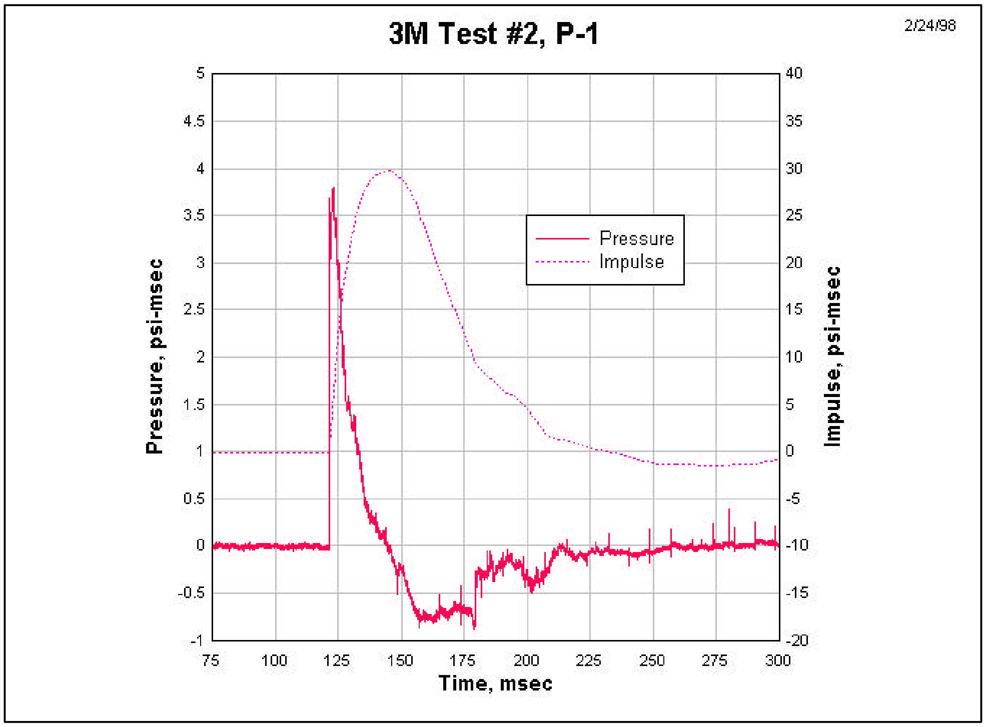
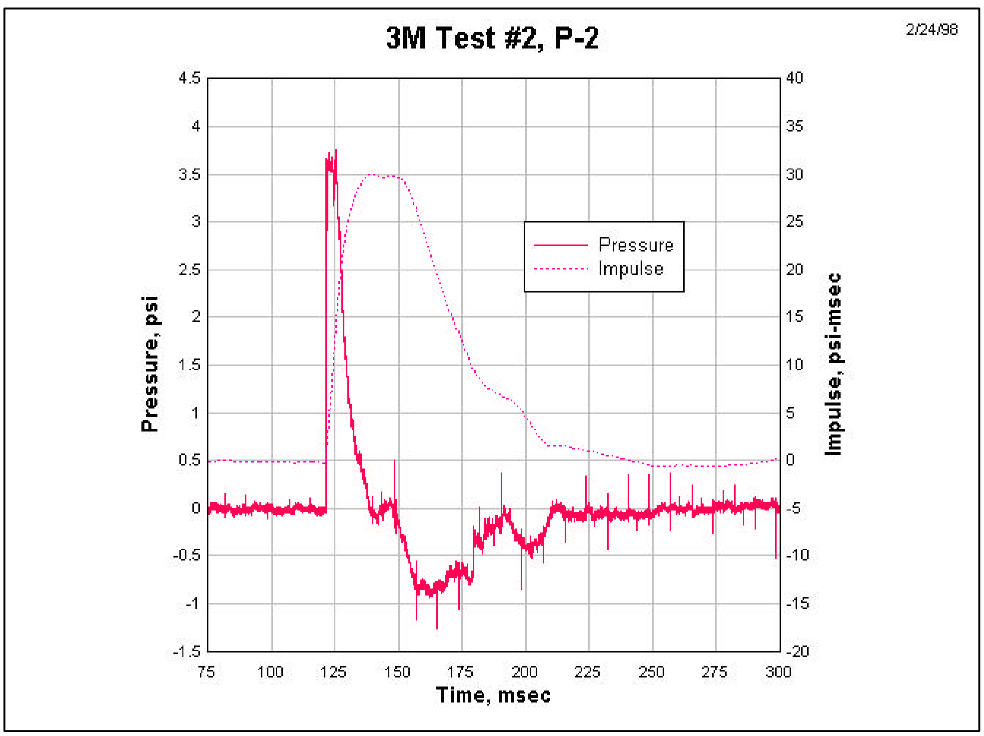
250
275
300


3M Test #2, P-1
2/24/98
Pressure, psi-msec
Impulse, psi-msec
Time, msec
Pressure
Impulse
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300


3M Test #2, P-2
2/24/98
Pressure, psi
Impulse, psi-msec
Time, msec
Pressure
Impulse
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
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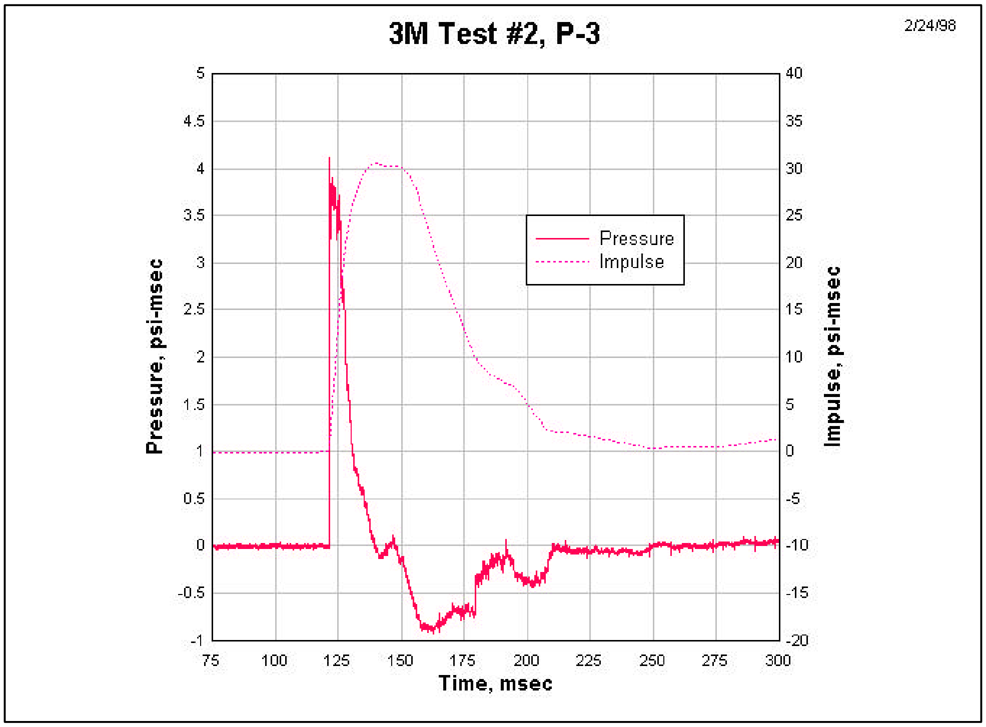
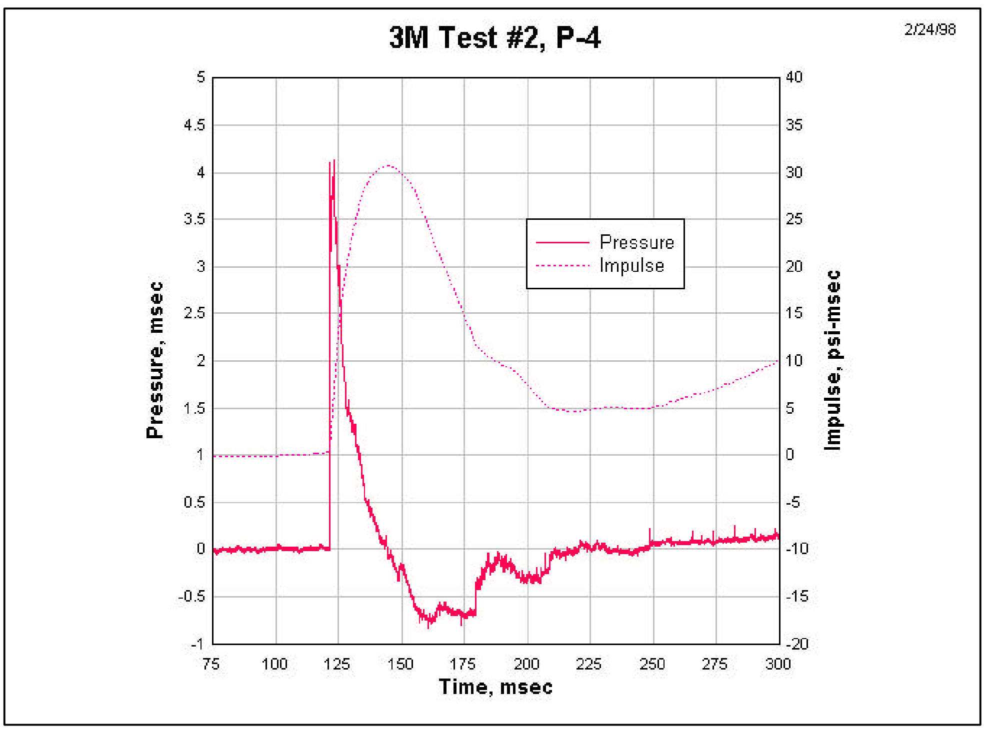
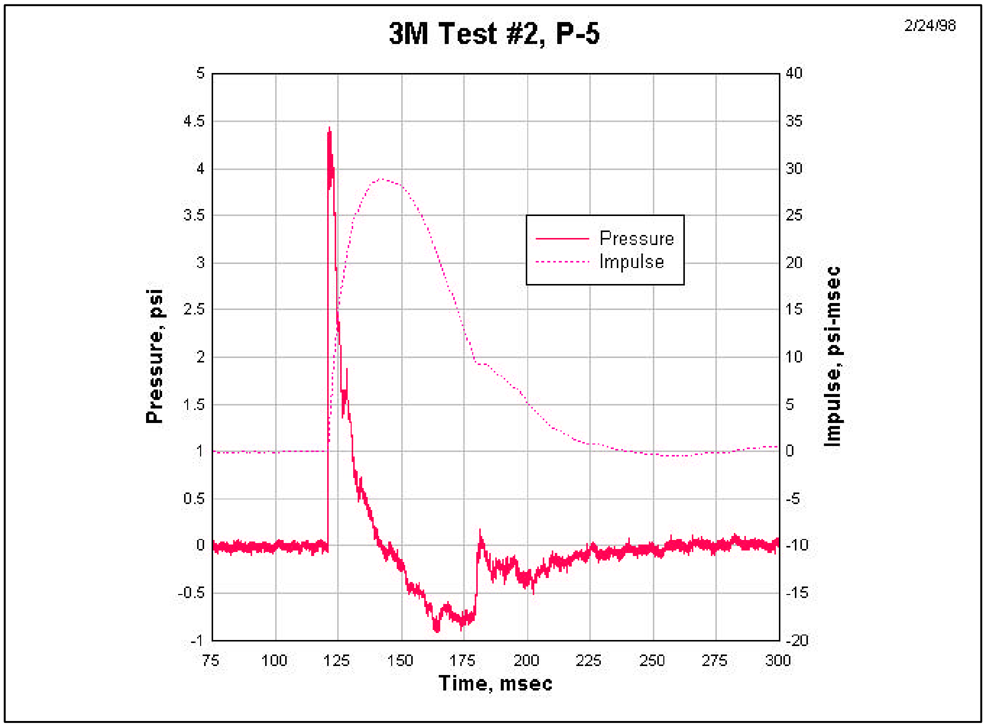
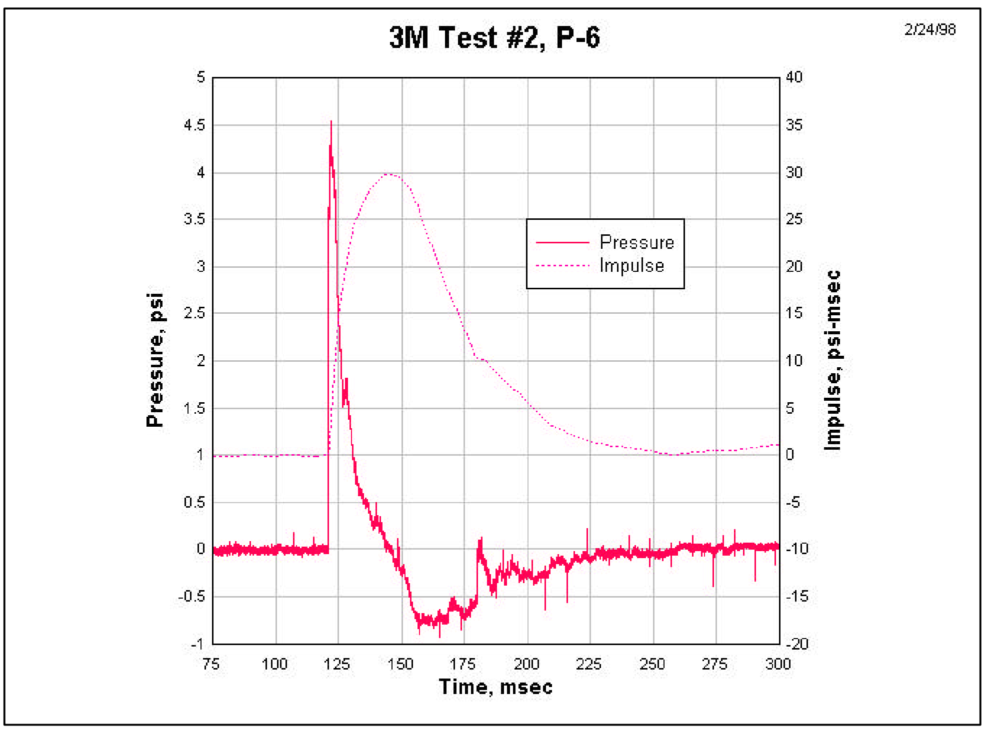
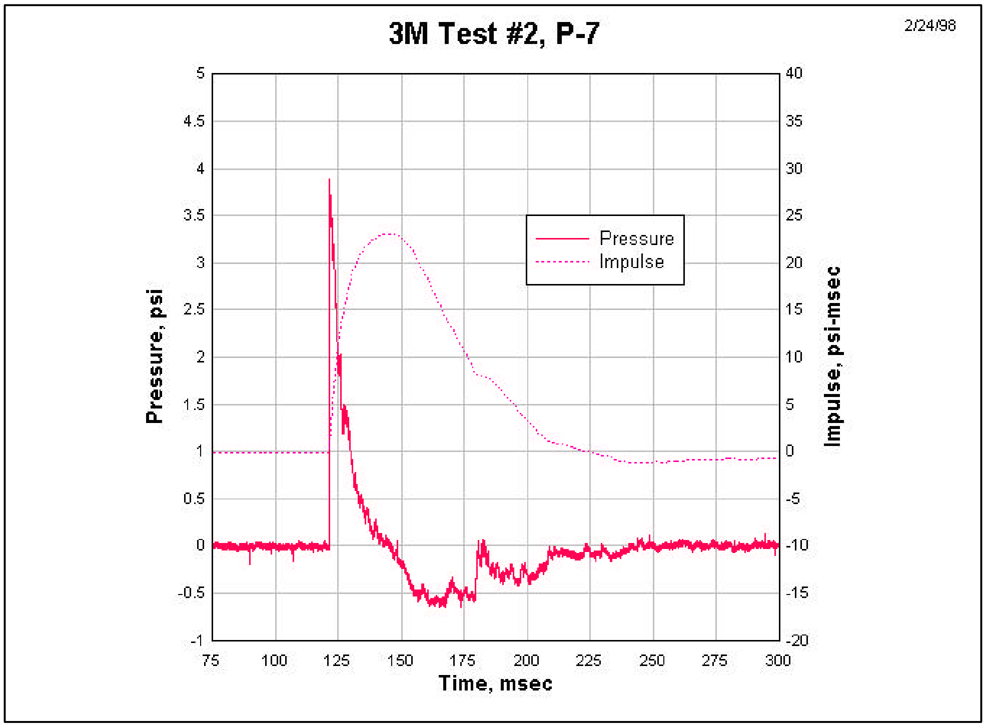
200
225
250
275
300

