BAKER ENGINEERING AND RISK CONSULTANTS, INC.

3330 Oakwell Court, Suite 100 • San Antonio, TX 78218-3024
Tel. (210) 824-5960 • Fax: (210) 824-5964
www.BakerRisk.com

March 20, 2008

Kerri Taylor
Solatube International, Inc.
2210 Oak Ridge Way
Vista, CA 92081-8341
ktaylor@solatube.com

Subject: **Solatube 21-C Skylight Blast Evaluation, Final Report**
BakerRisk Project No. 01-2101-001-08

Dear Ms. Taylor:

Baker Engineering and Risk Consultants, Inc. (BakerRisk) is pleased to submit our final report summary of the blast capacities for the Solatube 21-C skylight.

We appreciate the opportunity to perform this study, and look forward to working with you in the future. If you have any questions or comments, please do not hesitate to call me at (210) 824-5960.

Sincerely,

Barry L. Bingham, P.E.
Principal Engineer

Approval:

for

Raymond H. Bennett, P.E., Ph.D.
Manager, Protective Structures

cc: Amanda Harris, BakerRisk

SOLATUBE 21-C
SKYLIGHT BLAST EVALUATION

Final Report
March 20, 2008

Prepared for:
Solatube International

Prepared by:
Barry L. Bingham, P.E.

BakerRisk Project No.
01-2101-001-08

BAKERRISK
BAKER ENGINEERING AND RISK CONSULTANTS, INC.
3330 Oakwell Court, Suite 100
San Antonio, TX 78218-3024
Tel: (210) 824-5960
Fax: (210) 824-5964

Notice

Baker Engineering and Risk Consultants, Inc. (BakerRisk) made every reasonable effort to perform the work contained herein in a manner consistent with high professional standards.

The work was conducted on the basis of information made available by others to BakerRisk. Neither BakerRisk nor any person acting on its behalf makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information provided. All observations, conclusions and recommendations contained herein are relevant only to the project, and should not be applied to any other facility or operation.

Any third party use of this Report or any information or conclusions contained therein shall be at the user's sole risk. Such use shall constitute an agreement by the user to release, defend and indemnify BakerRisk from and against any and all liability in connection therewith (including any liability for special, indirect, incidental or consequential damages), regardless of how such liability may arise.

BakerRisk regards the work that it has done as being advisory in nature. The responsibility for use and implementation of the conclusions and recommendations contained herein rests entirely with the client.

Table of Contents

1.0 INTRODUCTION 1
2.0 DAMAGE CRITERIA 2
3.0 SKYLIGHT DESCRIPTION 3
4.0 FINITE ELEMENT MODEL 4
5.0 RESPONSE TO THE DESIGN BLAST LOAD 18
6.0 RESPONSE TO WORST-CASE BLAST LOAD 24
7.0 SUMMARY 33

List of Tables

Table 1. Material Properties Summary 5

List of Figures

Figure 1. Solatube 21-C Skylight with Self Flashing (8-inch Shown) 3
Figure 2. LS-DYNA Finite Element Model of the Solatube 21-C Skylight 6
Figure 3. LS-DYNA Finite Element Model (Exploded View) 7
Figure 4. LS-DYNA Finite Element Model (Exploded View with Mesh) 8
Figure 5. Contact Between Different Parts 9
Figure 6. Contact Between Flashing and Rigid Roof 10
Figure 7. Design Free-Field Overpressure Time History 10
Figure 8. Full Set of Load Surface Polygons 11
Figure 9. Load Region 1 12
Figure 10. Load Region 2 12
Figure 11. Load Region 3 13
Figure 12. Load Region 4 13
Figure 13. Load Region 6 14
Figure 14. Load Region 7 14

Figure 15. Load Region 8 15
Figure 16. Load Region 12 15
Figure 17. Load Region 13 16
Figure 18. Load Region 19 16
Figure 19. Load Region 25 17
Figure 20. Load Region 31 17
Figure 21. Plastic Strain in the Support Flashing 21
Figure 22. Contours of Peak Von-Mises Stress in the Acrylic Dome 21
Figure 23. Contours of Peak First Principal Stress in the Acrylic Dome 22
Figure 24. Fastener Reaction Forces Between the Acrylic Dome and Steel Flashing 22
Figure 25. Fastener Reaction Forces Between the Steel Flashing and Roof 23
Figure 26. Plastic Strain in the Steel Flashing at 13 ms (End of Positive Phase) 25
Figure 27. Plastic Strain in the Steel Flashing at 30 ms (End of Negative Phase and Rebound) 26
Figure 28. Dome Forward Fastener Forces (30 Degrees Off Centerline) 27
Figure 29. Dome Side Fastener Forces 27
Figure 30. Dome Rear Fastener Forces (30 Degrees Off Centerline) 28
Figure 31. Roof Front Fastener (6 Degrees Off Centerline) 28
Figure 32. Roof Side Fastener 29
Figure 33. Roof Rear Fastener (6 Degrees Off Centerline) 29
Figure 34. Contours of Peak Von-Mises Stress in the Acrylic Dome 30
Figure 35. Contours of Peak First Principal Stress in the Acrylic Dome 31
Figure 36. Contours of Plastic Strain in the PVC Dome Ring at Late Time 32

1.0 INTRODUCTION

This report summarizes BakerRisk's assessment of the blast capacities for the Solatube 21-C skylight with 11-inch self flashing for Solatube International (Solatube). This report also includes a discussion of the methods and criteria used in the analyses.

Blast evaluation is presented in terms of response to a specific threat specified by the document set of the *Unified Facilities Criteria* (UFC) resulting in a free-field incident peak pressure of 6.3 psi and impulse of 25.1 psi-ms.

2.0 DAMAGE CRITERIA

The dynamic responses of all structural components were calculated in accordance with the procedures noted by the U.S. Department of Defense (DOD)[1] and ASCE[2]. The United States Army Corps of Engineers (USACE)[3] provides response limits for antiterrorism design. The response criteria are provided in terms of the ductility ratio (μ) and support rotation (θ). The ductility ratio is a dimensionless parameter and is the ratio of the maximum deflection to the yield deflection. The support rotation is measured in degrees and is estimated as the arctangent of the maximum deflection divided by the distance to the closest support.

[1] Department of the Army Technical Manual TM5-1300 *Structures to Resist the Effects of Accidental Explosions*
[2] Conrath, E.J., Krauthammer, T., Marchand, K. A., and Mlakar, P. F., "Structural Design for Physical Security State of Practice," American Society of Civil Engineers (ASCE), ISBN 0-7844-0457-7
[3] U.S. Army Corps of Engineers Protective Design Center Technical Report, "Single Degree of Freedom Structural Response Limits for Antiterrorism Design," PDC-TR 06-08, 20 October 2006

3.0 SKYLIGHT DESCRIPTION

The Solatube 21-C skylight with self flashing is shown in Figure 1. An 8-inch flashing is shown in the figure. BakerRisk was tasked to perform analysis on an 11-inch version in which the flashing height in Figure 1 was increased to 11 inches.

The diameter at the base of the flashing was maintained, resulting in a steeper vertical slope of the main body of the flashing.

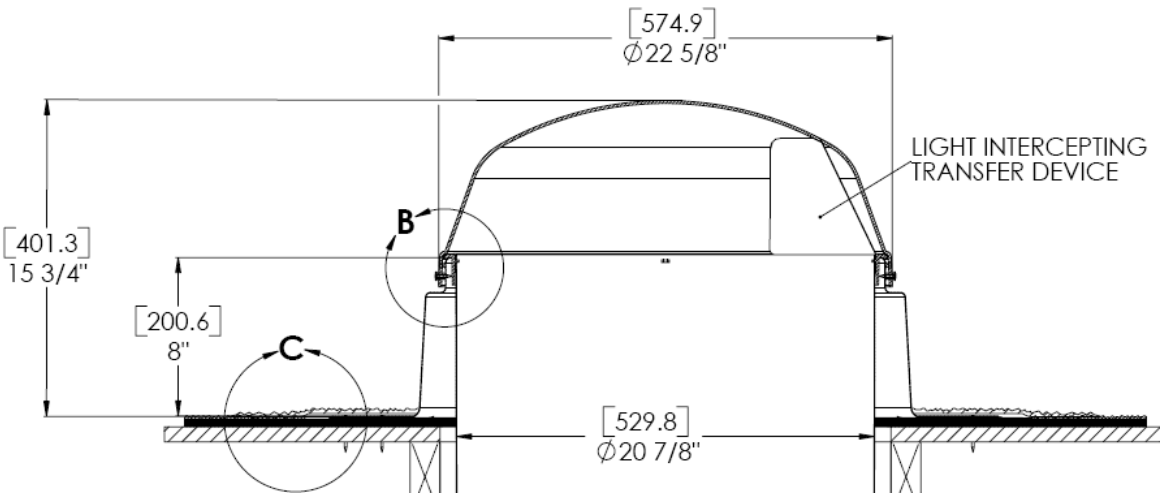

Figure 1. Solatube 21-C Skylight with Self Flashing (8-inch Shown)

4.0 FINITE ELEMENT MODEL

A finite element model of the skylight was built using LS-DYNA[4]. LS-DYNA is an explicit solution, large deformation, dynamic finite element analysis (FEA) code. The explicit formulation is ideally suited for analyzing the dynamic response of structures subjected to impulsive loading. LS-DYNA has a robust suite of constitutive material models and contact surface algorithms. The finite element model for the skylight is shown in Figure 2, Figure 3, and Figure 4. The grid consisted of 15,689 nodes, 15,372 shell elements, and 22 beam elements. A relatively fine mesh is used (0.25 inches to 0.40 inches, see Figure 4) in order to capture localized buckling behavior.

Figure 5 shows a close-up sliced view at the connection between the acrylic dome, PVC dome ring, and sheet steel flashing. The shell elements are shown at the location of the middle surfaces. LS-DYNA properly accounts for shell element thicknesses for contact. The acrylic dome rests on the PVC dome ring. The PVC dome ring sits on top of the sheet steel flashing. The acrylic dome is also connected to the sheet steel flashing with fastening screws at six locations. In LS-DYNA the fastening screws are modeled as 1/8-inch diameter beam elements so that resultant axial and shear forces in the fasteners can be determined.

The skylight assembly is supported by a flat roof surface in this case. For the purposes of this study, the roof is assumed to be rigid, which is a worst-case condition for tie strength of the fasteners to the roof. In the LS-DYNA model (see Figure 6), nodes coinciding with sixteen fastener locations are restricted from translation. The rest of the flashing support interfaces with the rigid roof surface with a friction coefficient of 0.10 and is free to bounce off of the roof surface, but cannot move through it. The sixteen fastener locations are the only thing preventing the assembly from bouncing off of the roof. Restricting translations at these locations allows LS-DYNA to output resultant forces at these locations.

Two different load cases were investigated. The first load case is the design load case as specified by the United States Army Corp of Engineers. The design pressure load is a right triangular pulse with a peak pressure of 6.3 psi, impulse of 25.1 psi-ms, and load duration of 7.97 ms. This load case assumes that the skylight is shielded from direct exposure (such as from a roof eave or parapet) to the blast source. The skylight is loaded uniformly in all directions.

The second load case involves a more intense loading where the skylight is exposed through line of site to the design threat explosive source. For this condition, the exterior surface is loaded with a traveling blast pressure wave. The associated free-field incident overpressure time history is shown in Figure 7. This pressure time history was obtained using the TNT-Standard[5] methodology. The TNT-Standard provides a complete set of hydrodynamic-consistent environmental parameters.

---

[4] LS-DYNA User's Manual, "Nonlinear Dynamic Analysis of Structures," Livermore Software Technology Corporation, Version 970, August 31, 2003.
[5] Hikida, S., "Status Report: TNT Model," SSS-DVR-14463, S-Cubed, La Jolla, California, February, 1994

The free-field blast environment is modified into target surface loads using the LAMB methodology[6]. Front surfaces of the skylight experience reflected pressure loads well above free field. The full set of surface load polygons is shown in Figure 8. The load surface is broken up into 31 different regions for definition of the traveling blast wave. Figure 9 through Figure 20 show samples of a few of those regions and the resulting pressure wave forms.

Table 1 presents a summary of the material properties used in the finite element model. ASCE recommends the use of strength increase factors (SIF) and dynamic increase factors (DIF) for design to blast loads. TM5-1300[7] specifies an SIF of 1.21 and a DIF of 1.1 for cold-formed steel panels, which was used for the steel flashing. No SIF and DIF are specified by ASCE for the acrylic or PVC. However, published test results[8] show a DIF of 1.64 at a strain rate (3.0/sec) that can be expected in blast response. Therefore, SIF and DIF from ASCE for low strength steels were used for the Plexiglas and PVC, which are conservative compared to available test data. The SIF and DIF were applied to the published tensile strengths rather than published flexural strengths to determine dynamic yield strength. For some materials (such as concrete), flexural strength is one measure of tensile strength and they are nearly equal. For other materials (such as fiber-reinforced glasses, ceramics, and Plexiglas) flexural strength is often observed to be higher than their tensile strength. In order to be conservative, the lower tensile strength for the acrylic and the PVC were used, and the resulting dynamic yield strength was less than the published flexural strength.

Table 1. Material Properties Summary

Description	Thk (in)	γ (pcf)	E (psi)	f_y (ksi)	SIF	DIF	f_{dy} (ksi)	$\varepsilon_{failure}$
Glazing, Type DA acrylic classified as CC2 material	0.143	72.1	2.7e5	5.5	1.1	1.29	7.80	0.50
High impact PVC (dome ring)	0.134	90.1	4.0e5	6.53	1.1	1.29	9.27	0.80
ASTM A653/A653M Galvanized Steel Sheet	0.028	495	29.e6	50	1.21	1.10	66.6	0.12

[6] Hikida, S. and Needham, C.E., "Low Altitude Multiple Burst (LAMB) Model, Volume I – Shock Description," DNA 5863Z-1, Defense Nuclear Agency, Washington, D.C., 30 June 1981.
[7] Department of the Army Technical Manual TM5-1300 *Structures to Resist the Effects of Accidental Explosions*
[8] Christman, D. R., "Dynamic Properties of Poly (Methylmethacrylate) (PMMA) (Plexiglas)," Materials and Structures Laboratory, General Motors Technical Center, Warren, Michigan, March 1972.

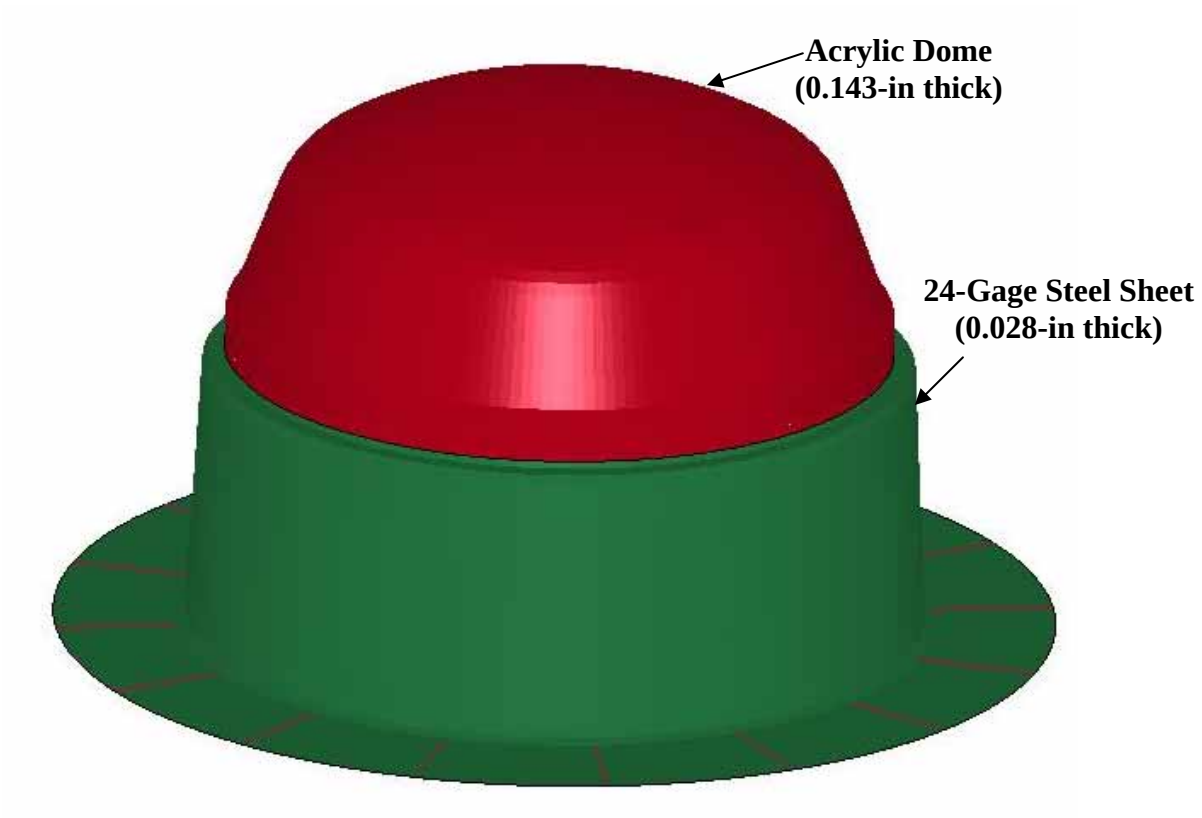

Figure 2. LS-DYNA Finite Element Model of the Solatube 21-C Skylight

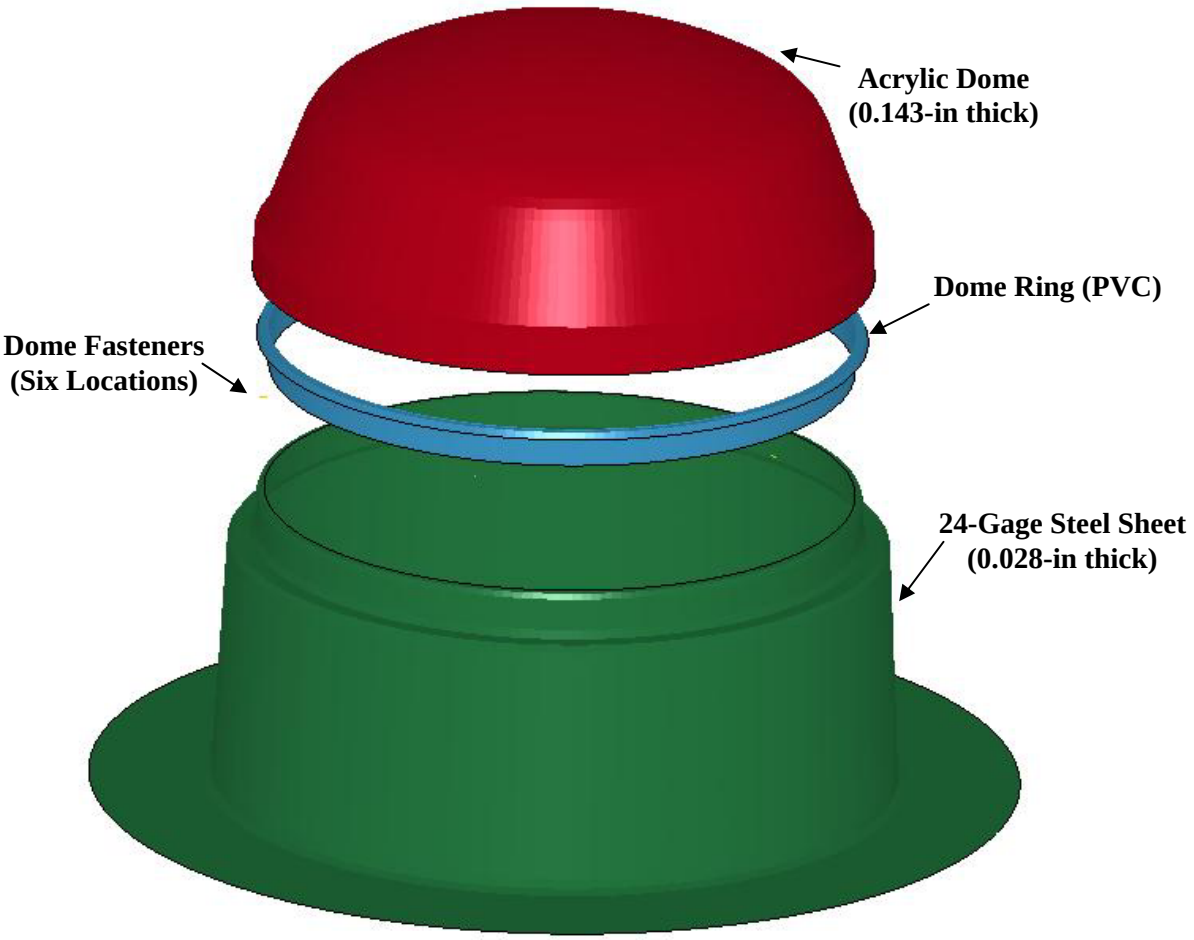

Figure 3. LS-DYNA Finite Element Model (Exploded View)

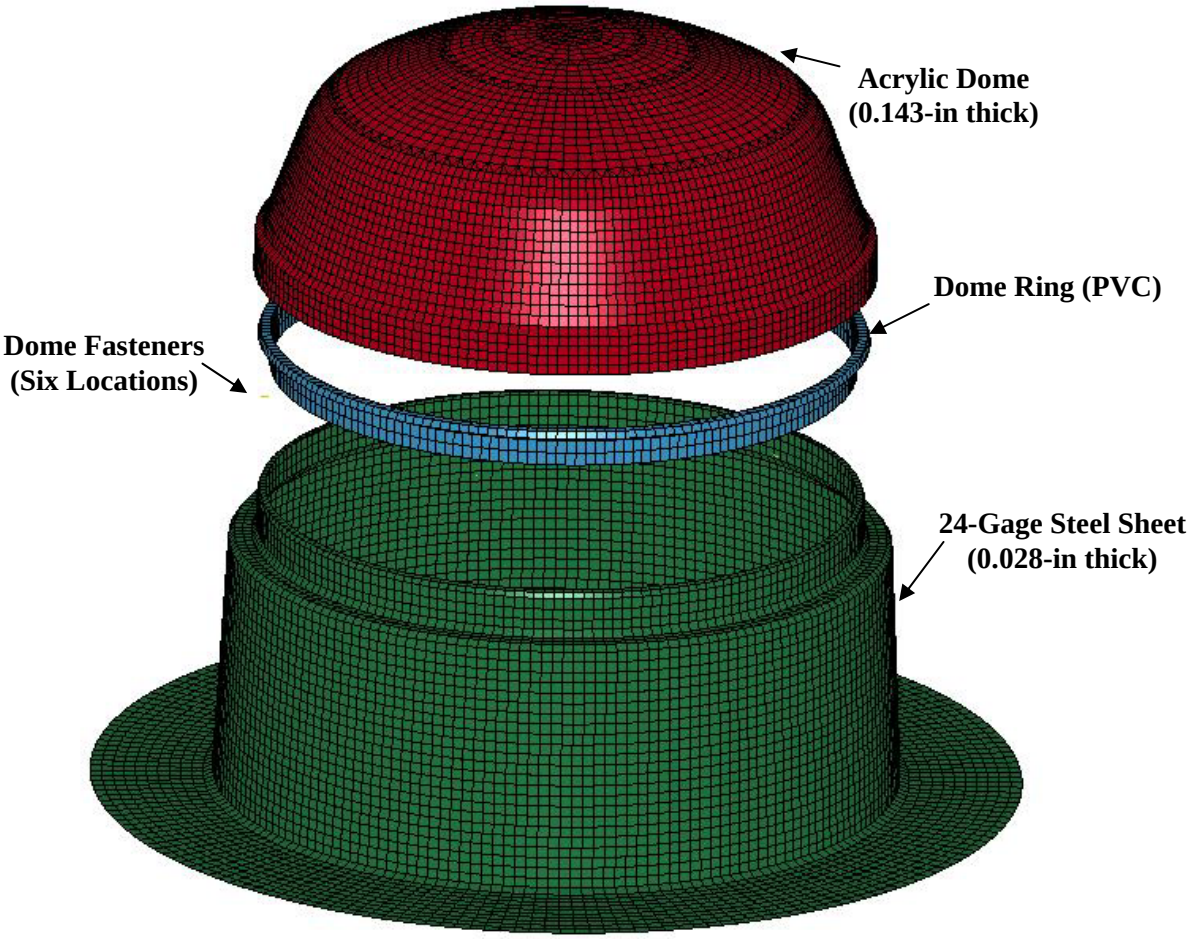

Figure 4. LS-DYNA Finite Element Model (Exploded View with Mesh)