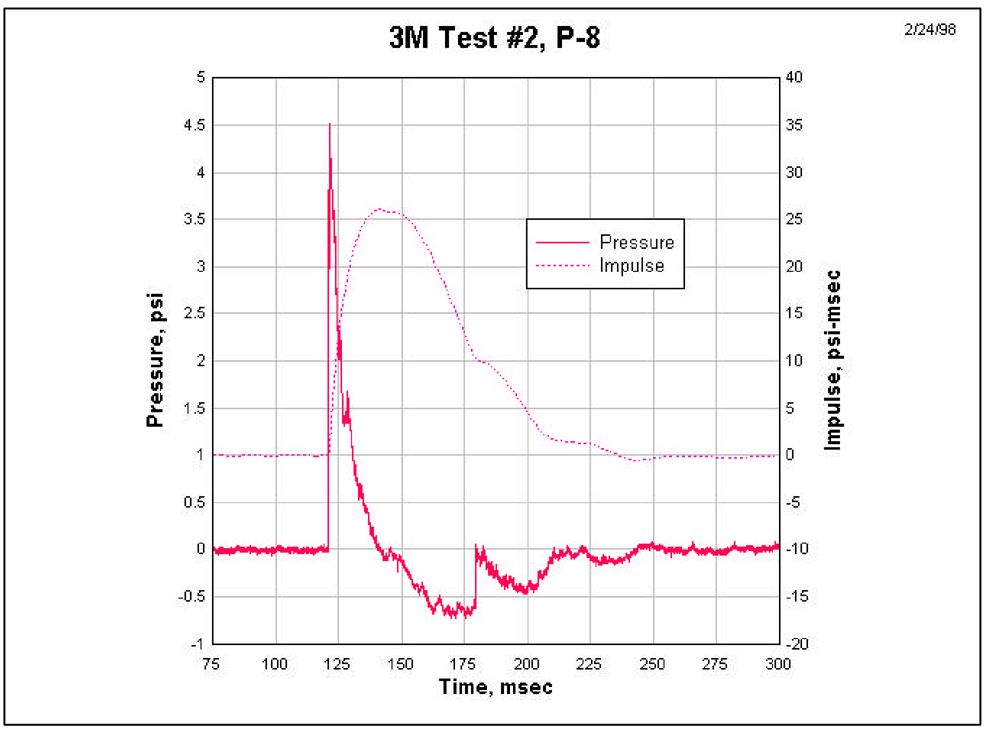

3M Test #2, P-3
2/24/98
Pressure
Impulse
Pressure, psi-msec
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

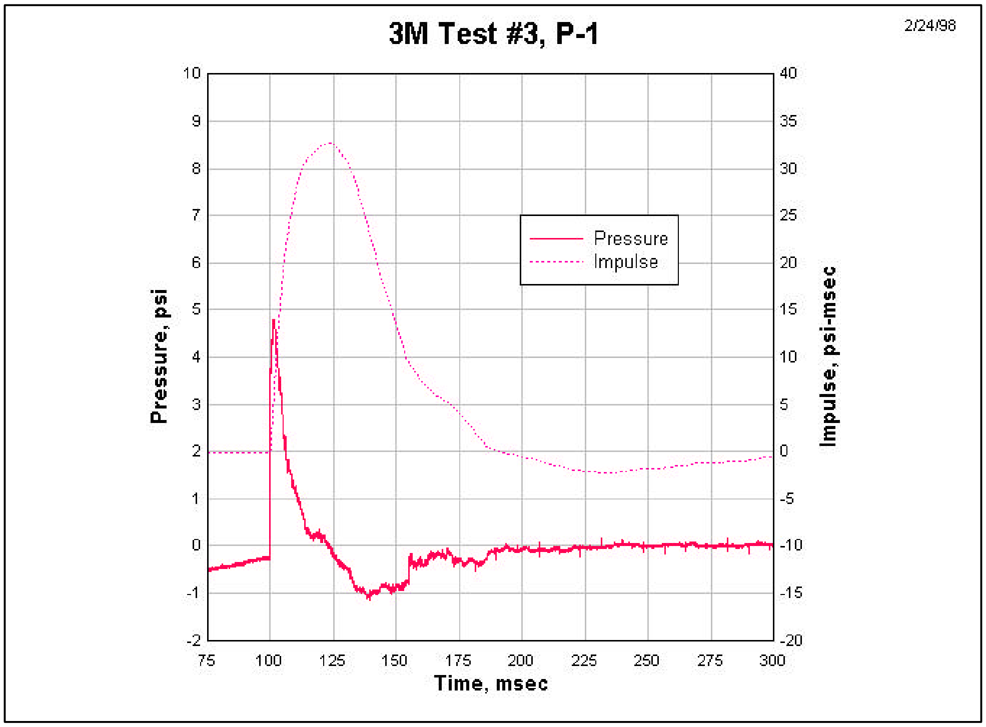

3M Test #2, P-4
2/24/98
Pressure
Impulse
Pressure, msec
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