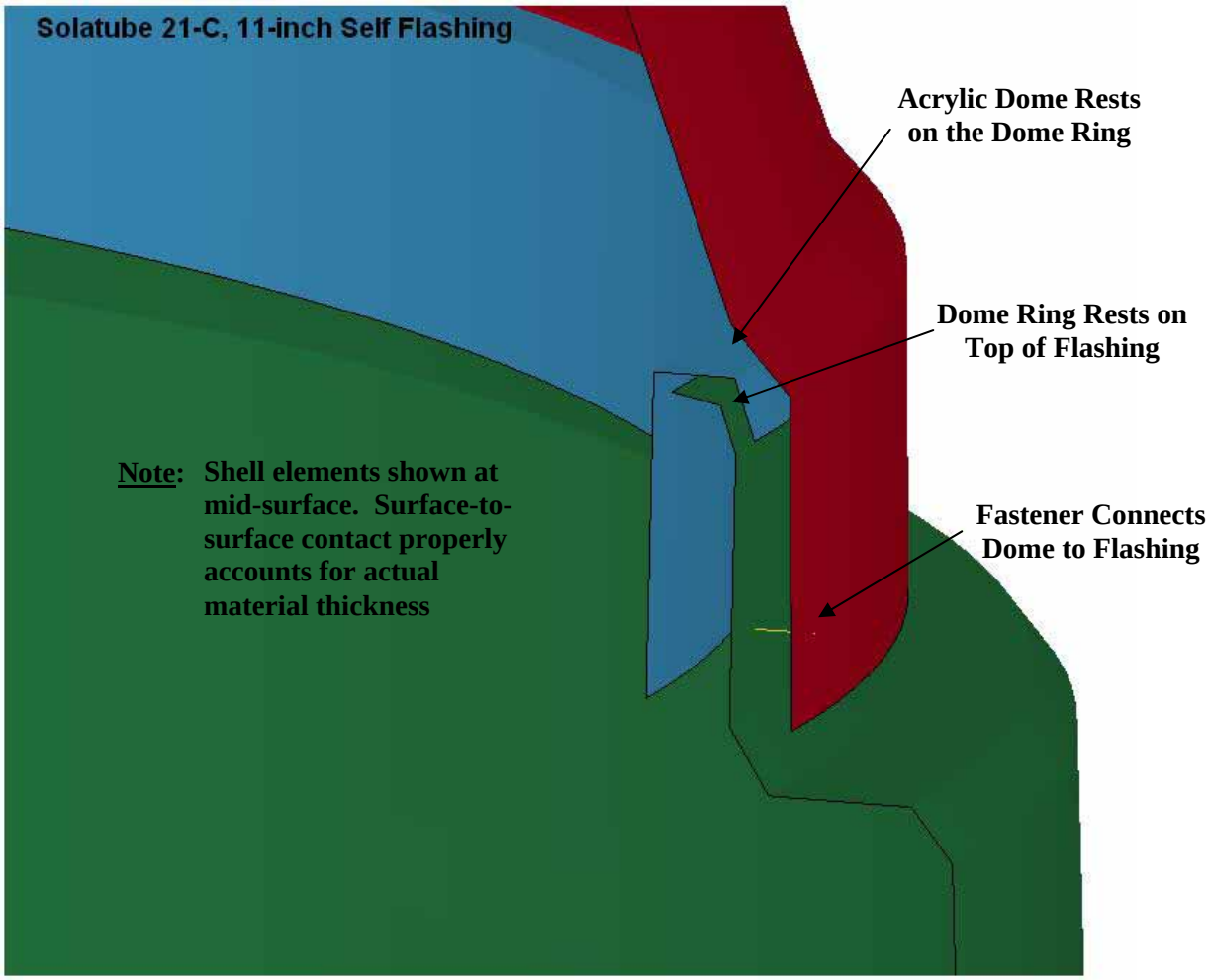

Figure 5. Contact Between Different Parts

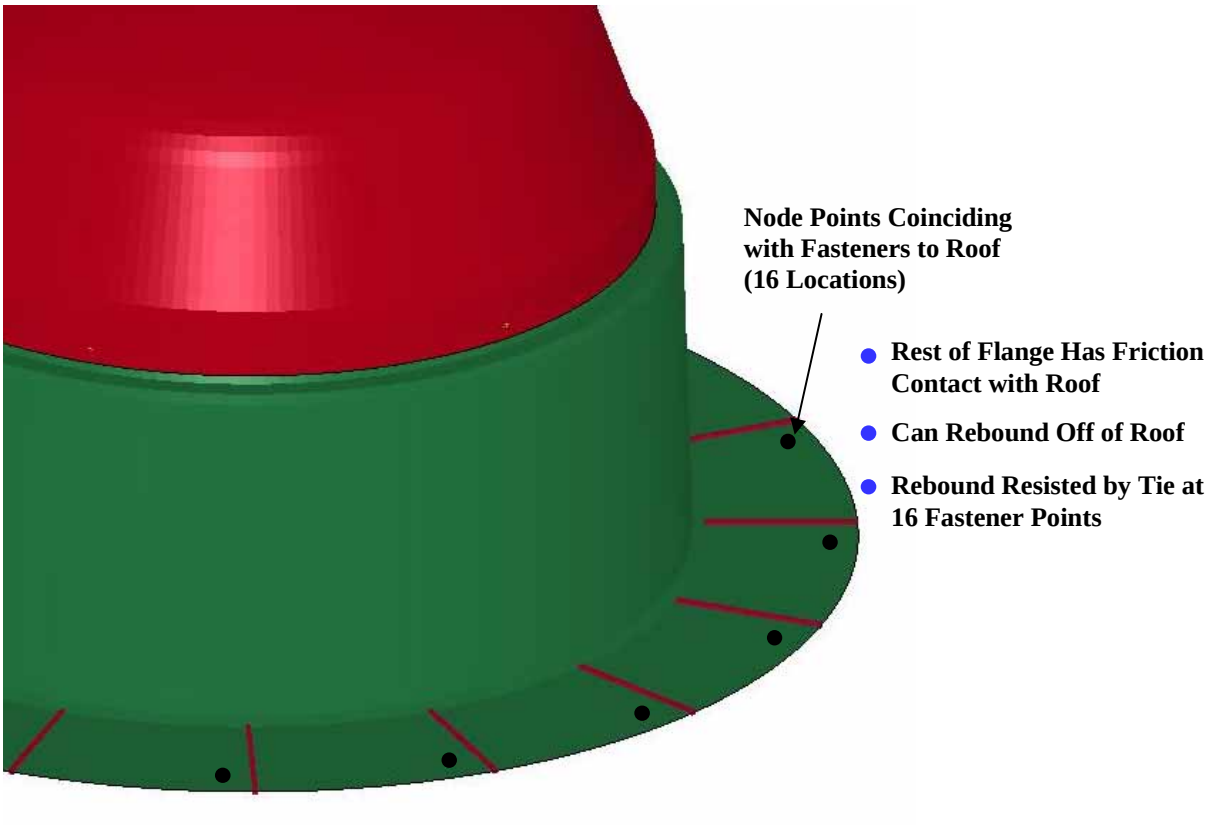

Figure 6. Contact Between Flashing and Rigid Roof

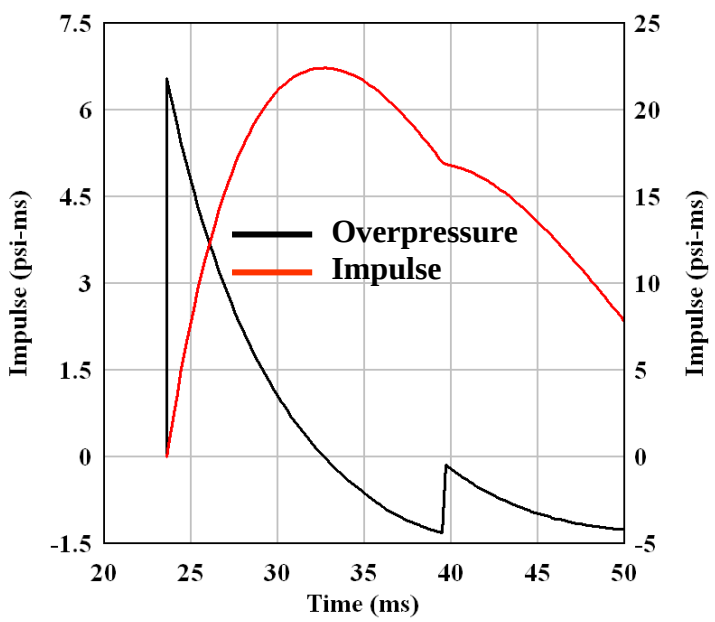

Figure 7. Design Free-Field Overpressure Time History

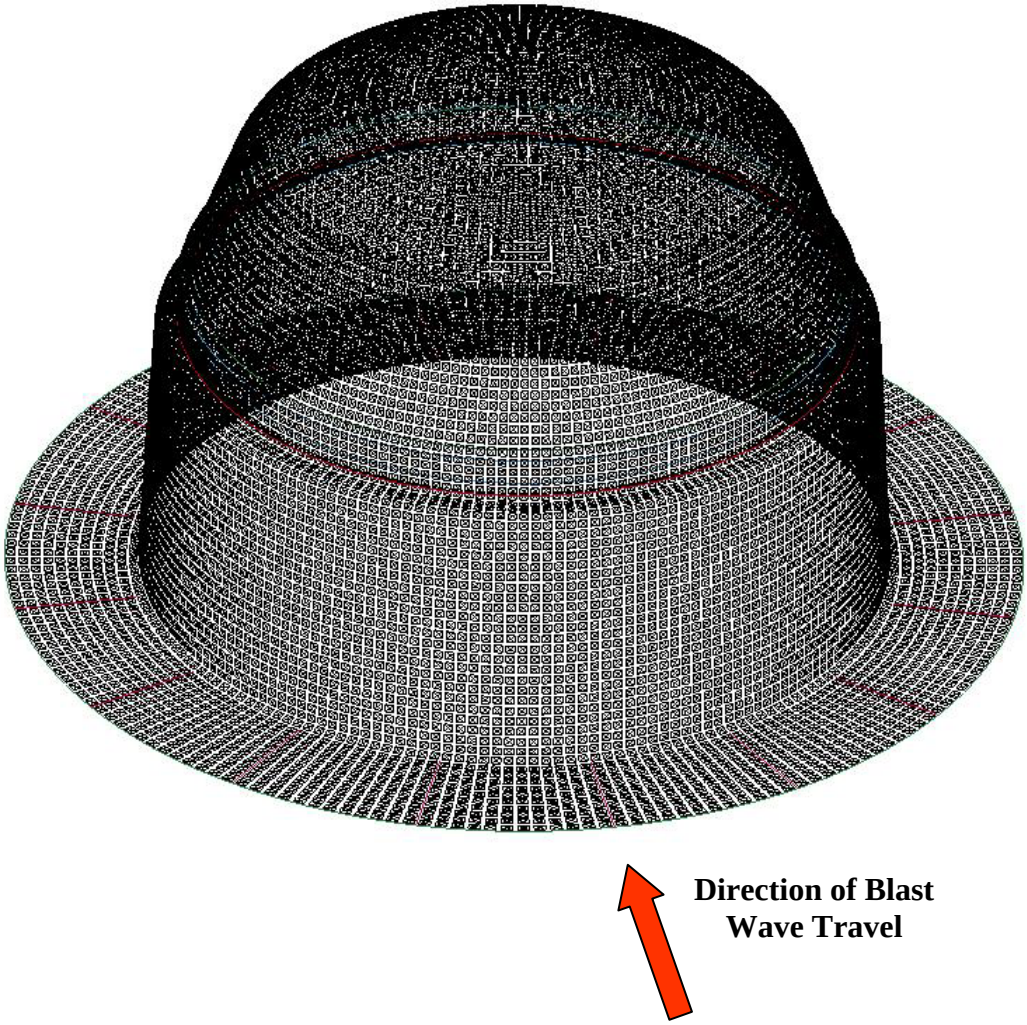

Figure 8. Full Set of Load Surface Polygons

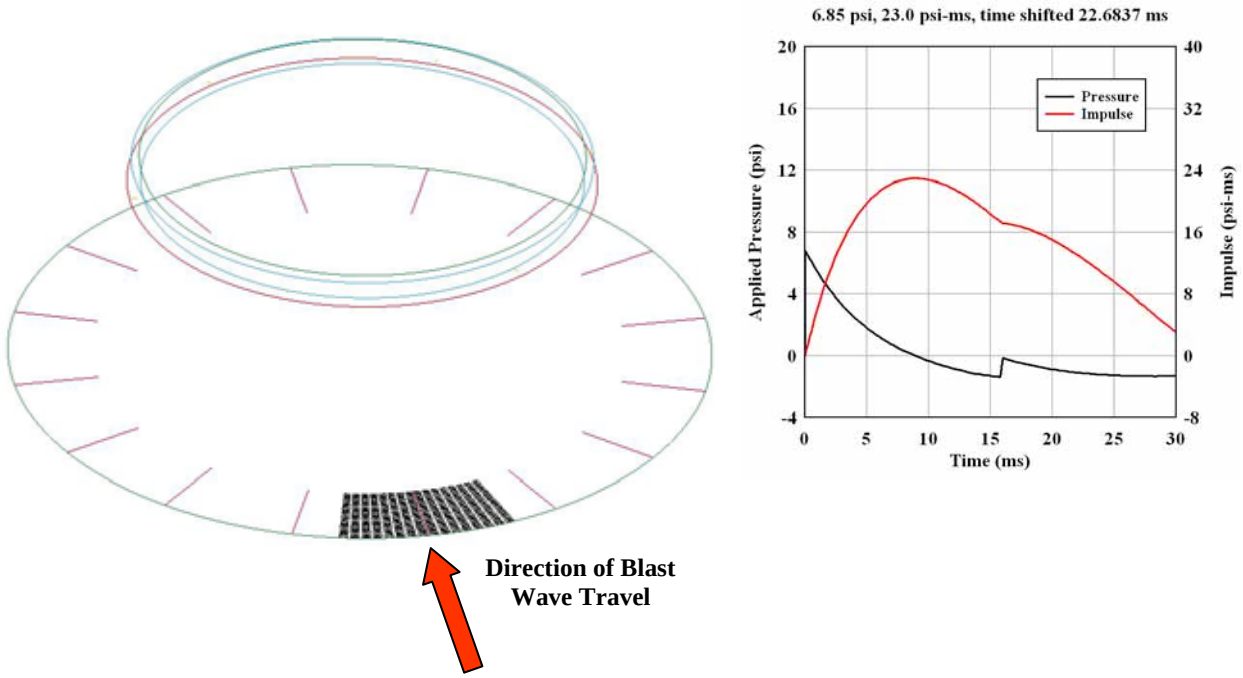

Figure 9. Load Region 1

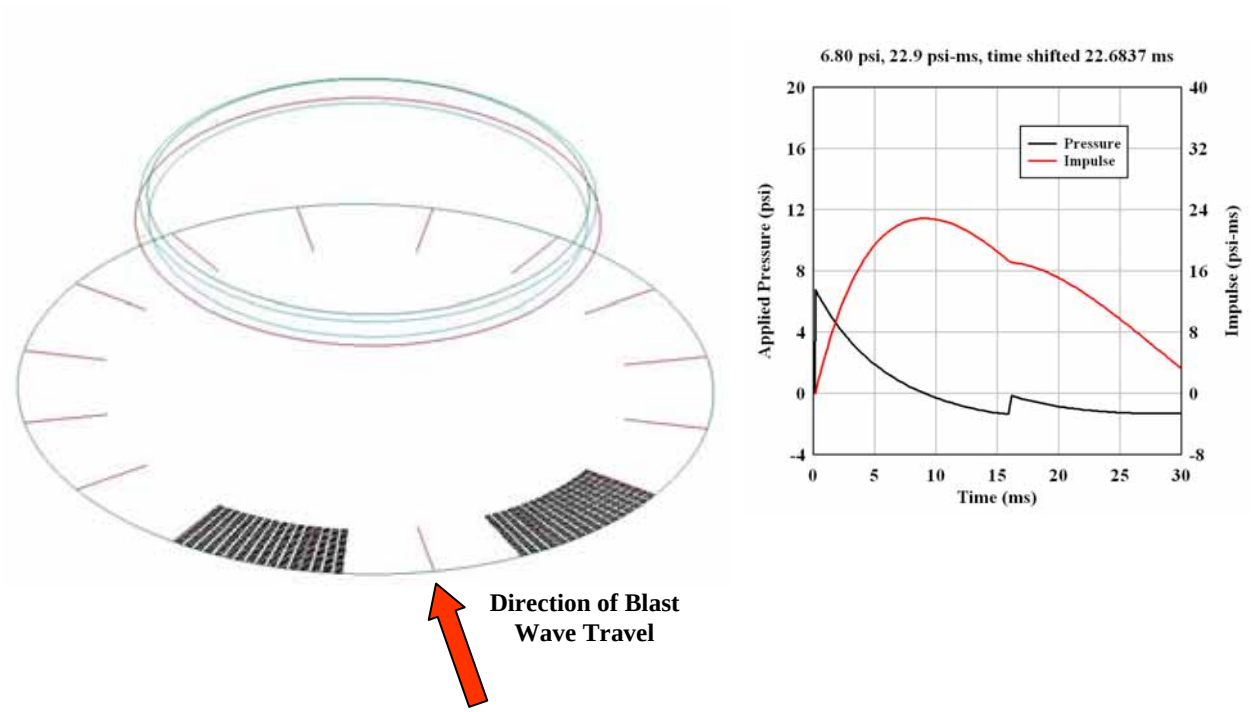

Figure 10. Load Region 2

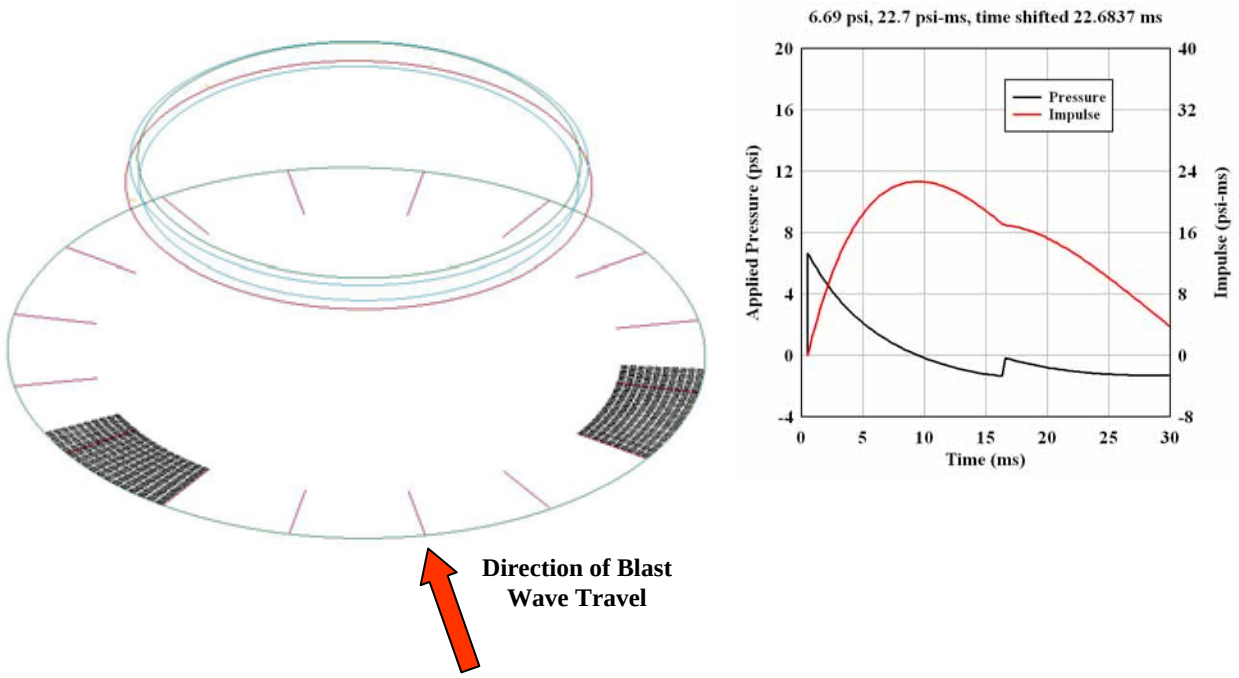

Figure 11. Load Region 3

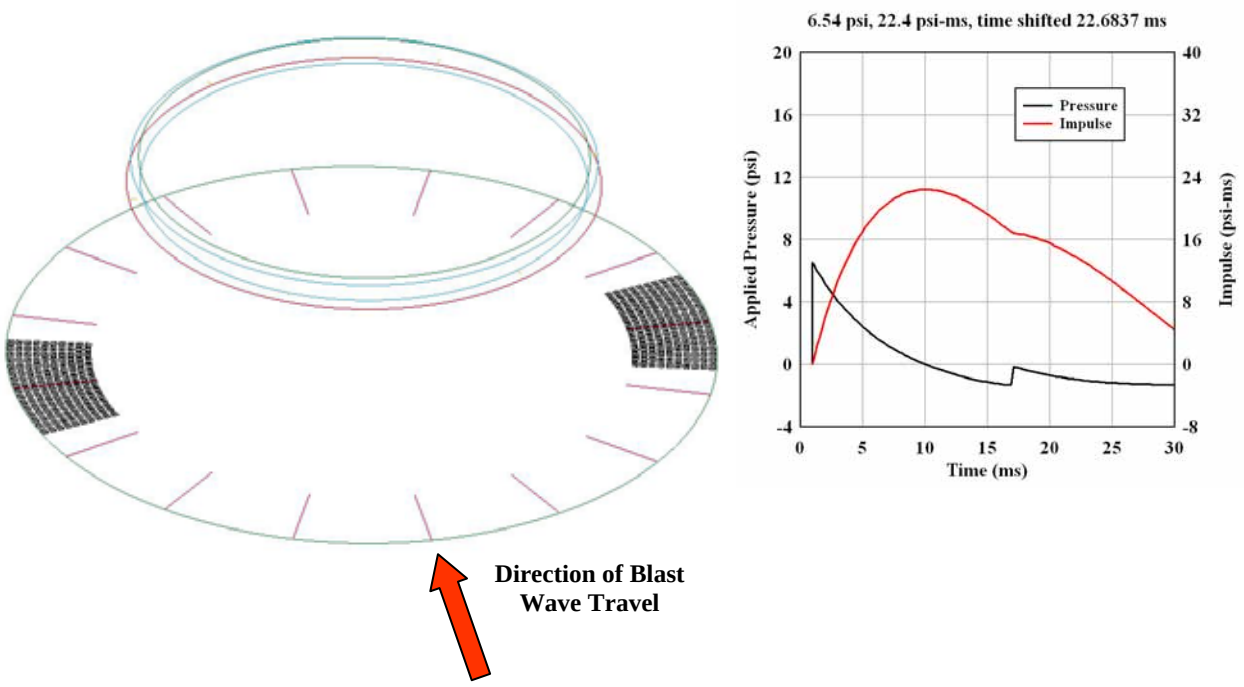

Figure 12. Load Region 4

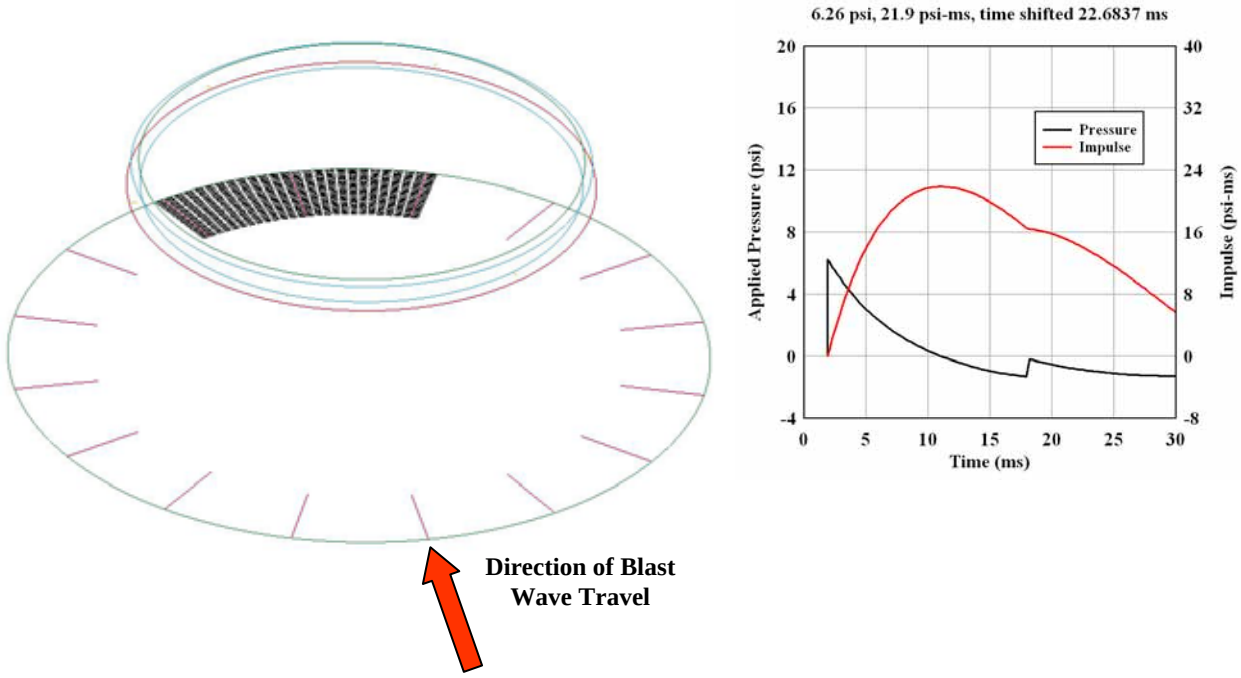

Figure 13. Load Region 6

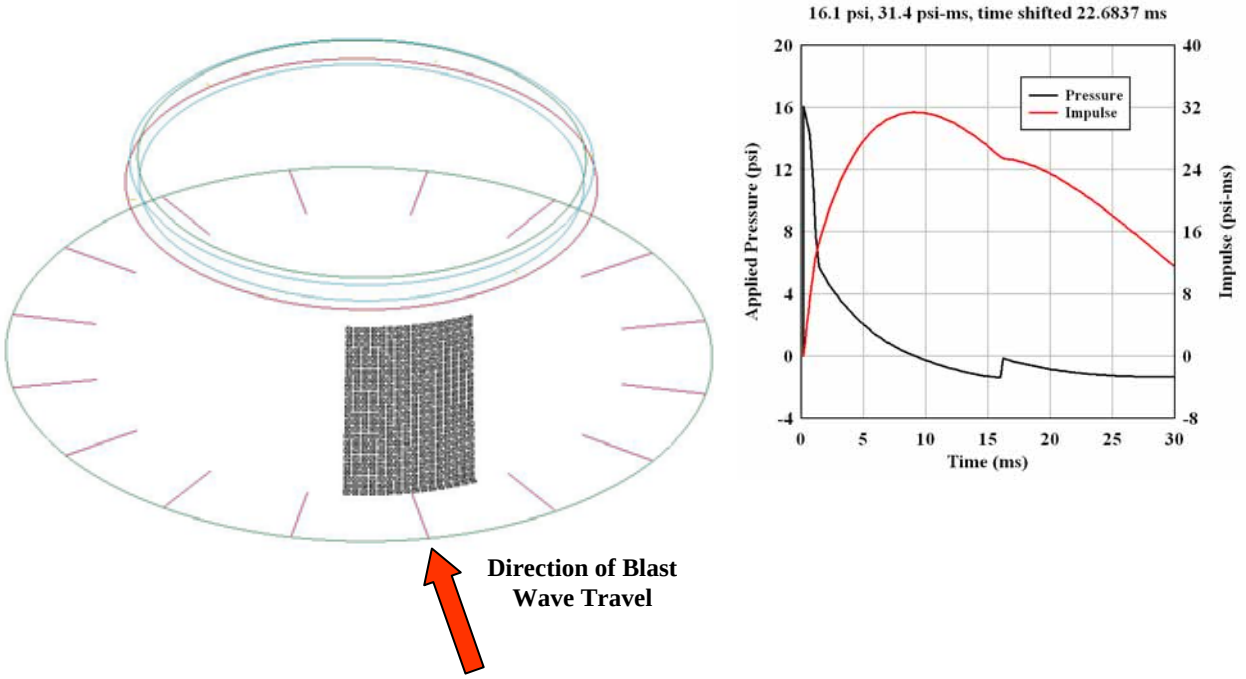

Figure 14. Load Region 7

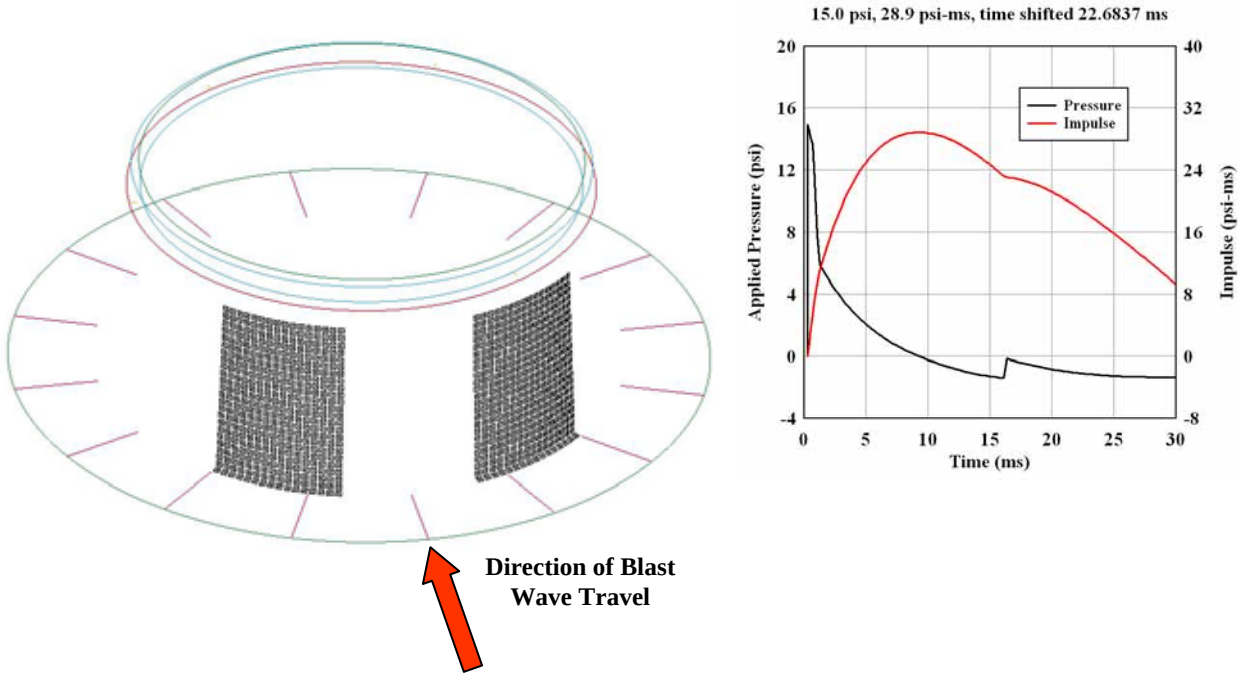

Figure 15. Load Region 8

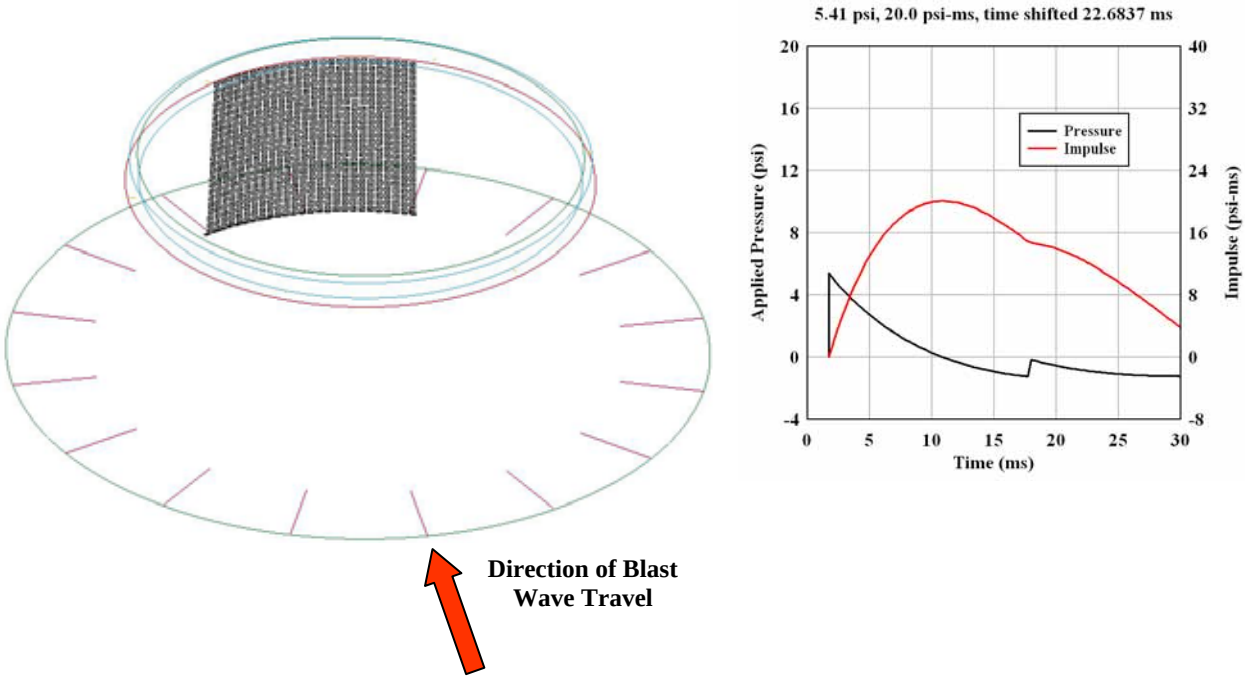

Figure 16. Load Region 12

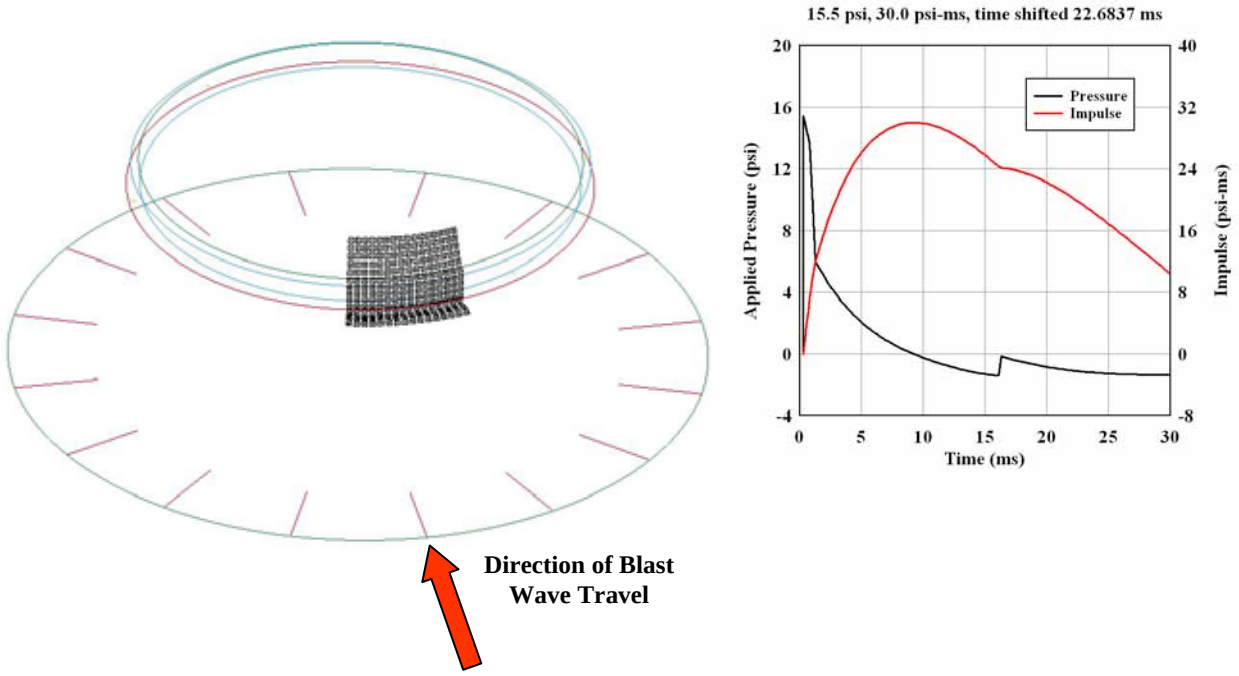

Figure 17. Load Region 13

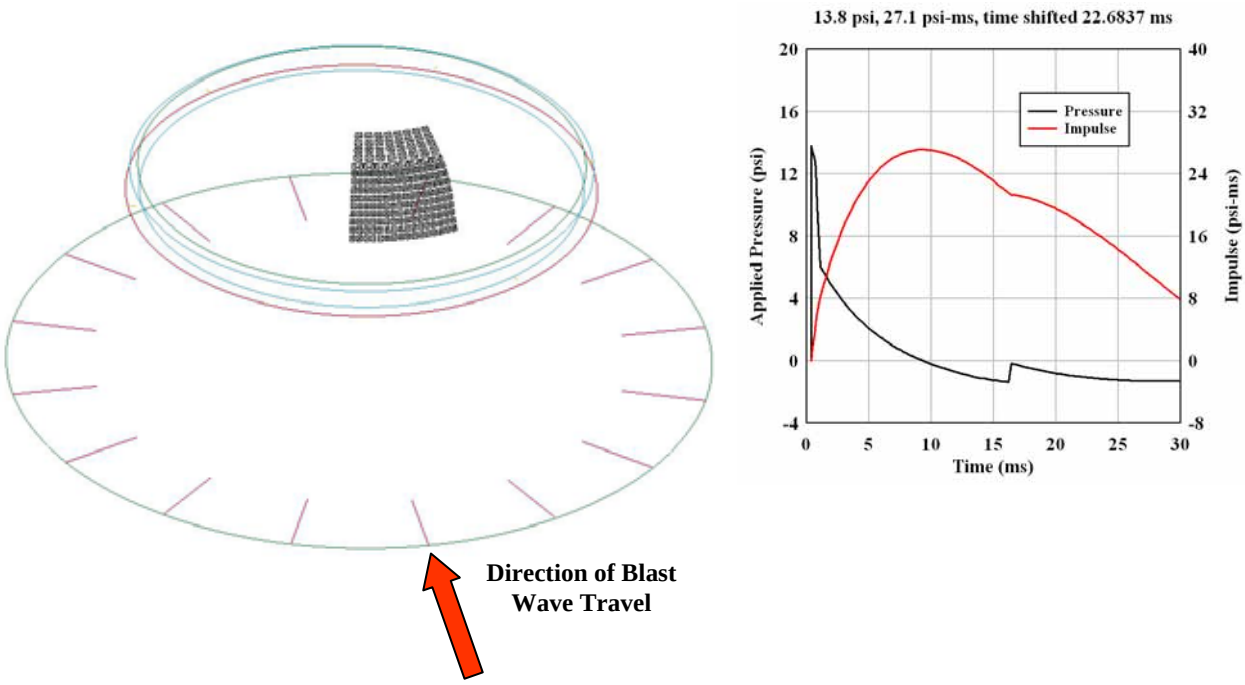

Figure 18. Load Region 19

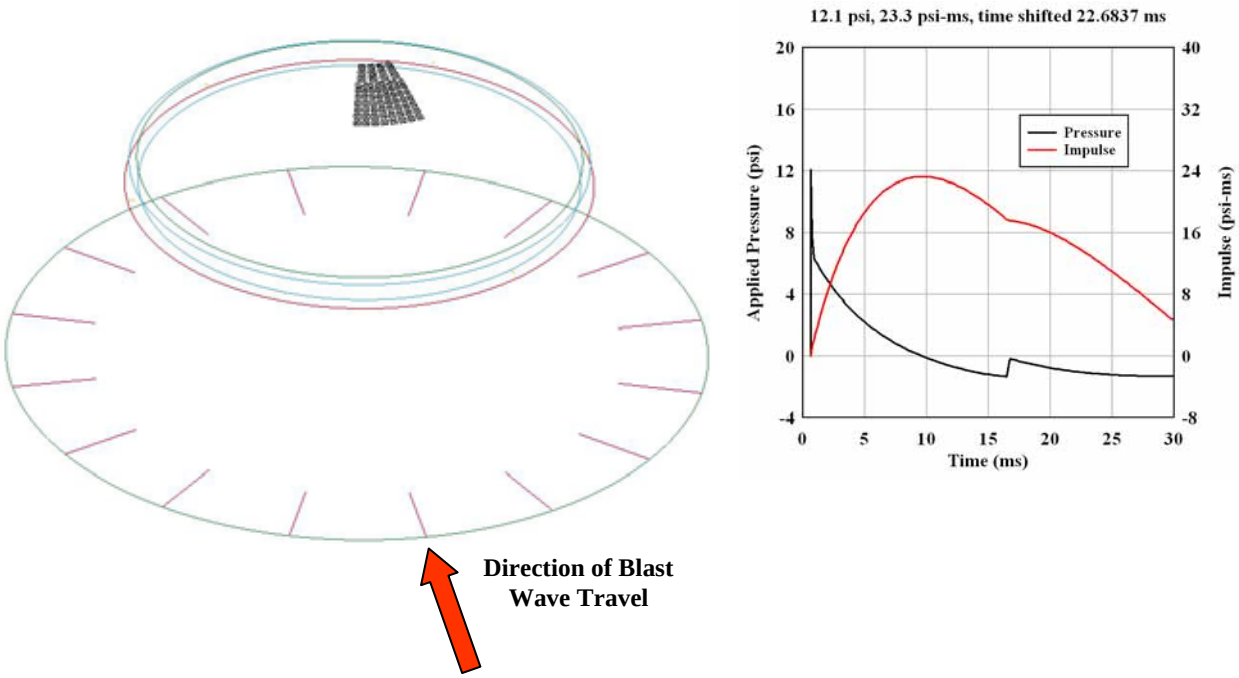

Figure 19. Load Region 25

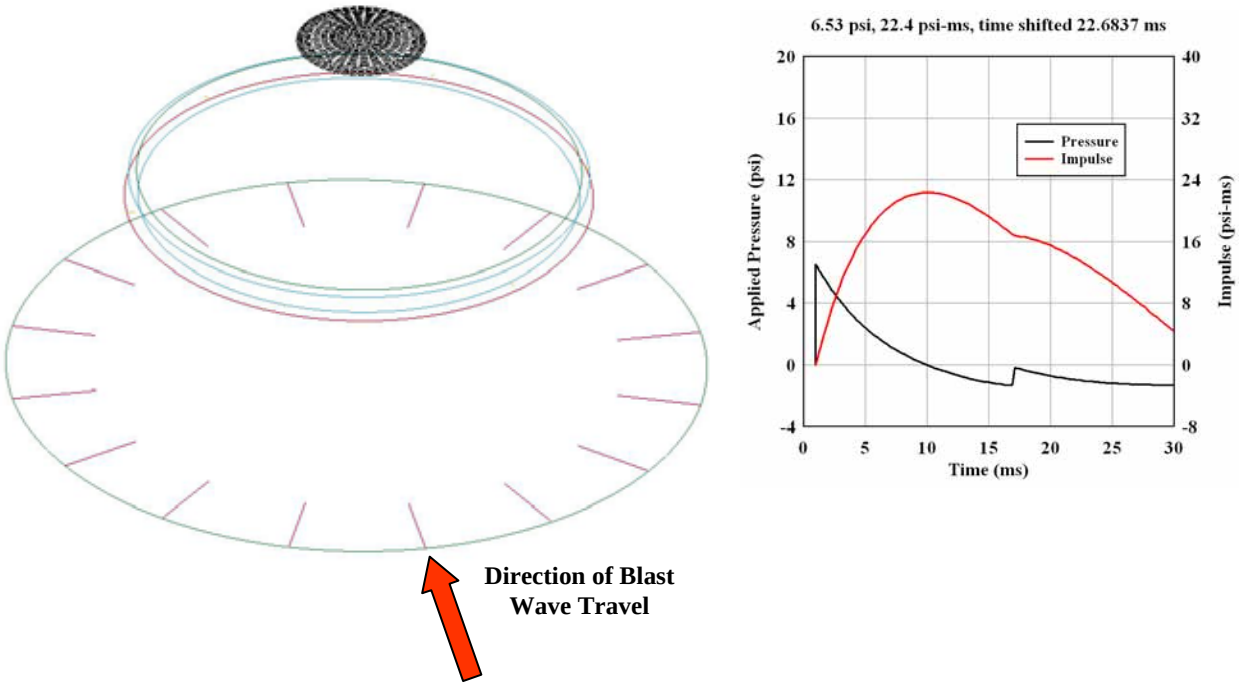

Figure 20. Load Region 31

5.0 RESPONSE TO THE DESIGN BLAST LOAD

The design pressure load is a right triangular pulse with a peak pressure of 6.3 psi, impulse of 25.1 psi-ms, and load duration of 7.97 ms. The pressure is applied simultaneously around the exterior surface of the skylight assembly. The calculation was run for a 20 ms duration. In response to the load, the acrylic dome pushes down against the dome ring and flashing support. The flashing, in-turn, pushes down against the roof support in addition to receiving its own blast load. The flat portion of the steel flashing just below the base of the acrylic dome experiences the highest plastic strain (see Figure 21). The peak plastic strain is 0.0110, which represents an equivalent localized ductility ratio, μ_{equiv}, equal to 5.8. The equivalent localized ductility ratio, μ_{equiv}, is the plastic strain