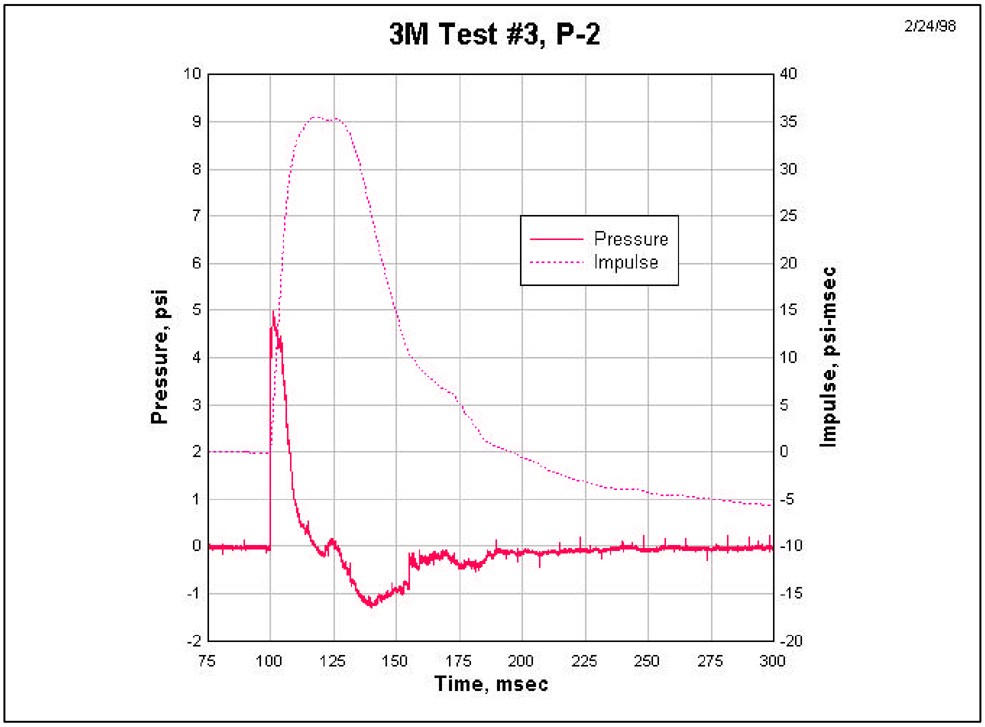

3M Test #2, P-5
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

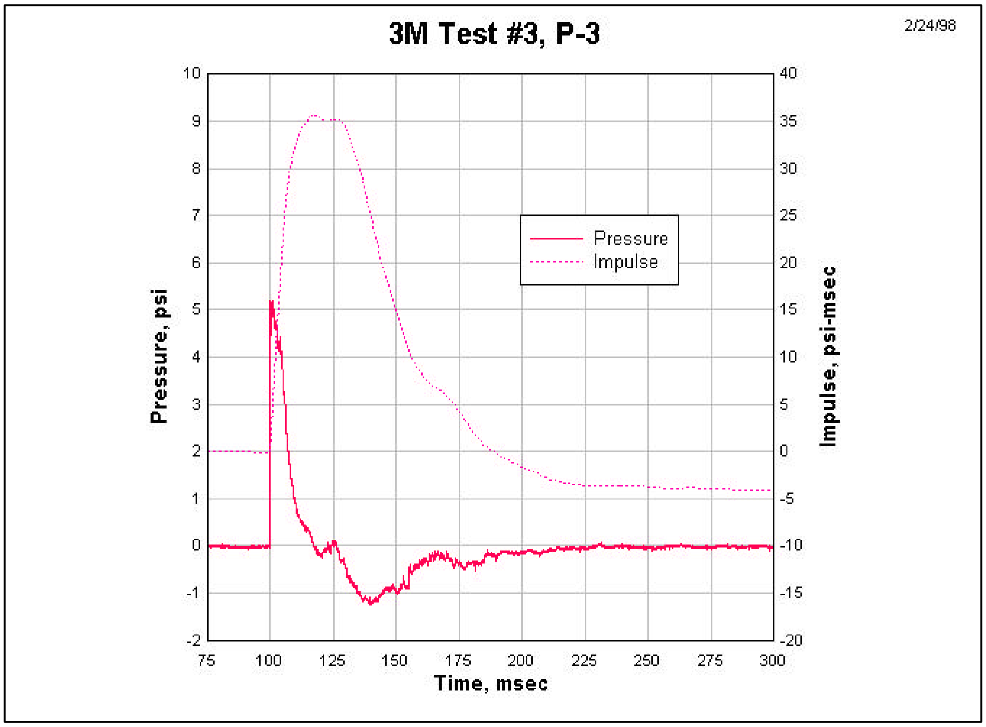

3M Test #2, P-6
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

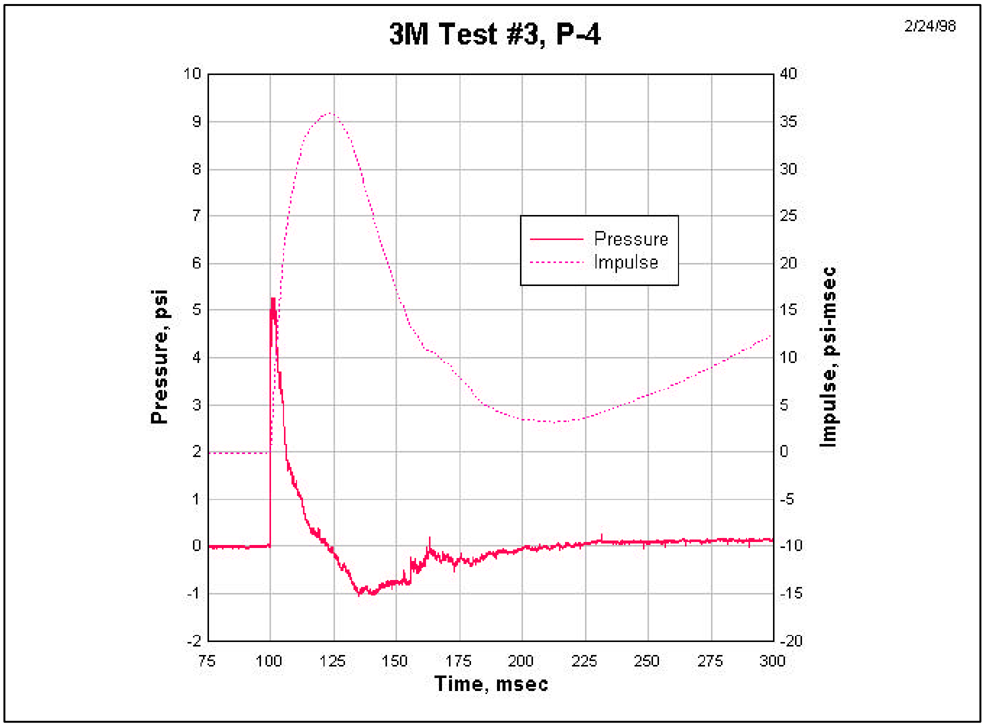

3M Test #2, P-7
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

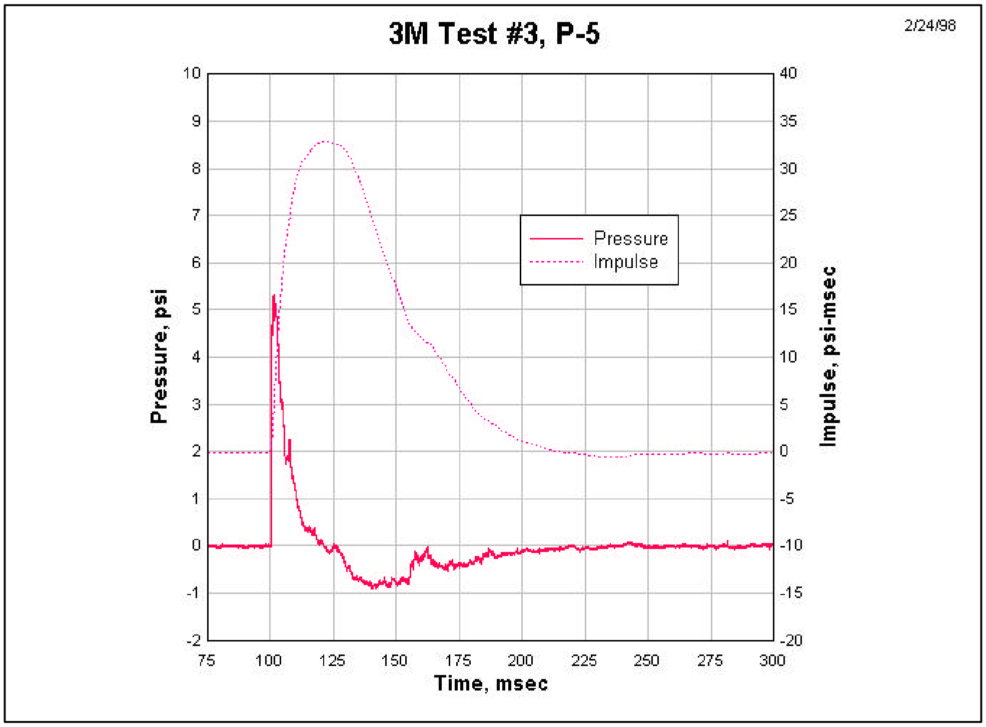

3M Test #2, P-8
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

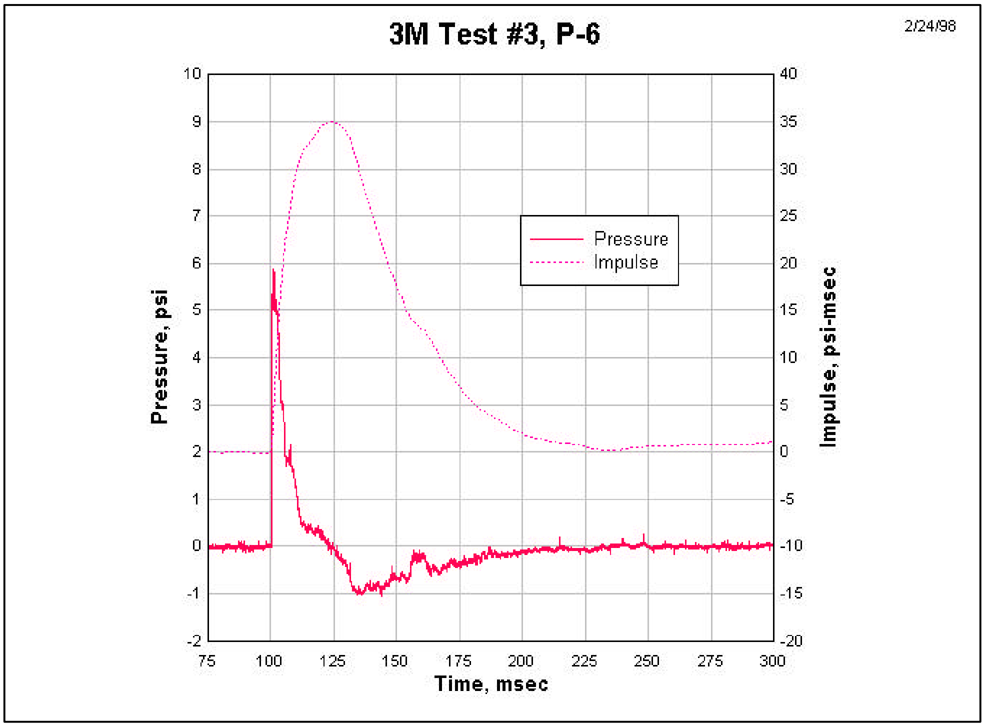

3M Test #3, P-1
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

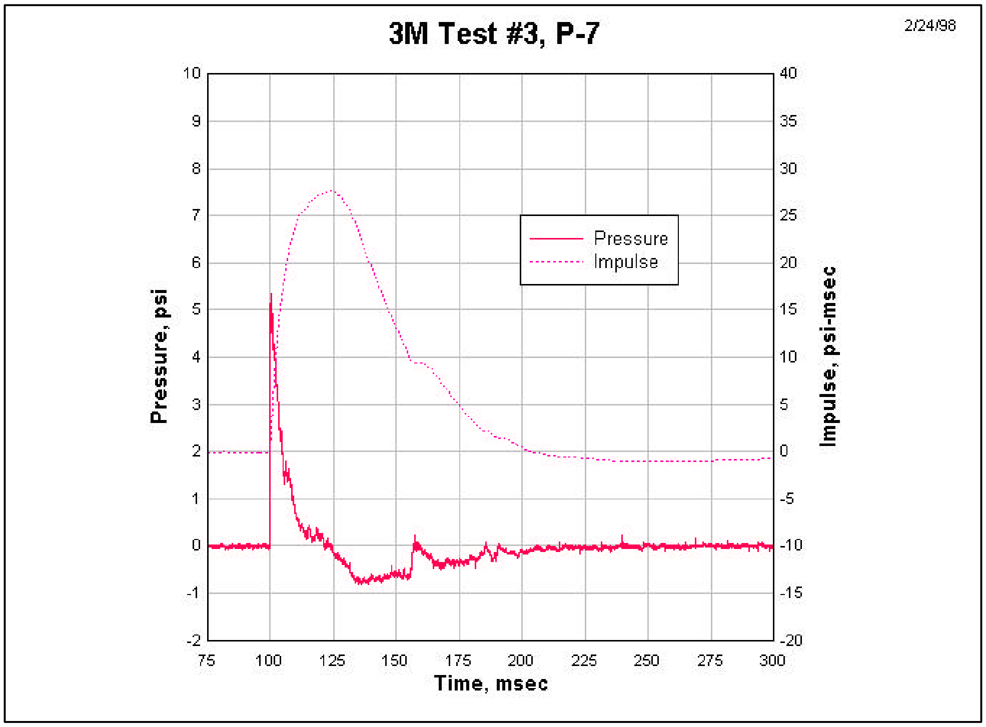

3M Test #3, P-2
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300


3M Test #3, P-3
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

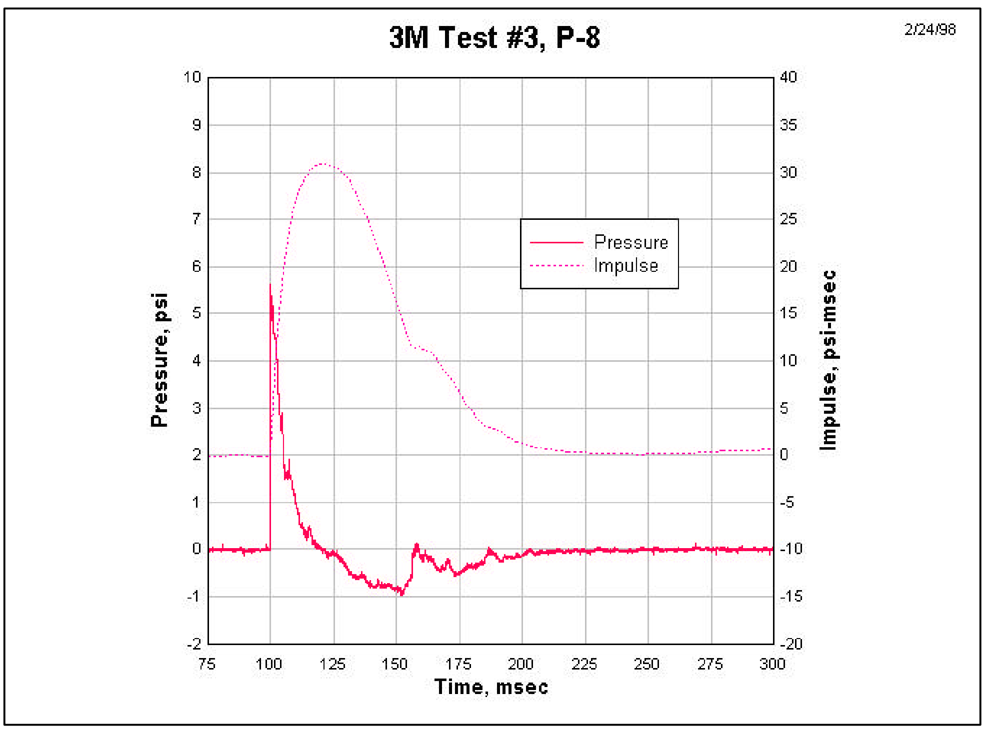

3M Test #3, P-4
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300


3M Test #3, P-5
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

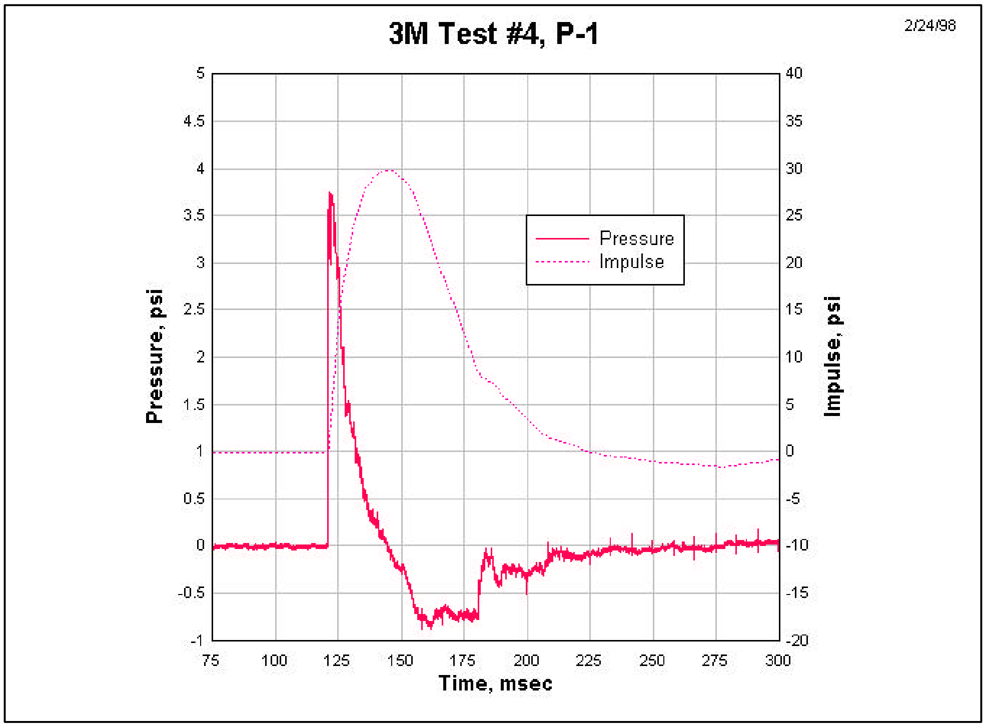

3M Test #3, P-6
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

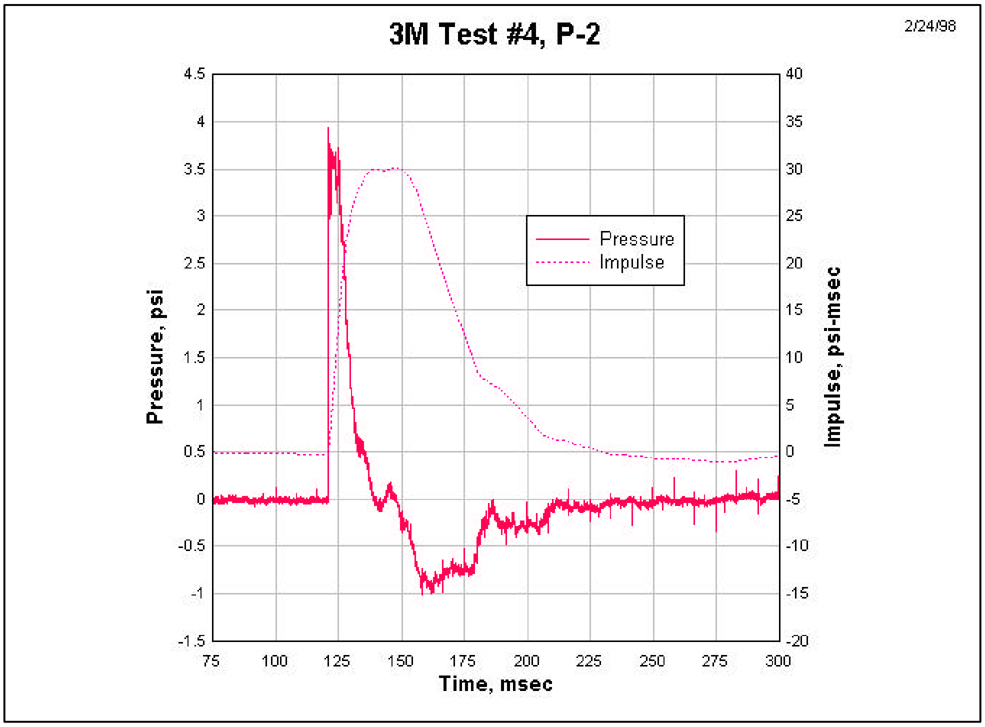


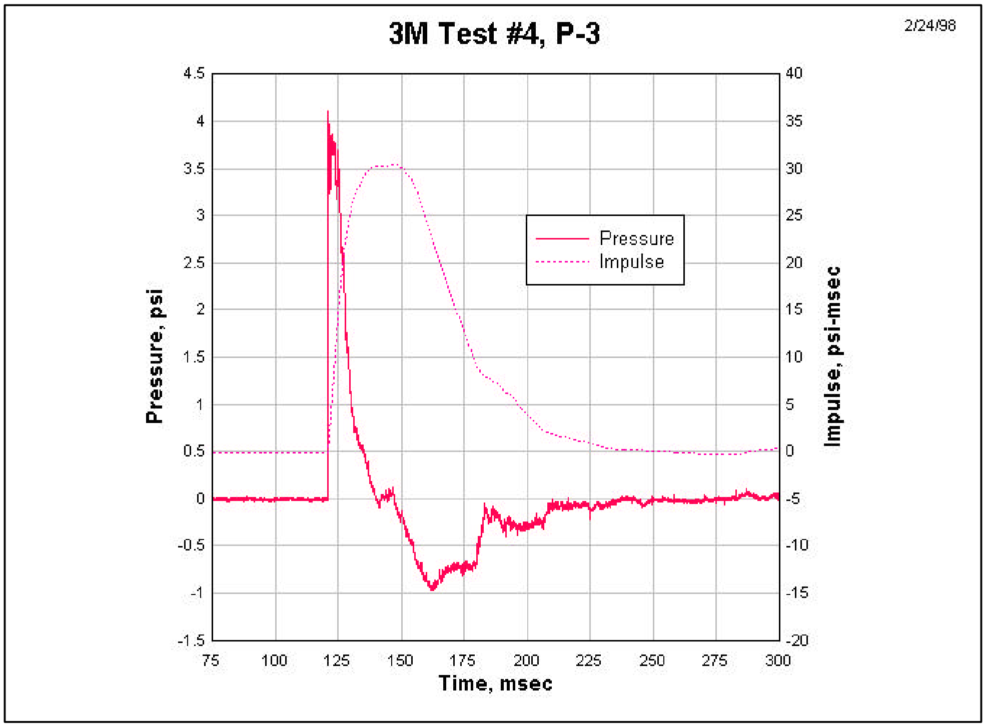
3M Test #3, P-7
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300