divided by the elastic strain limit (0.00229 in this case), plus 1. The value of 1 is added since ductility ratio is typically defined to be 1.0 at the onset of plastic strain (elastic response limit). For the limit of heavy damage (B3 from the USACE[9]) Table 4-6 for cold-formed steel specifies a maximum allowable ductility ratio, μ, of 6.0 for metal decking with solid support connections (fastener design discussed below). Relating the equivalent ductility ratio, μ_{equiv}, to standard ductility ratio, μ, the response level of 5.8 is acceptable for design against blast. Also, the finite element analysis explicitly demonstrates that none of the skylight components are at risk of blowing into the protected facility.

BakerRisk examined the response criteria associated with standard window glazing. TM5-1300, Section 6-30.3 states:

> *"The window frame must develop the static design strength, r_u, of the glass pane."*

Section 4.2.4.2 of a design document associated with United States government buildings[10] states:

> *"Design the window frames so that they do not fail before the glazing under lateral load. Likewise, the anchorage should be stronger than the window frame, and the supporting wall should be stronger than the anchorage. The design strength of a window frame and associated anchorage is related to the breaking strength of the glazing."*

These design criteria are typically associated with flat panes and window frames that grip the outer edges of the pane. Standard window frames are designed to remain elastic under the full capacity loads of the supported glazing. The proposed Solatube skylight presented in this report is different from standard window systems such that slight ductile response of the flashing support (within acceptable Department of Defense response limits) does not place the acrylic dome at risk of flying into the protected space. Low levels of ductile response in the support flashing can be beneficial in reducing fastener reaction levels and response of the dome itself.

---

[9] U.S. Army Corps of Engineers Protective Design Center Technical Report, "Single Degree of Freedom Structural Response Limits for Antiterrorism Design," PDC-TR 06-08, 20 October 2006

[10] "ISC Security Design Criteria for New Federal Office Buildings and Major Modernization Projects," The Interagency Security Committee, September 29, 2004.

The acrylic dome and the PVC dome ring remain elastic. Figure 22 shows contours of peak Von-Mises stress occurring in the acrylic dome. The highest Von-Mises stress occurs near the fastener locations, reaching 3,916 psi, which is well below the dynamic yield strength of 7,800 psi. Figure 23 shows contours of peak first principal stress (tension being positive) with a maximum of 3,244 psi, which, again, is well below the dynamic tensile strength (from which the dynamic yield strength of 7,800 psi is based).

Figure 24 shows the resulting reaction forces in the fasteners connecting the acrylic dome to the steel flashing. Due to the symmetry in the skylight configuration and the uniform distribution of pressure, the reaction forces are the same in all six fasteners. The peak axial force is 46.5 lb, while the peak shear force is 60.2 lb. Design of the fastener is taken from Section E4 of the American Iron and Steel Institute *North American Specification for the Design of Cold-Formed Steel Structural Members* (AISI). A screw connection is assumed, along with the dynamic material strengths shown in Table 1. The screws should be thread-forming or thread-cutting, with or without a self-drilling point. Screws should be installed and tightened in accordance with the manufacture's recommendations. From Section E4.3 of AISI, regarding shear, a #6 screw connection will have 416 lb capacity (486 lb for the flashing, 416 lb for the acrylic, and 740 lb for the screw, with 416 lb controlling). From Section E4.4 of AISI, regarding tension, the head of the screw or washer should not be less than 5/16 inches. Washers, if used, should be at least 0.050 inches thick. The