3M Test #3, P-8
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300


3M Test #4, P-1
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300


3M Test #4, P-2
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300



3M Test #4, P-3
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
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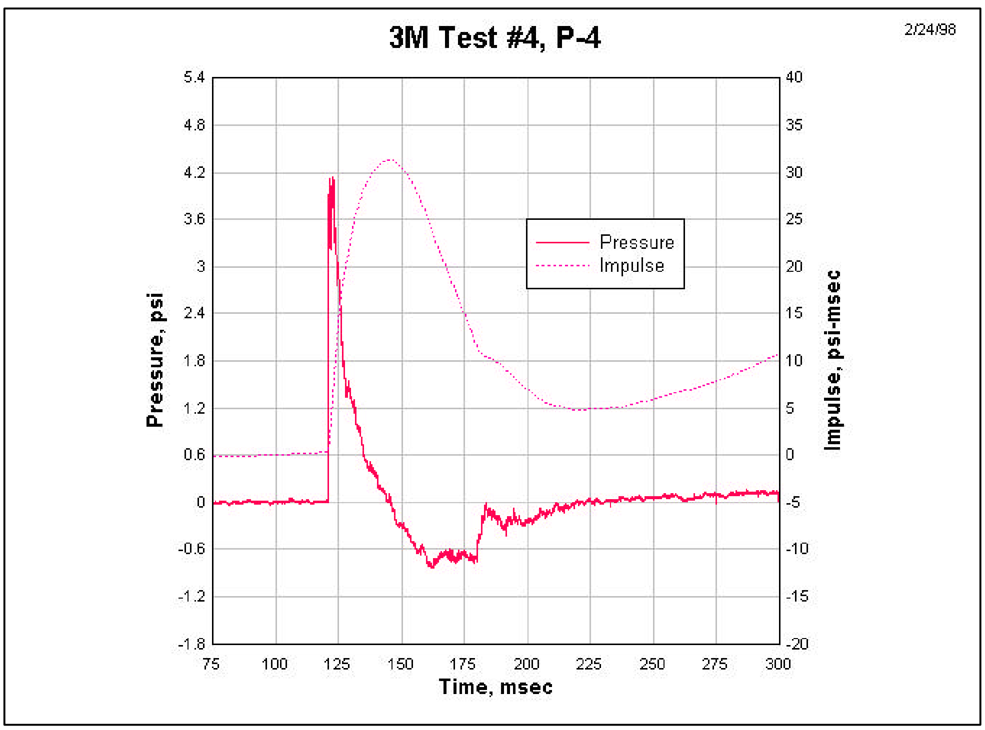
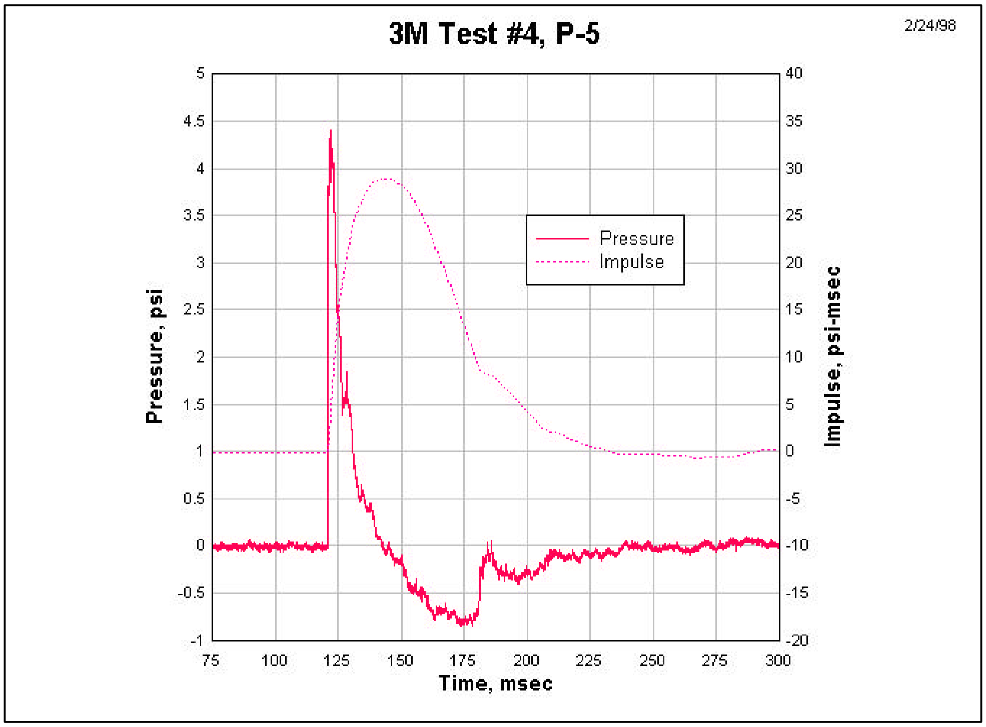
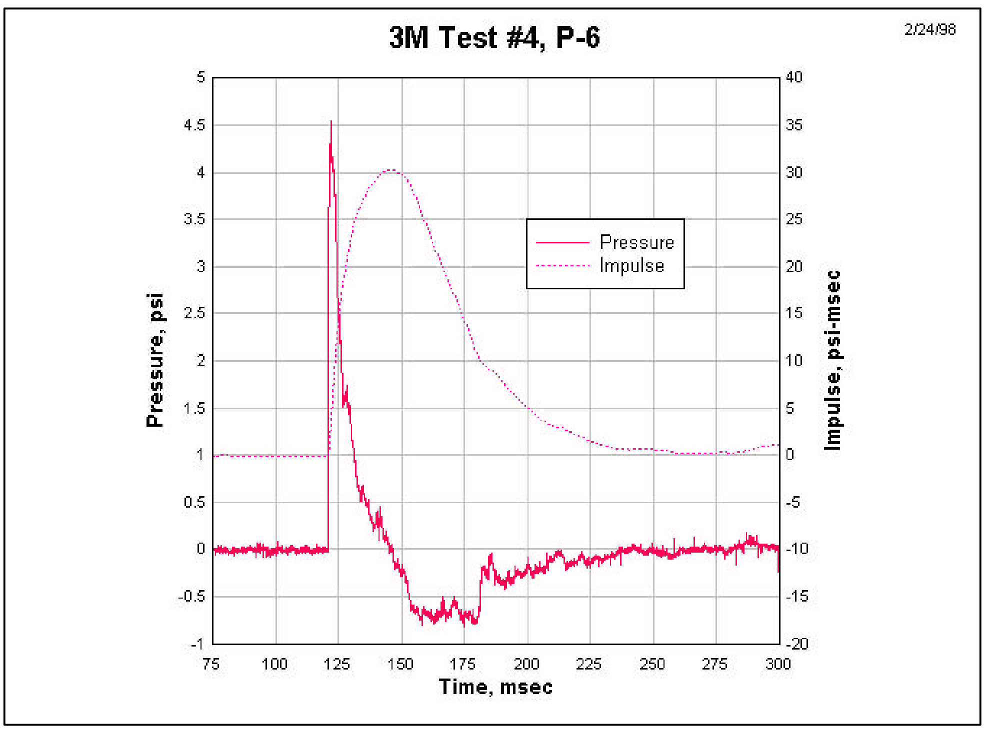
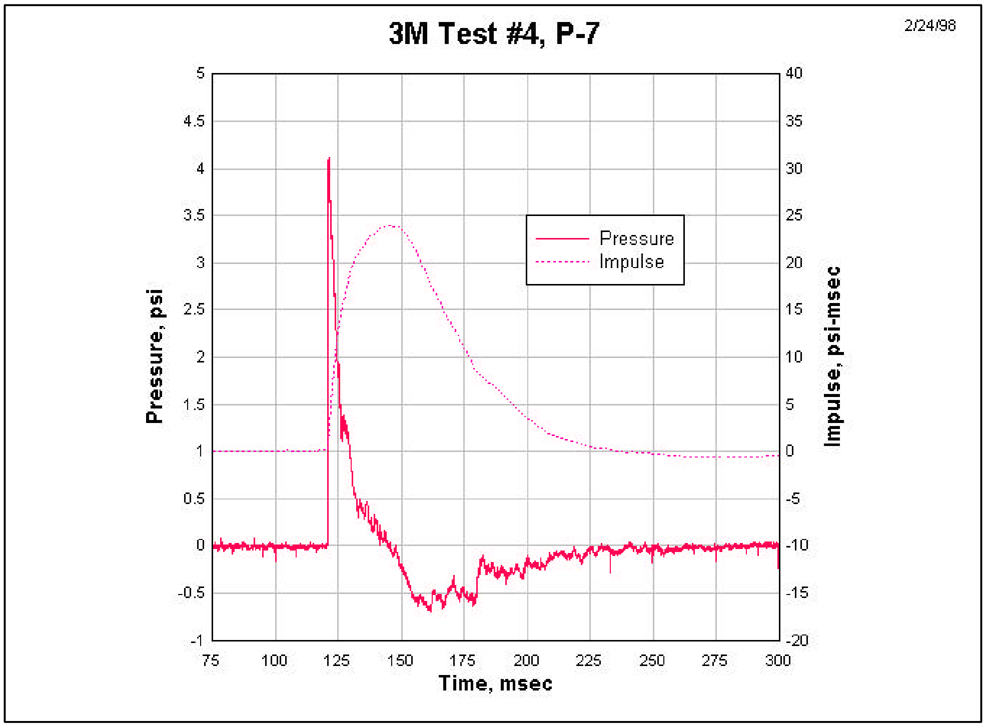
175
200
225
250
275
300

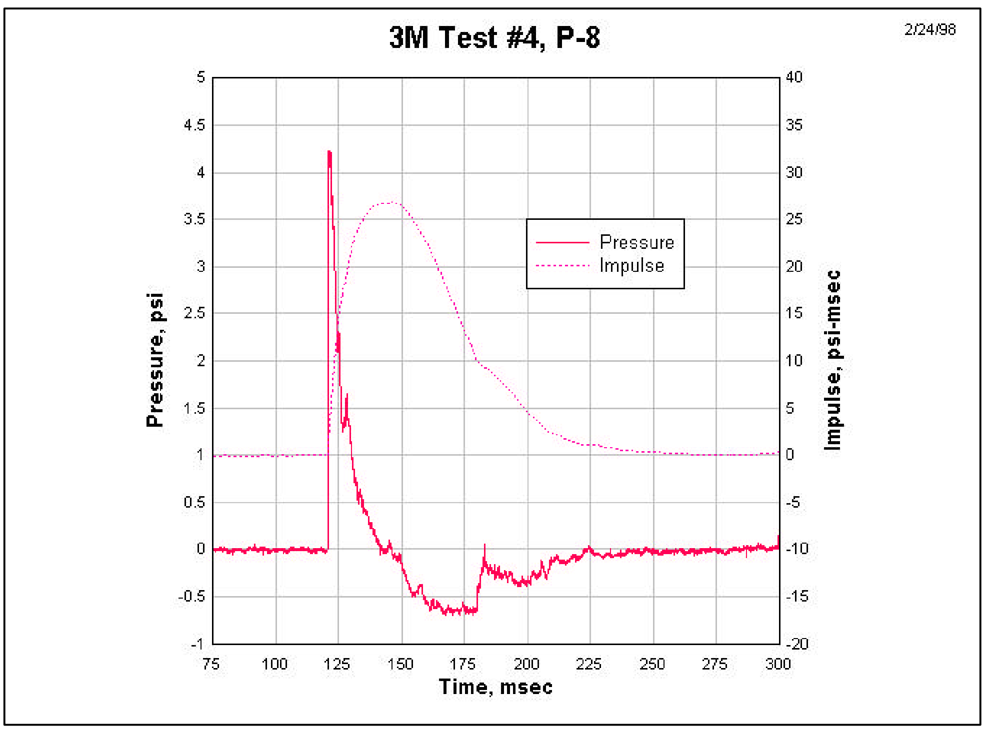


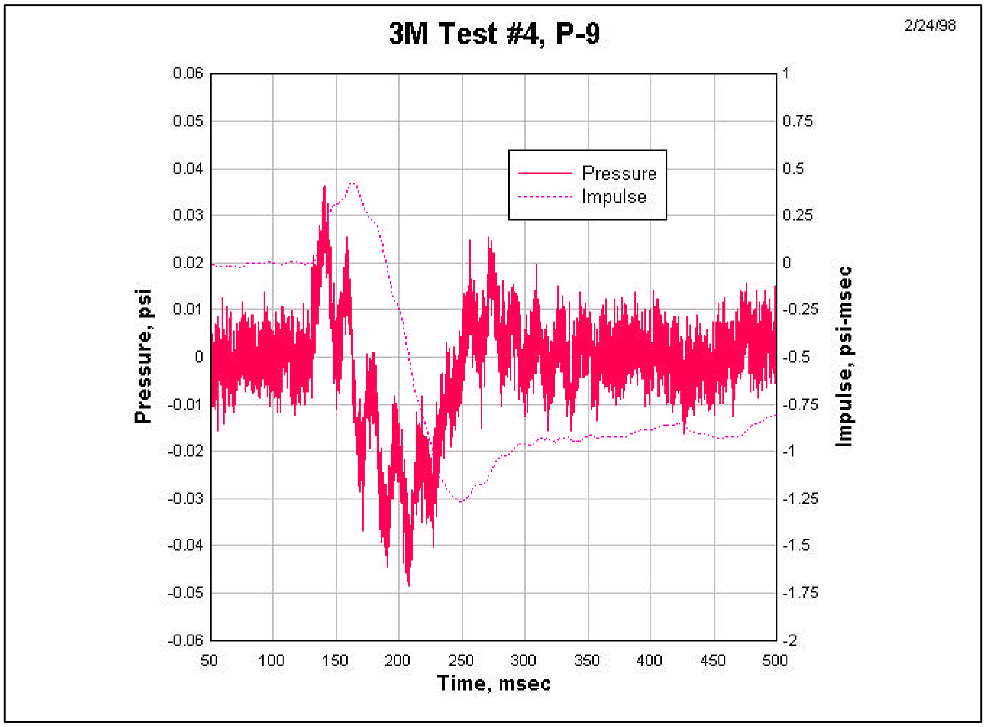
3M Test #4, P-4
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
5.4
4.8
4.2
3.6
3
2.4
1.8
1.2
0.6
0
-0.6
-1.2
-1.8
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

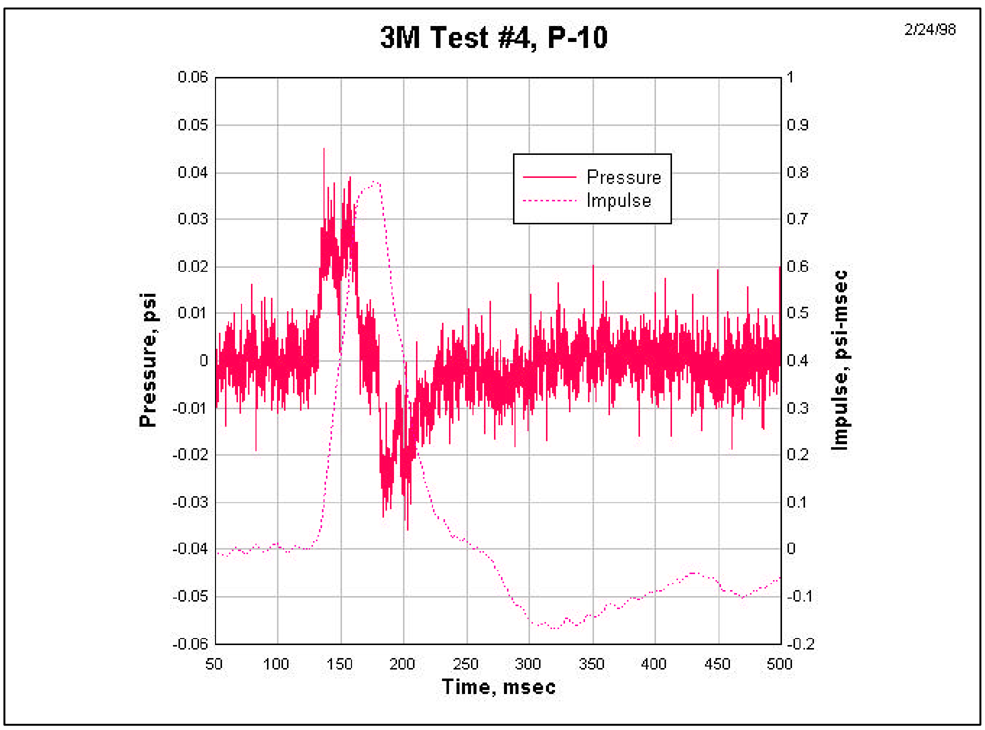

3M Test #4, P-5
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

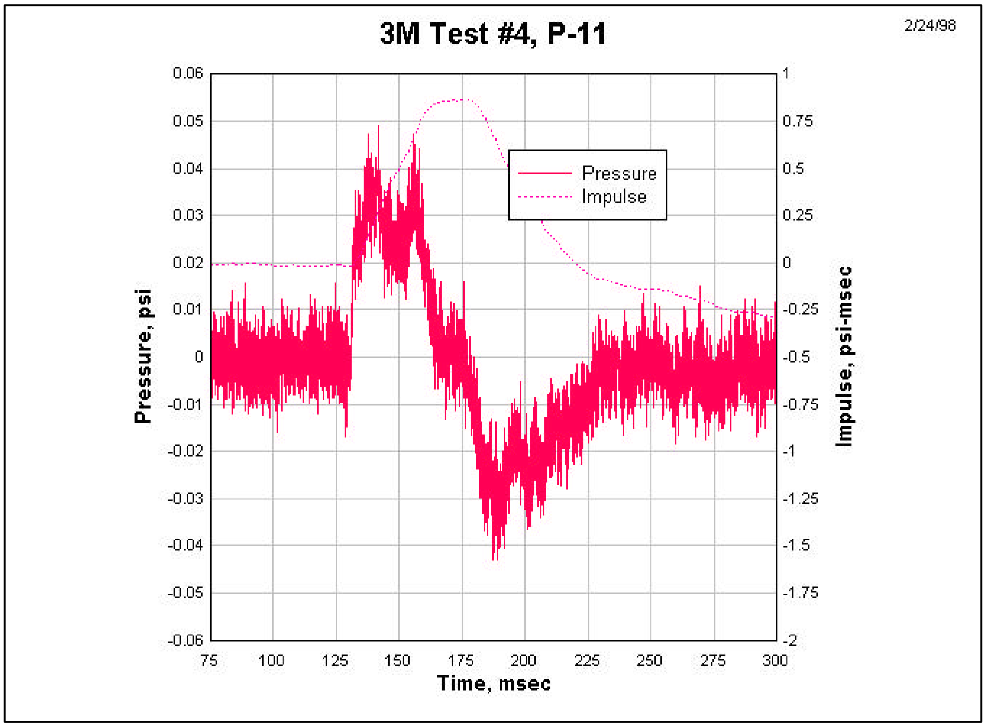

3M Test #4, P-6
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

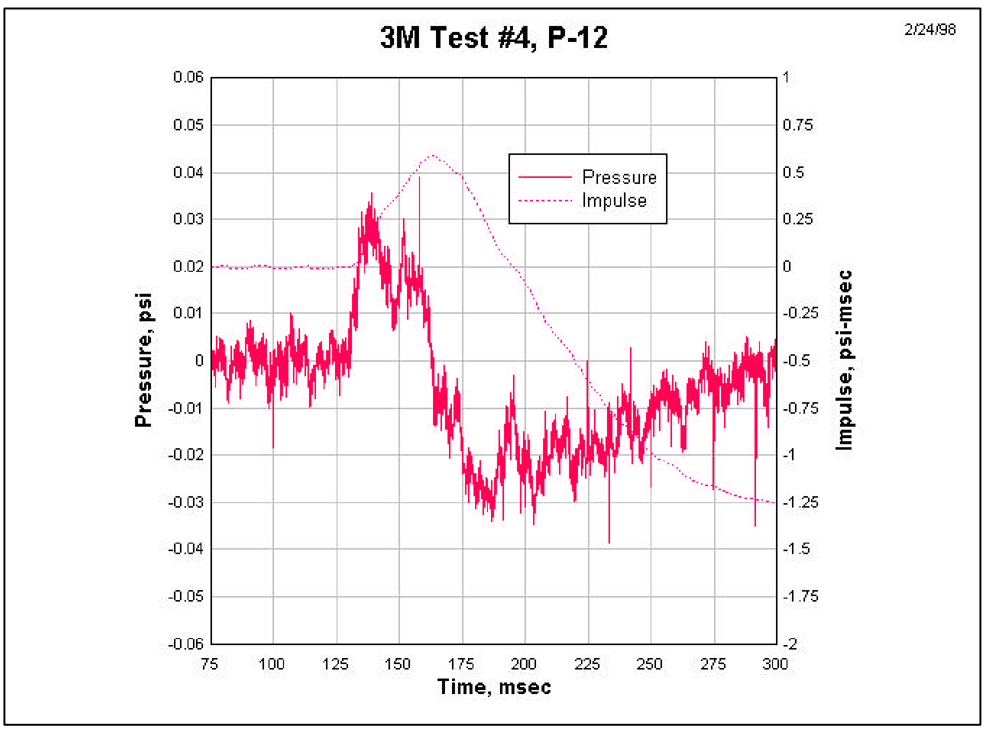

3M Test #4, P-7
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

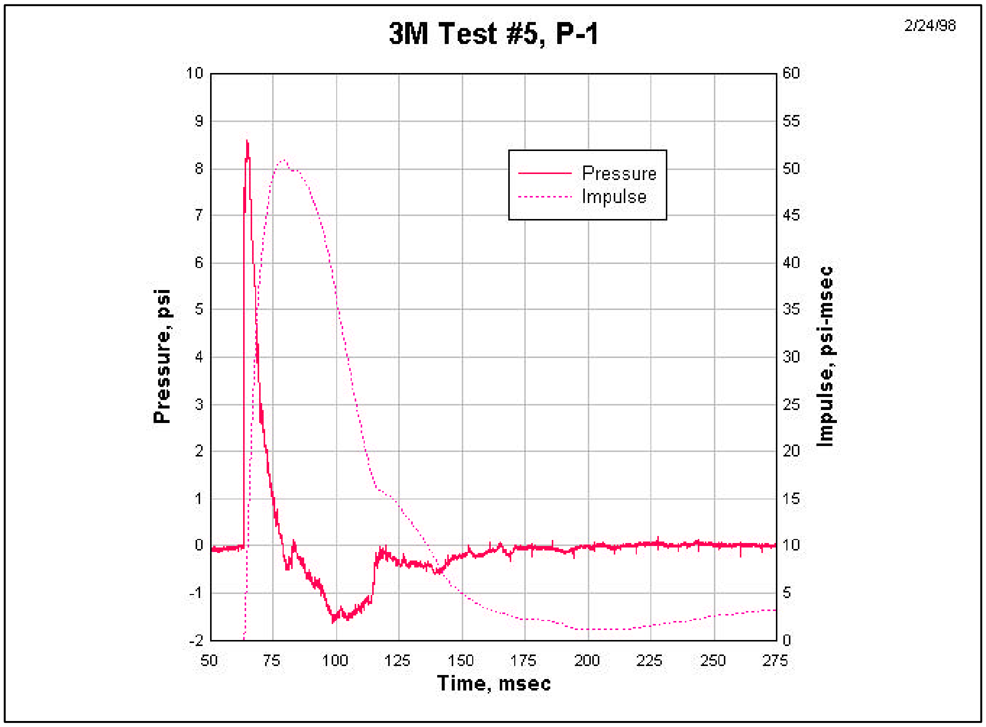

3M Test #4, P-8
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
75
100
125
150
175
200
225
250
275
300

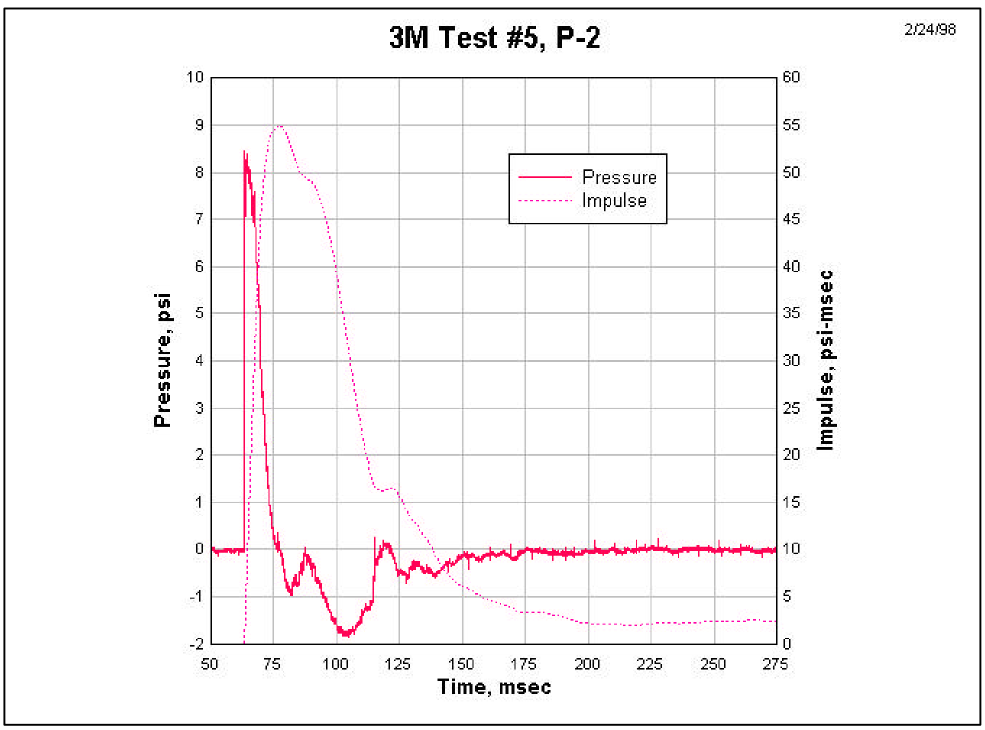

3M Test #4, P-9
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
50
100
150
200
250
300
350
400
450
500

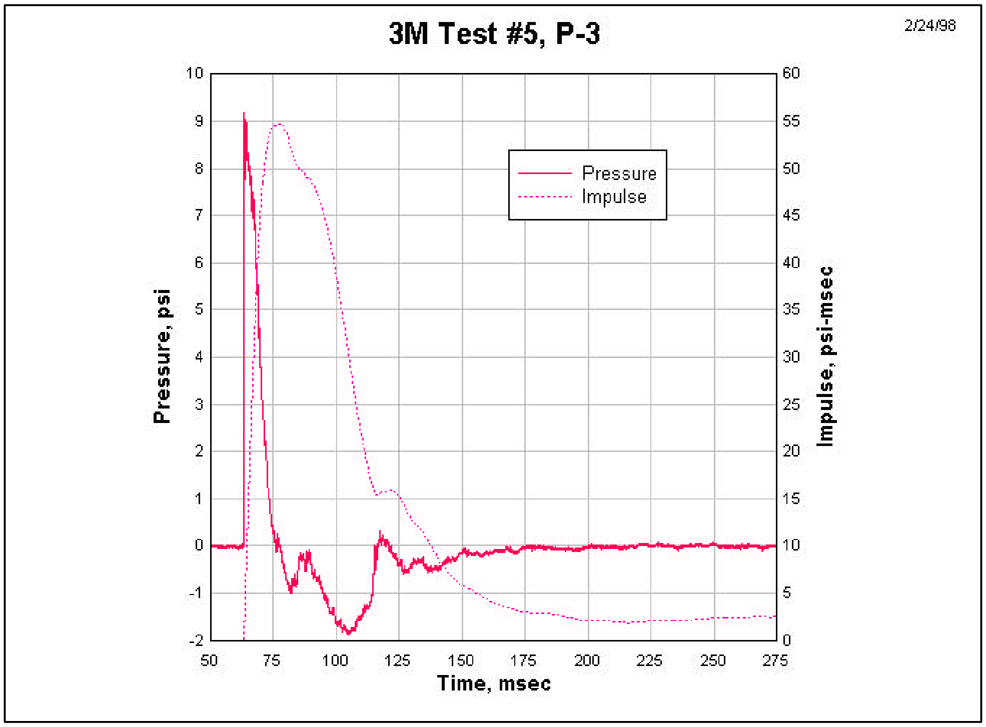

3M Test #4, P-10
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
50
100
150
200
250
300
350
400
450
500


3M Test #4, P-11
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
75
100
125
150
175
200
225
250
275
300

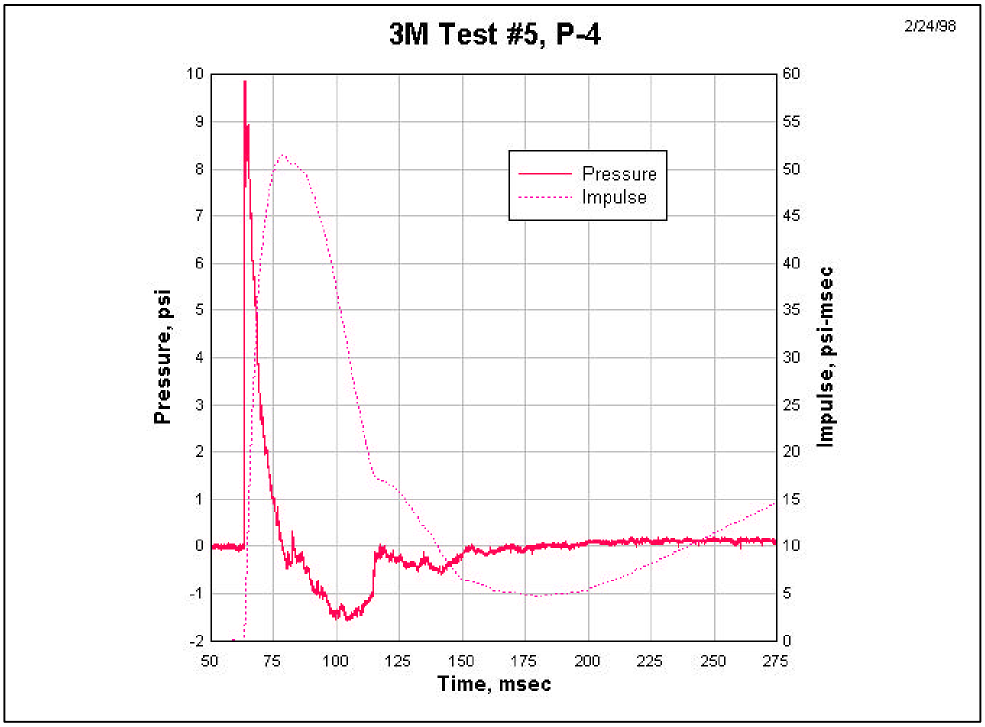

3M Test #4, P-12
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
75
100
125
150
175
200
225
250
275
300