pullout strength (associated with the material not connected to the screw head, i.e. the flashing) of the #6 screw is 219 lb. The pull-over strength (associated with the material in contact with the screw head, i.e. the acrylic dome) involves the acrylic dome pulling out over the screw head and is strongly dependent on the diameter of the screw head and/or washer, if used. For the moment, if we assume the minimum diameter required by Section E4.4 (5/16 or 0.3125 inches), the pull-over strength is 523 lb. Since the connection is subjected to a combination of shear and tension forces, the connection must meet requirements of Section E4.5:

$$\frac{Q}{P_{ns}} + 0.71\frac{T}{P_{nov}} \leq \frac{1.10}{\Omega} \qquad \textbf{Equation 1}$$

where

Q	=	Required shear strength (60.2 lb)
P_{ns}	=	Nominal shear strength (416 lb)
T	=	Required tension strength (46.5 lb)
P_{nov}	=	Nominal pull-out strength (523 lb)
Ω	=	Safety factor (2.35)

For the #6 screw the left side of Equation 1 is 0.208, which is significantly less than the right side value of 0.468 and, therefore, meets design requirements.

Figure 25 shows the reaction forces in the fasteners between the flashing base and supporting roof. The roof is assumed to be a rigid surface in this simulation, so the reaction forces,

particularly the late-time rebound forces can be considered upper bound. It is during rebound that the highest fastener forces occur. The peak axial force is 63.2 lb, while the peak shear force is 376 lb. The shear force is pointed radial in towards the center as the rebound pulls the flashing flanges in towards the middle as it attempts to lift off of the roof. The fastener shear forces are larger than the axial forces since the fasteners are located towards the outer edge of the flashing flange. The ribs in the flashing flange (modeled in the finite element model) help increase the bending stiffness of the flange, but not enough to balance the axial and shear forces.