3M Test #5, P-1
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

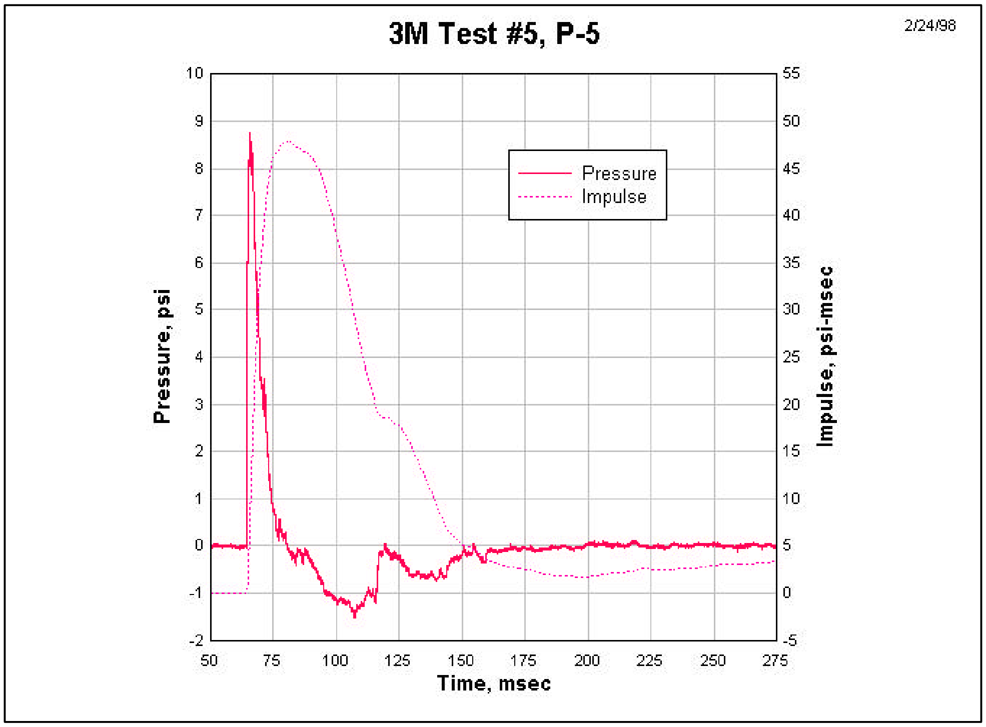

3M Test #5, P-2
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

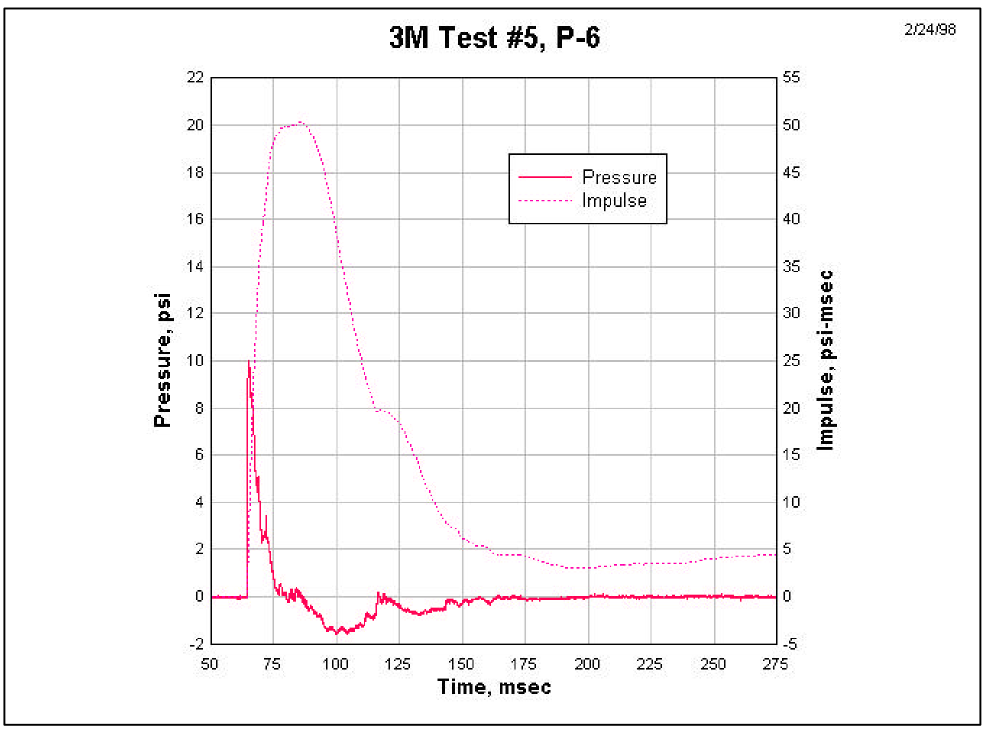


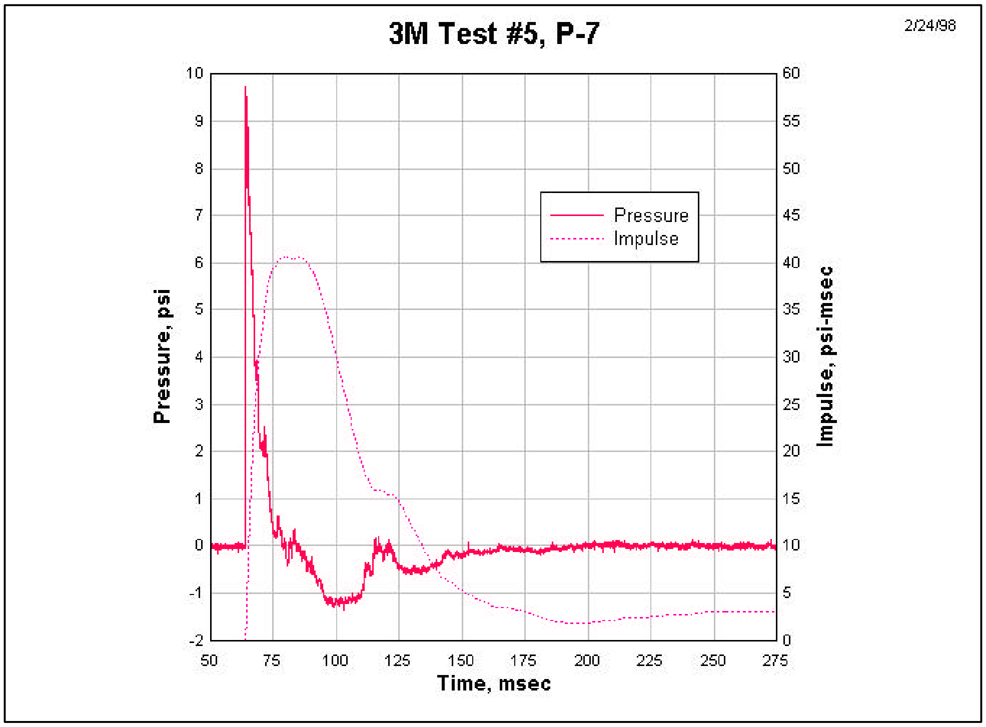
3M Test #5, P-3
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

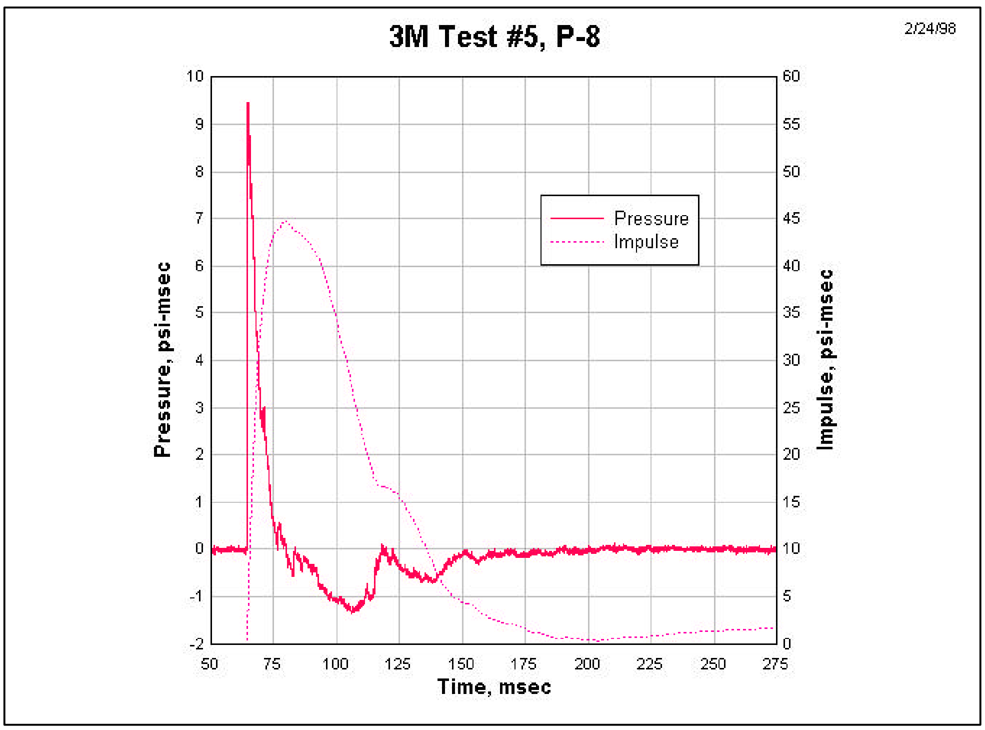


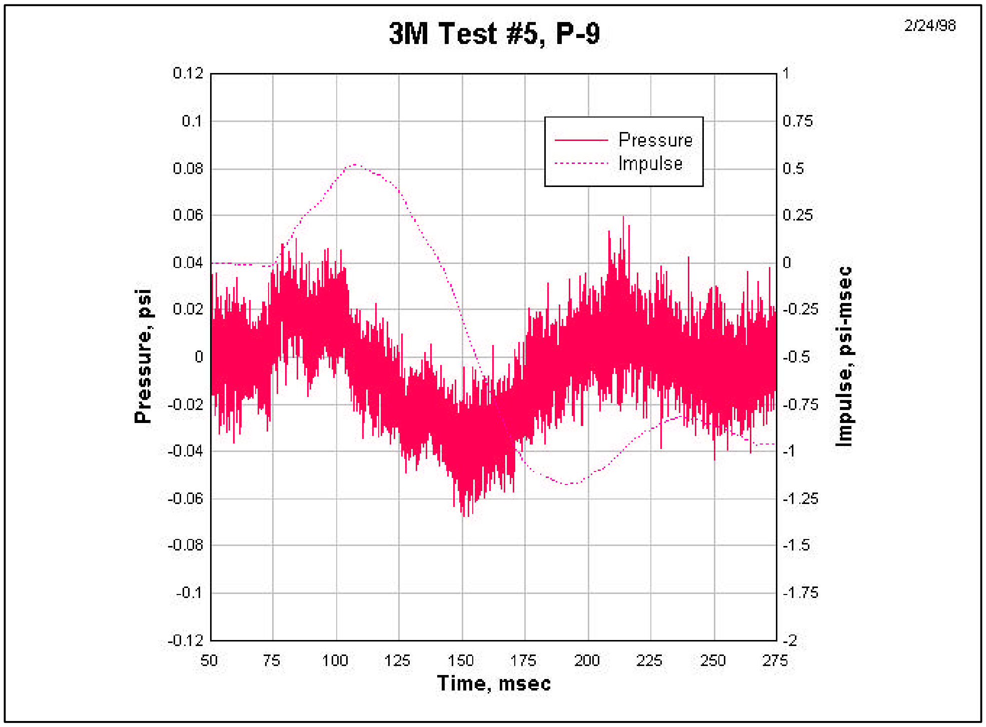
3M Test #5, P-4
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

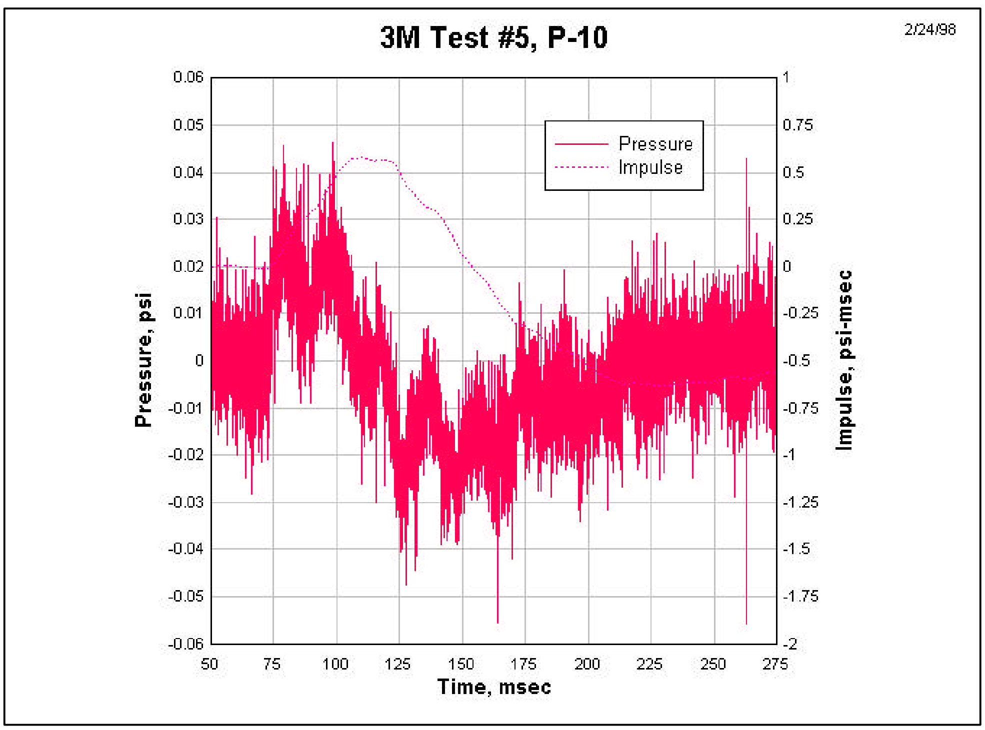

3M Test #5, P-5
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
55
50
45
40
35
30
25
20
15
10
5
0
-5
50
75
100
125
150
175
200
225
250
275

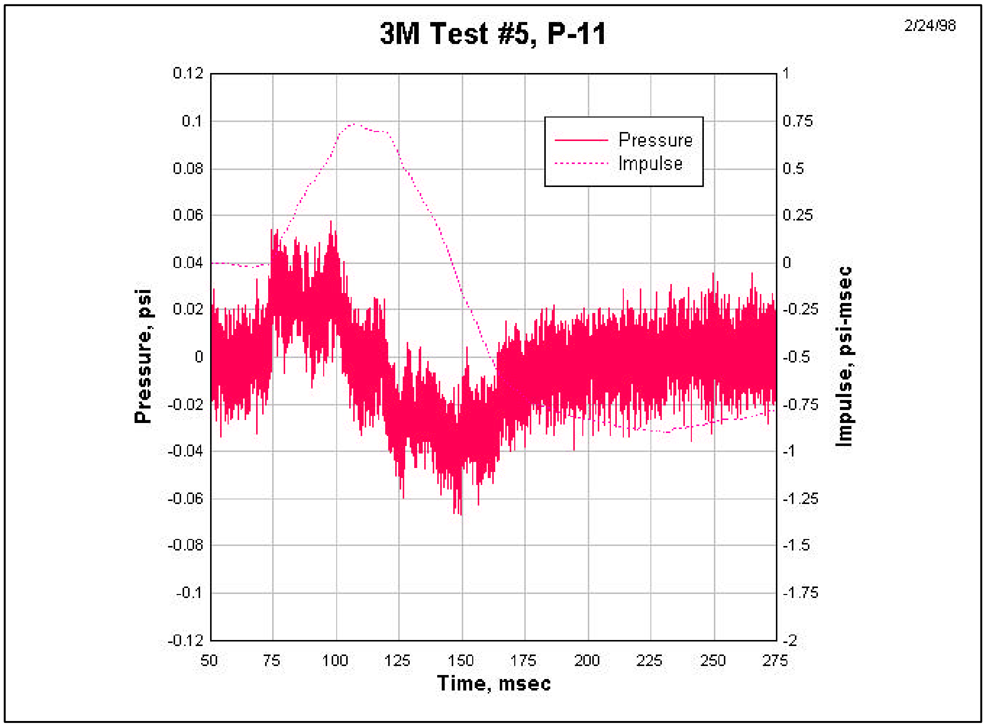

3M Test #5, P-6
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
22
20
18
16
14
12
10
8
6
4
2
0
-2
55
50
45
40
35
30
25
20
15
10
5
0
-5
50
75
100
125
150
175
200
225
250
275

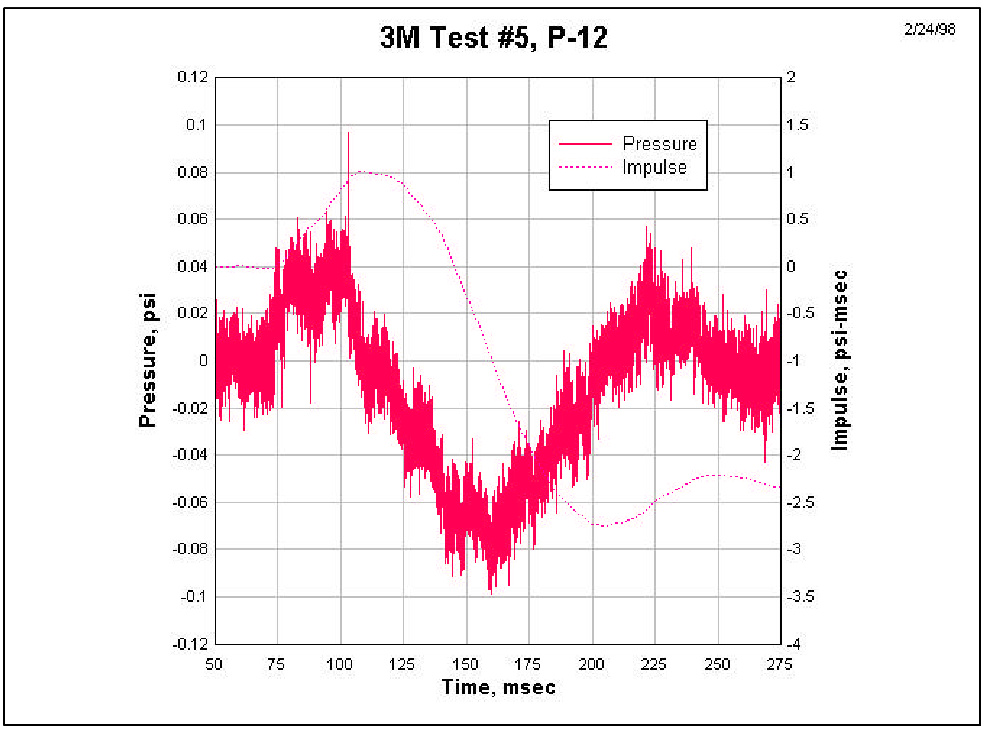

3M Test #5, P-7
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

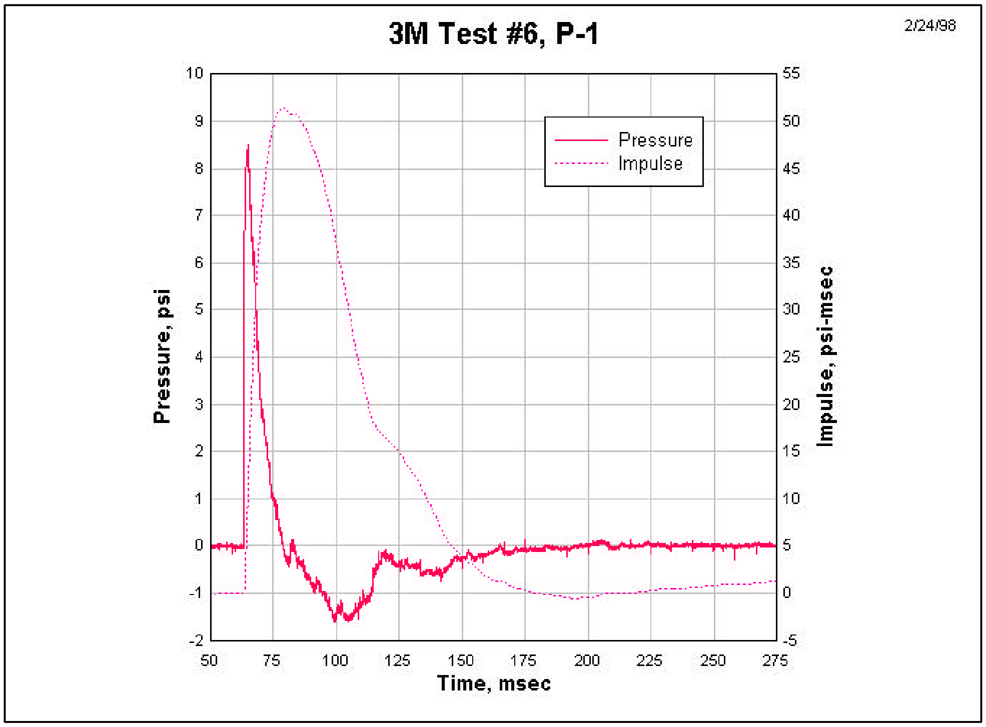

3M Test #5, P-8
2/24/98
Pressure
Impulse
Pressure, psi-msec
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

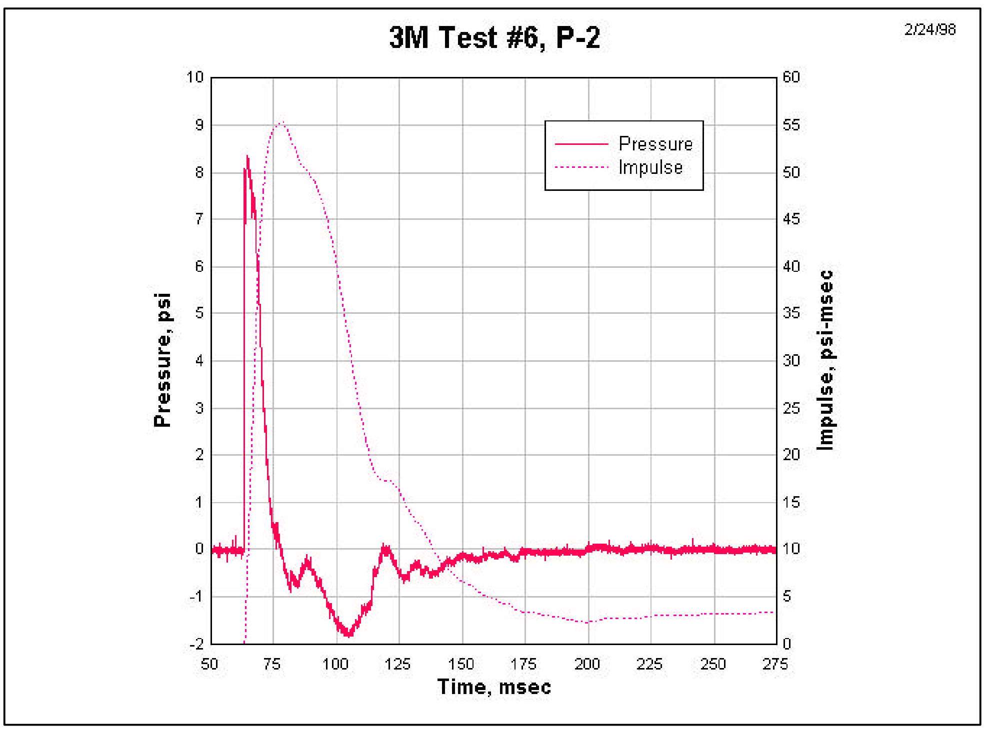

3M Test #5, P-9
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
50
75
100
125
150
175
200
225
250
275

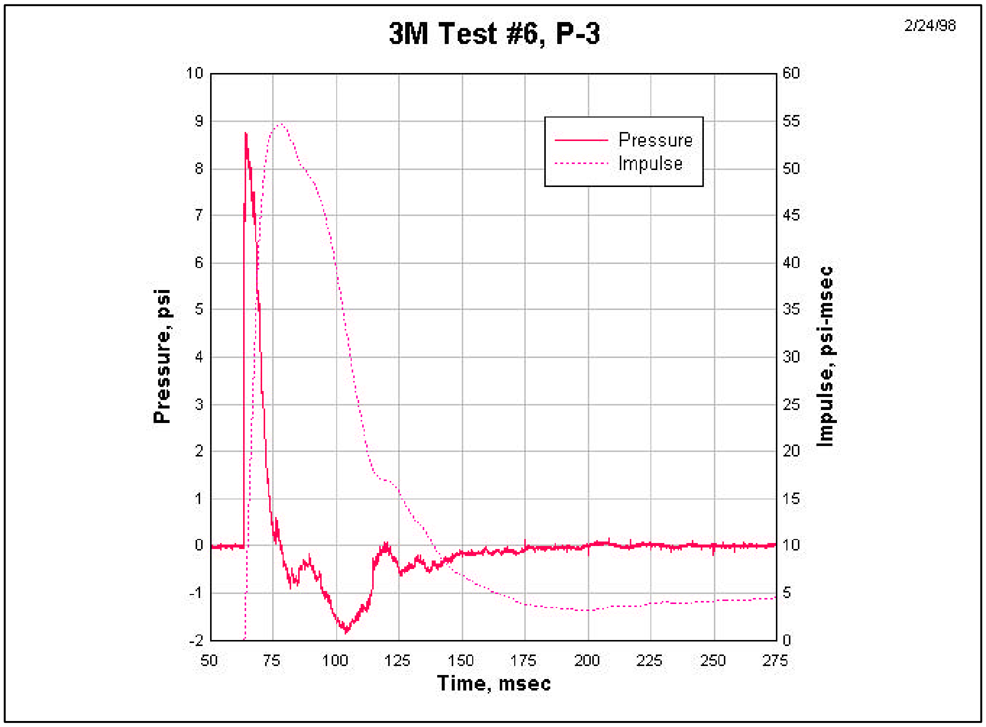

3M Test #5, P-10
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
50
75
100
125
150
175
200
225
250
275


3M Test #5, P-11
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
50
75
100
125
150
175
200
225
250
275

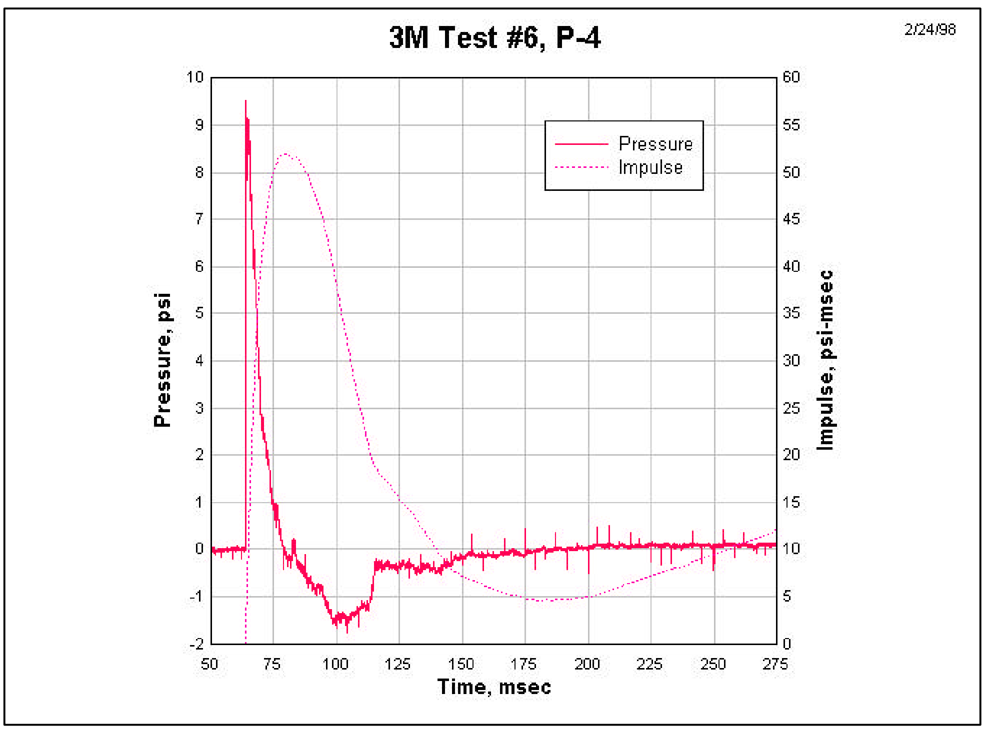

3M Test #5, P-12
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
50
75
100
125
150
175
200
225
250
275


3M Test #6, P-1
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
55
50
45
40
35
30
25
20
15
10
5
0
-5
50
75
100
125
150
175
200
225
250
275