The design of the roof fastener again comes from the AISI manual. This design assumes a screw connection and accounts for dynamic material strengths shown in Table 1. The screws should be thread-forming or thread-cutting, with or without a self-drilling point. Screws should be installed and tightened in accordance with the manufacture's recommendations. For this fastener, the metal flashing is now the material adjacent to the screw head. Again, considering a #6 screw fastener the shear capacity is 694 lb (694 lb for the flashing and 740 lb for the screw, controlled by the flashing). The ratio of required shear strength (376 lb) to capacity (694 lb) is already equal to 0.54, which is greater than the right side value of Equation 1 (0.468). Therefore, a larger screw is needed. A #8 screw barely fails the design criteria of Equation 1. Therefore, a #10 screw is required for this connection with a minimum head diameter of 5/16 inch, as per Section E4.4. The large shear force on this connection drives the need for the larger fastener. The size of the fastener can be reduced either by making the flange ribs more substantial (which will in-turn reduce the ratio of shear versus tension), or by increasing the number of fasteners. For example, if the number of fasteners to the roof is increased from 16 to 21, the required resistance per fastener reduces to 286 lb shear and 48.2 lb tension. For 21 fasteners, a #6 fastener with a minimum head diameter of 5/16 inches results in a value of 0.451 for the left side of Equation 1, which meets the design requirements.

For 26 gage roof decking, the sheet steel thickness is 0.0198 inches. This is thinner than the Solatube flashing thickness, so Equation E4.3.1-1 of the AISI applies regarding nominal shear strength of the fastener connection. In order to meet the design requirements of AISI the size of the fasteners has to be increased to ¼-inch sheet metal screws, and their number needs to increase to 36. This places the fasteners 2.79 inches apart, which is greater than the AISI Section E4.1 minimum spacing of 3d (0.75 inches).