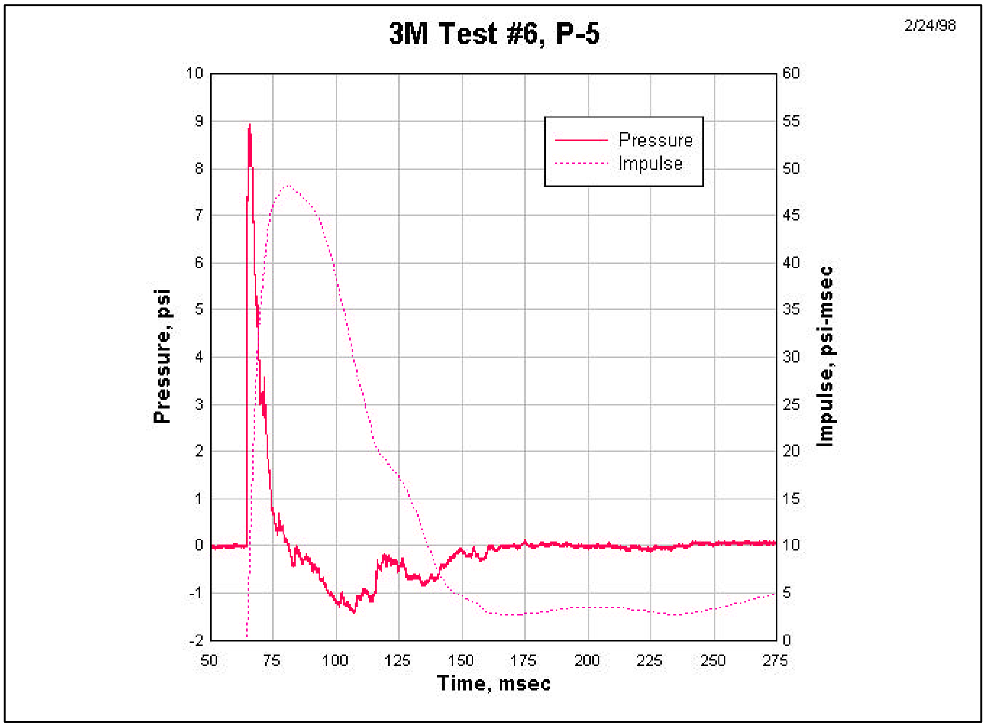

3M Test #6, P-2
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

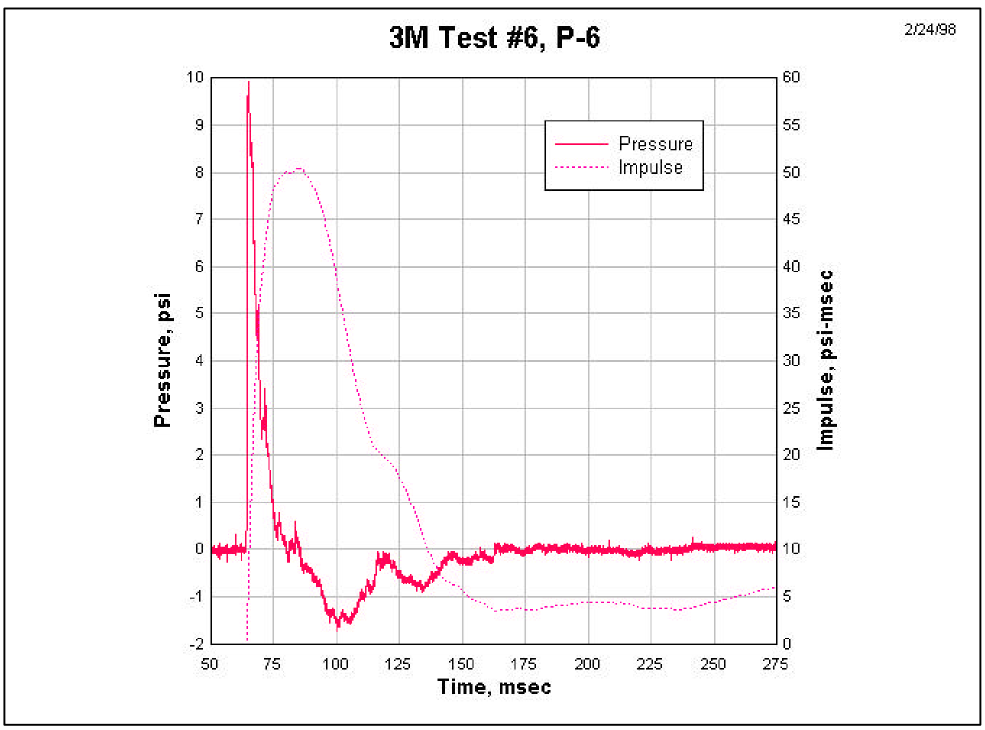


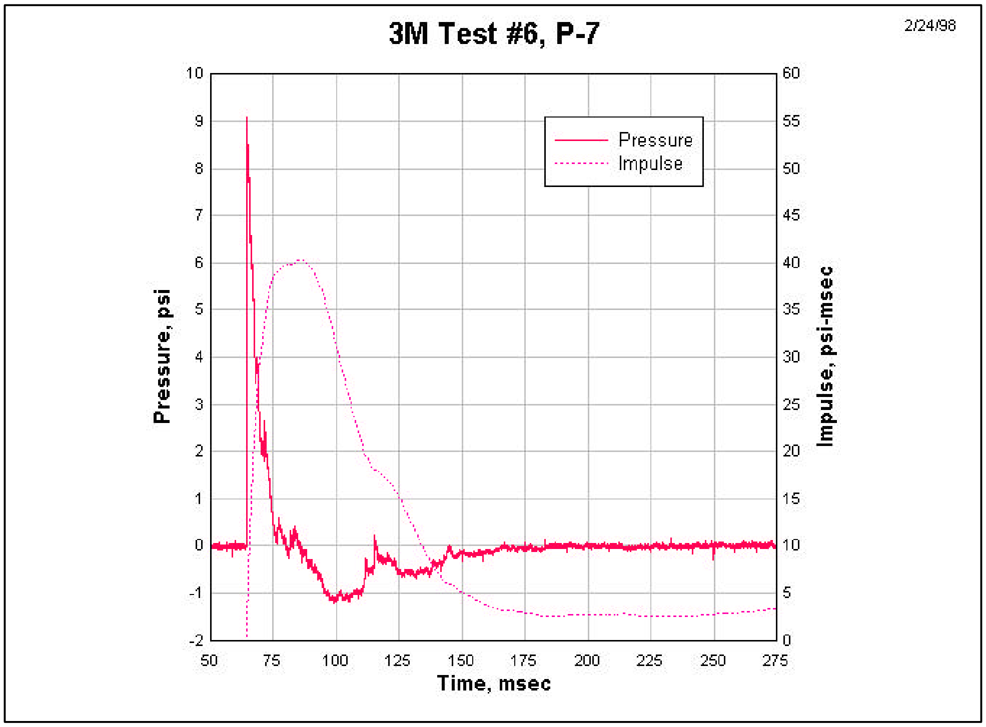
3M Test #6, P-3
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

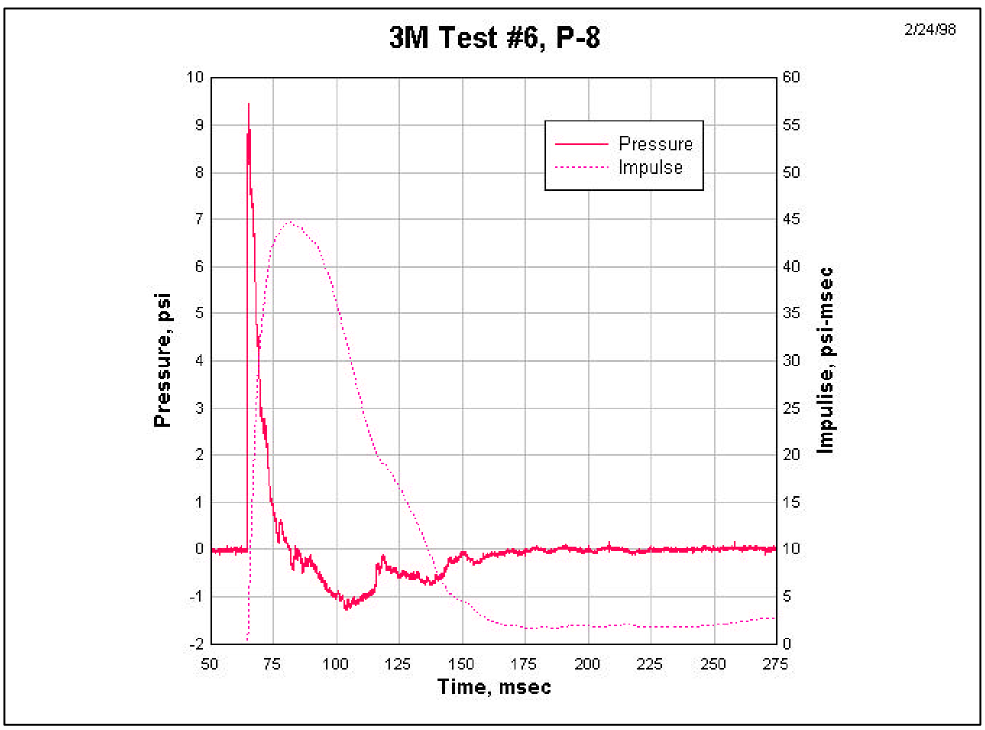


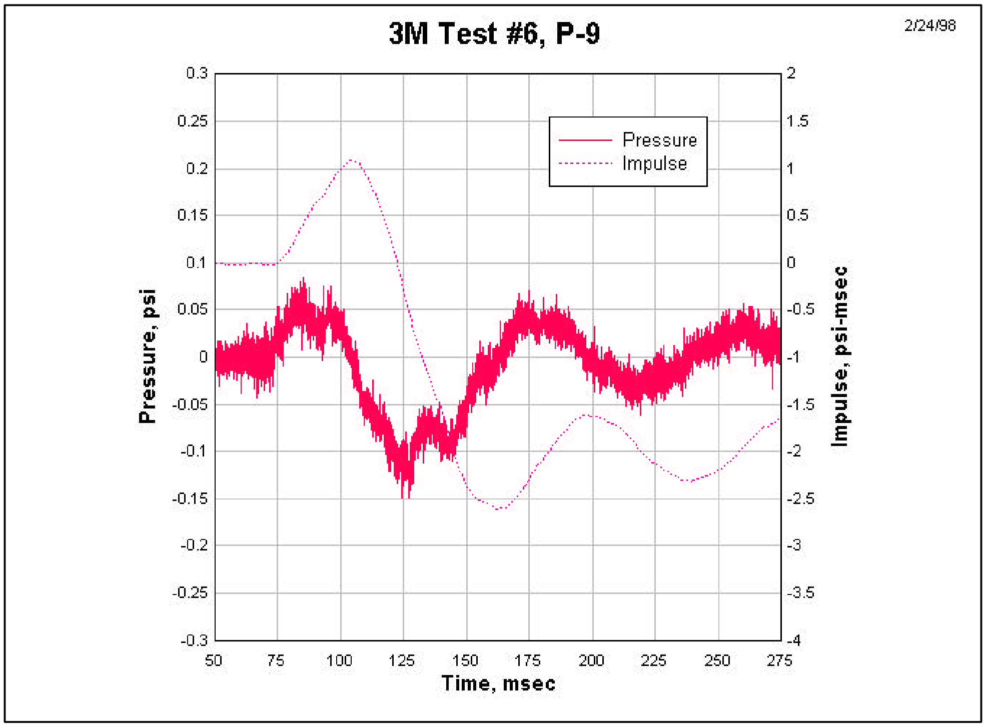
3M Test #6, P-4
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

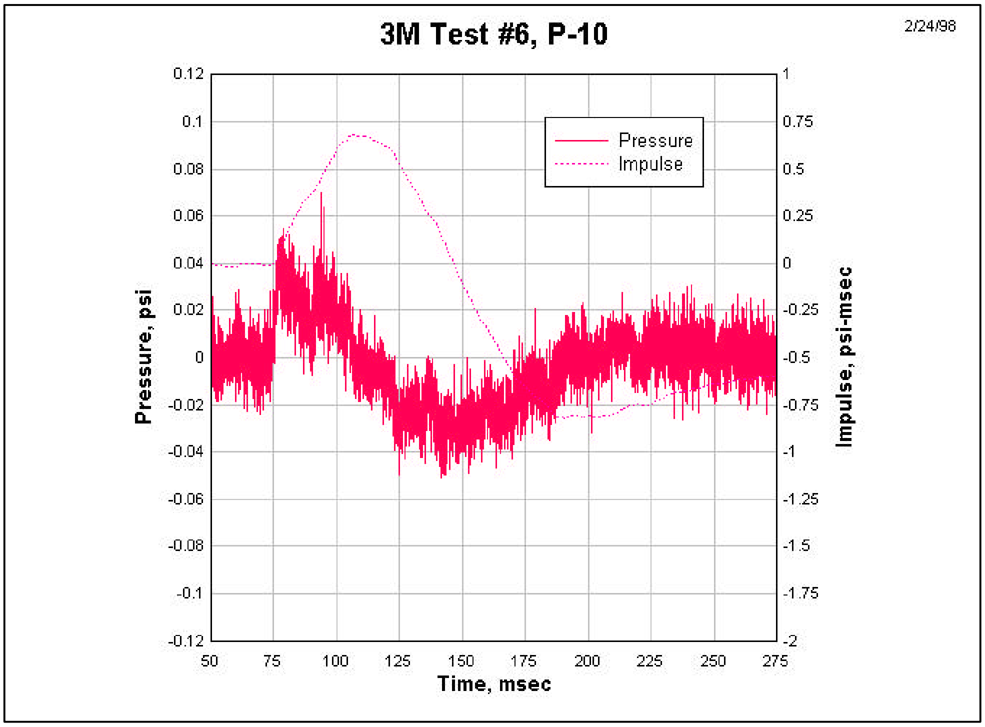

3M Test #6, P-5
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

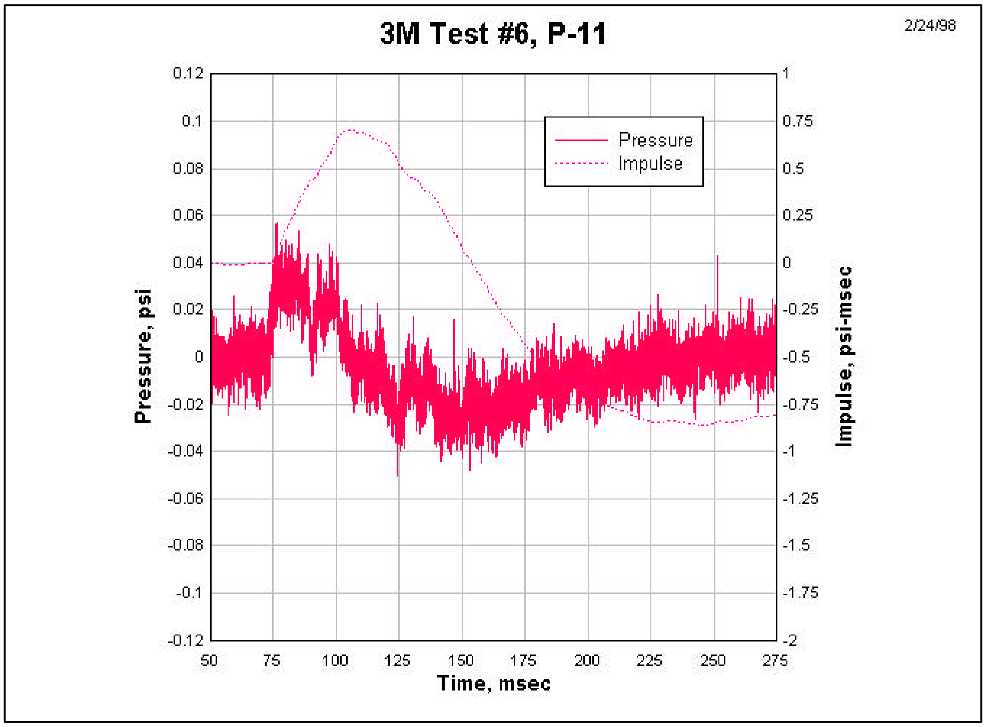

3M Test #6, P-6
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275

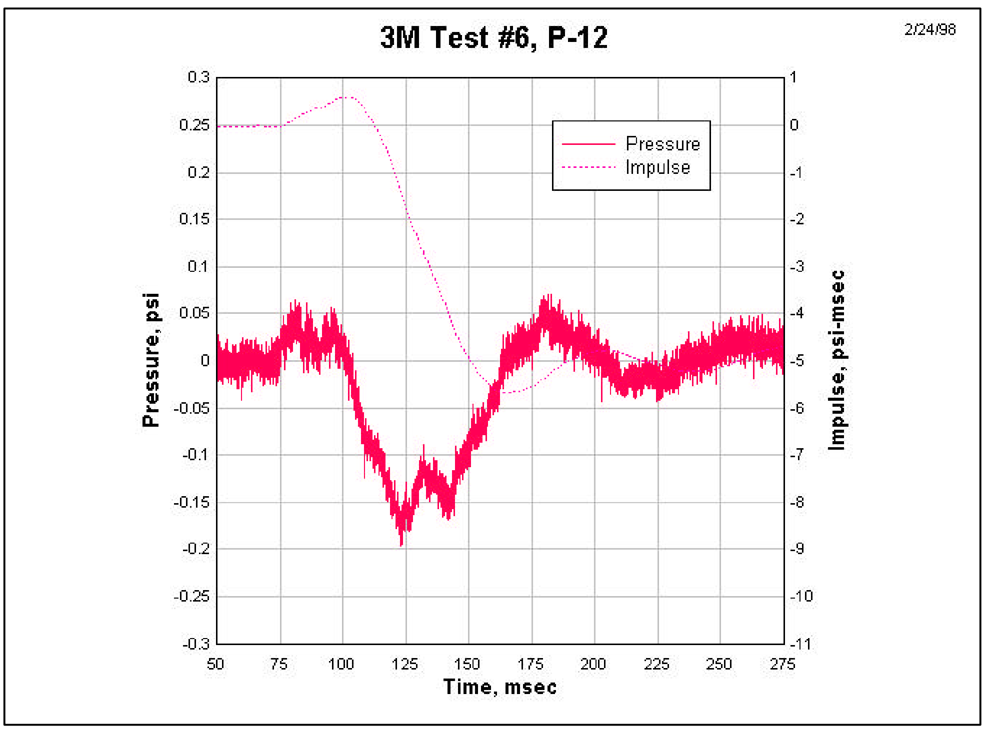

3M Test #6, P-7
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275


3M Test #6, P-8
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
10
9
8
7
6
5
4
3
2
1
0
-1
-2
60
55
50
45
40
35
30
25
20
15
10
5
0
50
75
100
125
150
175
200
225
250
275


3M Test #6, P-9
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
50
75
100
125
150
175
200
225
250
275


3M Test #6, P-10
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
50
75
100
125
150
175
200
225
250
275


3M Test #6, P-11
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
50
75
100
125
150
175
200
225
250
275


3M Test #6, P-12
2/24/98
Pressure
Impulse
Pressure, psi
Impulse, psi-msec
Time, msec
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
50
75
100
125
150
175
200
225
250
275