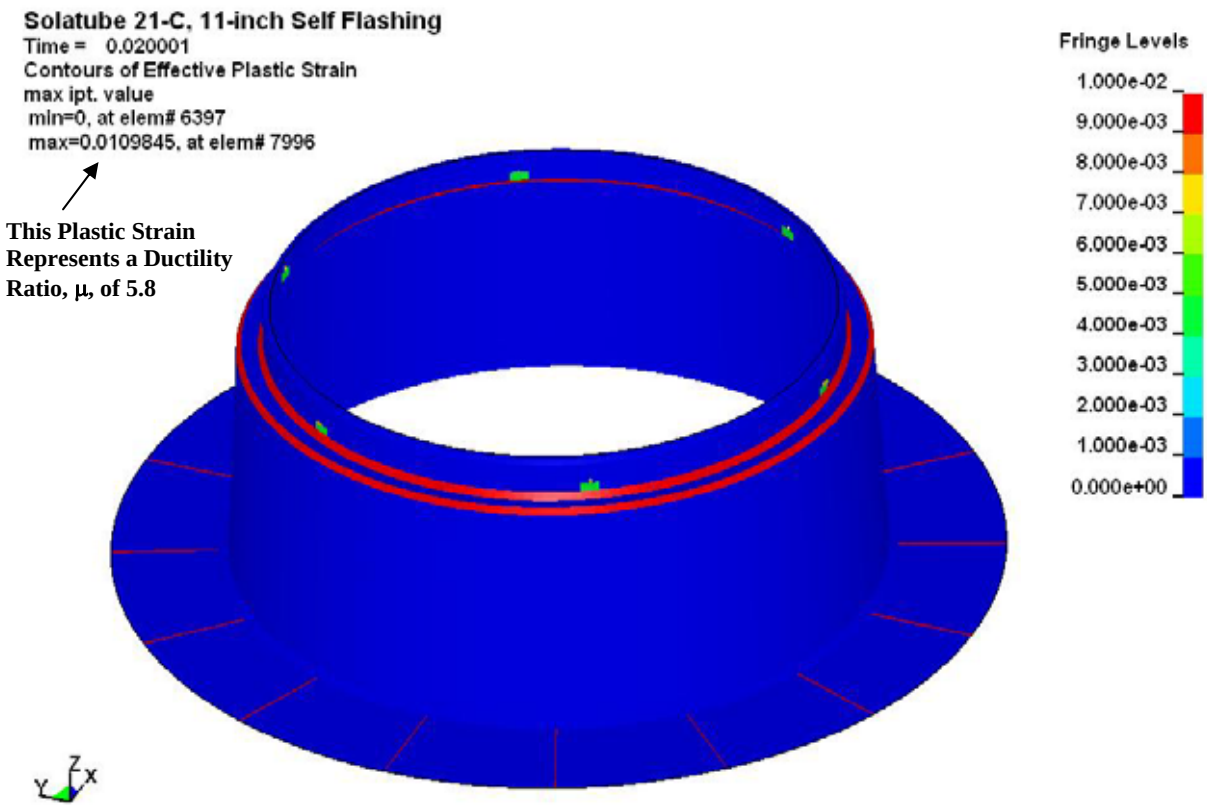

Figure 21. Plastic Strain in the Support Flashing

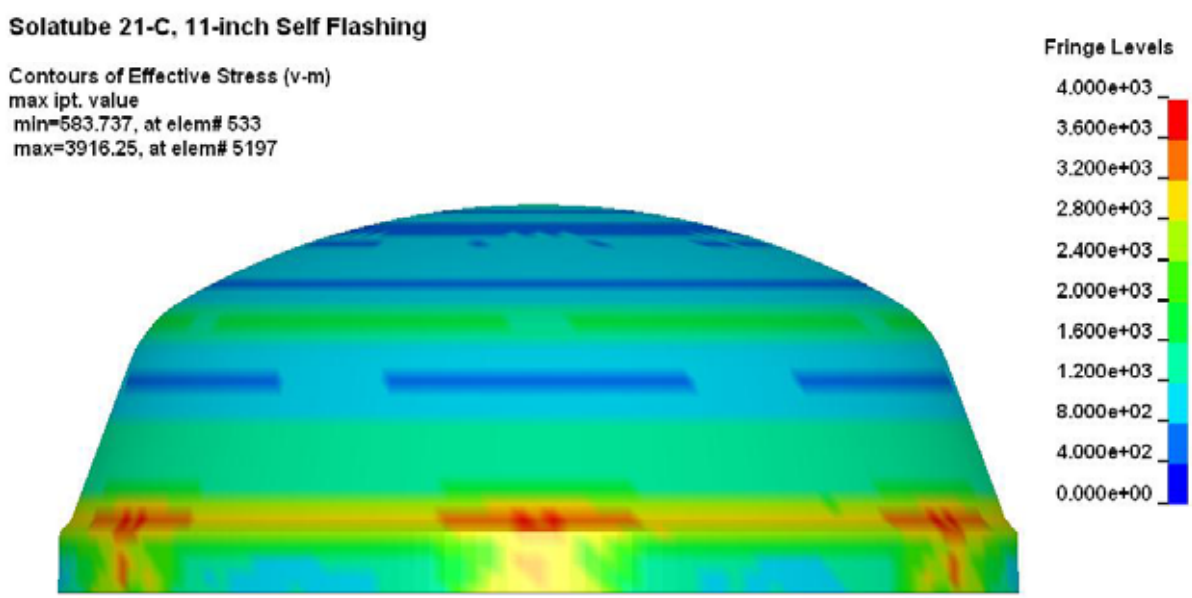

Figure 22. Contours of Peak Von-Mises Stress in the Acrylic Dome

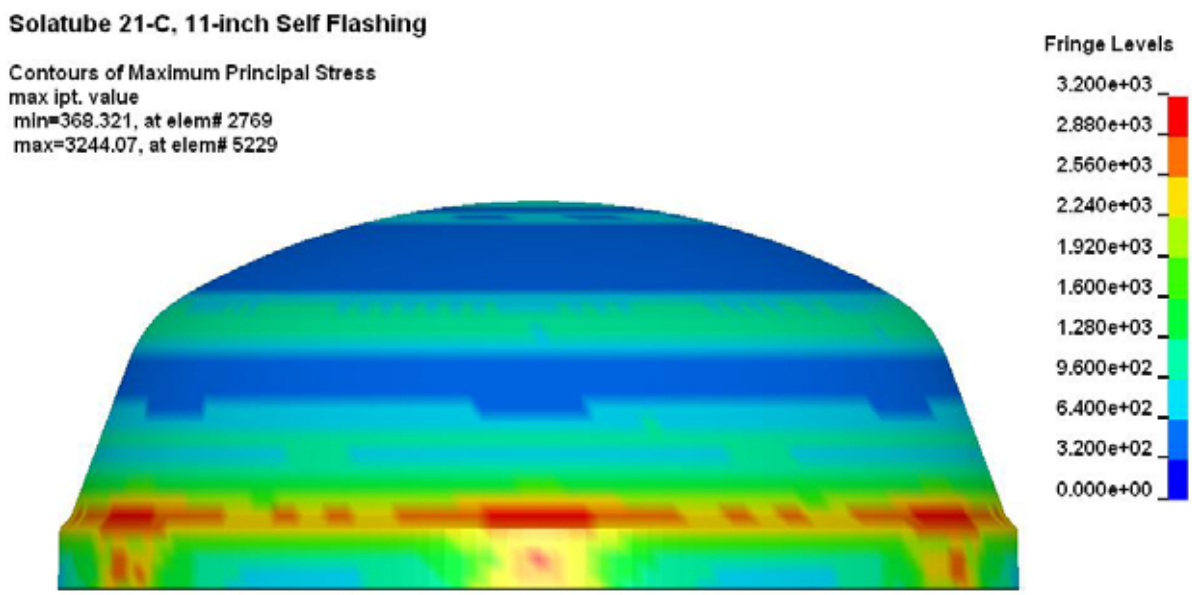

Figure 23. Contours of Peak First Principal Stress in the Acrylic Dome

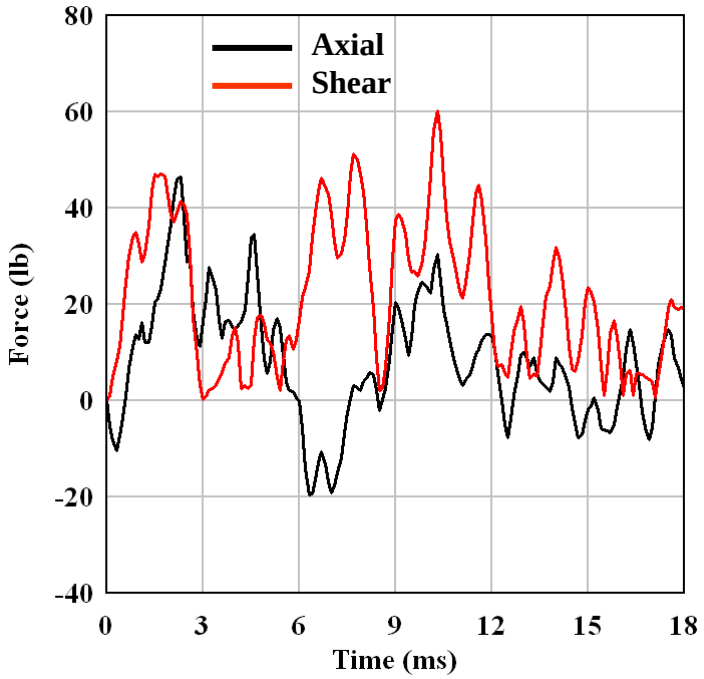

Figure 24. Fastener Reaction Forces Between the Acrylic Dome and Steel Flashing

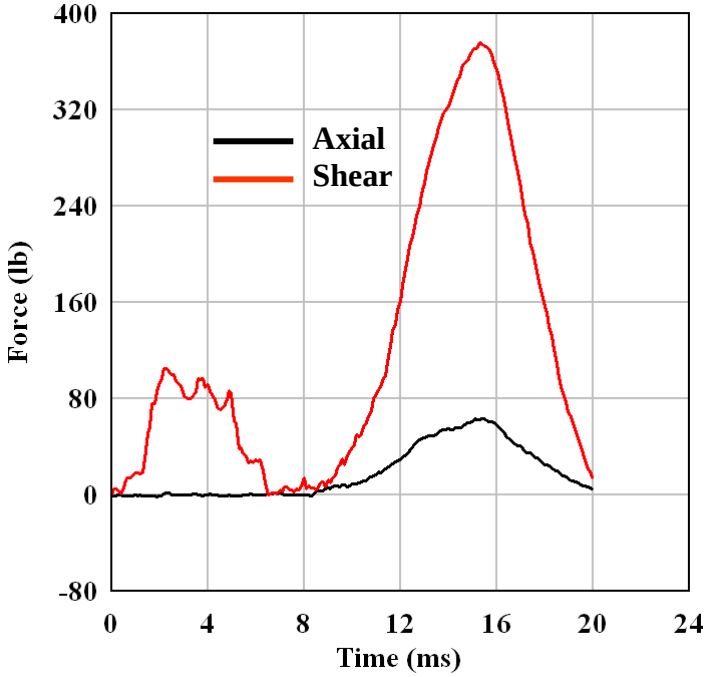

Figure 25. Fastener Reaction Forces Between the Steel Flashing and Roof

6.0 RESPONSE TO WORST-CASE BLAST LOAD

The blast load described in Section 4.0 comes from the +X direction for the finite element model. The acrylic dome rocks back on the flashing support during the positive phase of the pressure loading. The flat portion of the steel flashing, just below the base of the acrylic dome, and the back side of the flashing (-X side) experiences the highest plastic strain (see Figure 26). At the end of the positive phase (13 ms) the peak plastic strain in this area is 0.0231, which represents an equivalent localized ductility ratio, μ_{equiv}, of 11.1.

The rebound of the skylight assembly noted in Section 5.0 is exacerbated by the negative phase pressure associated with the traveling blast wave. The negative pressure pulls up on the dome during rebound causing a significant increase in fastener forces. The upward pull on the acrylic dome causes the top edge of the flashing to crimp, resulting in severe plastic strain at this location at late time, as shown in Figure 27.

Figure 28, Figure 29, and Figure 30 show the resulting forces in the fasteners connecting the acrylic dome to the flashing. In the model, the dome fasteners are relatively free to rotate due to the separation distance between the dome and flashing. Therefore, the largest forces tend to be axial. Since the load is not uniform, the dome fasteners experience different forces from front to back. The fastener at the rear of the dome (Figure 30) experiences the largest forces, reaching peaks of 184 lb during the positive phase and 348 lb during the negative phase. These loads are significantly higher than the design load case, and it can be expected that the fasteners would fail, unless they are increased to handle the higher threat.

Figure 31, Figure 32, and Figure 33 show forces in three of the sixteen roof fasteners. The largest forces occur during the late time rebound of the skylight assembly in conjunction with the negative phase pressure. The roof is assumed to be a rigid surface in this simulation, so the reaction forces, particularly the late-time rebound forces, can be considered upper bound. The fastener shear forces are larger than the axial forces since the fasteners are located towards the outer edge of the flashing flange. The ribs in the flashing flange (modeled in the finite element model) help increase the bending stiffness of the flange, but not enough to balance the axial and shear forces. The rear fastener experiences the largest forces, reaching 168 lb axial and 1,078 lb shear, which are significantly higher than the design load case due to the added upward force of the negative phase pressure. Again, the fasteners can be expected to fail unless they are increased to handle the higher loads.

The acrylic dome remained elastic in the blast load simulation. Figure 34 shows contours of peak Von-Mises stress in the acrylic dome. The highest Von-Mises stress is 7,090 psi occurring near the rear fastener location. This is 91% of the dynamic yield strength (7,800 psi) of the material. Figure 35 shows contours of peak first principal stress. The peak is 7,855 psi, which is slightly higher than the peak tensile strength of 7,800 psi. A more sophisticated tensile fracture model (rather than relating tensile failure to Von-Mises stress) could result in fracture strain at this first principal stress level.

The PVC dome ring remained elastic during the positive phase of the blast load. However, at

late time when the top of the steel flashing crimps in (see Figure 27), it places severe load on the PVC ring, causing it to go plastic at late time (see Figure 36). The PVC ring reaches a peak plastic strain of 56.4%, which is approaching the elongation limit of 80% (see Table 1).

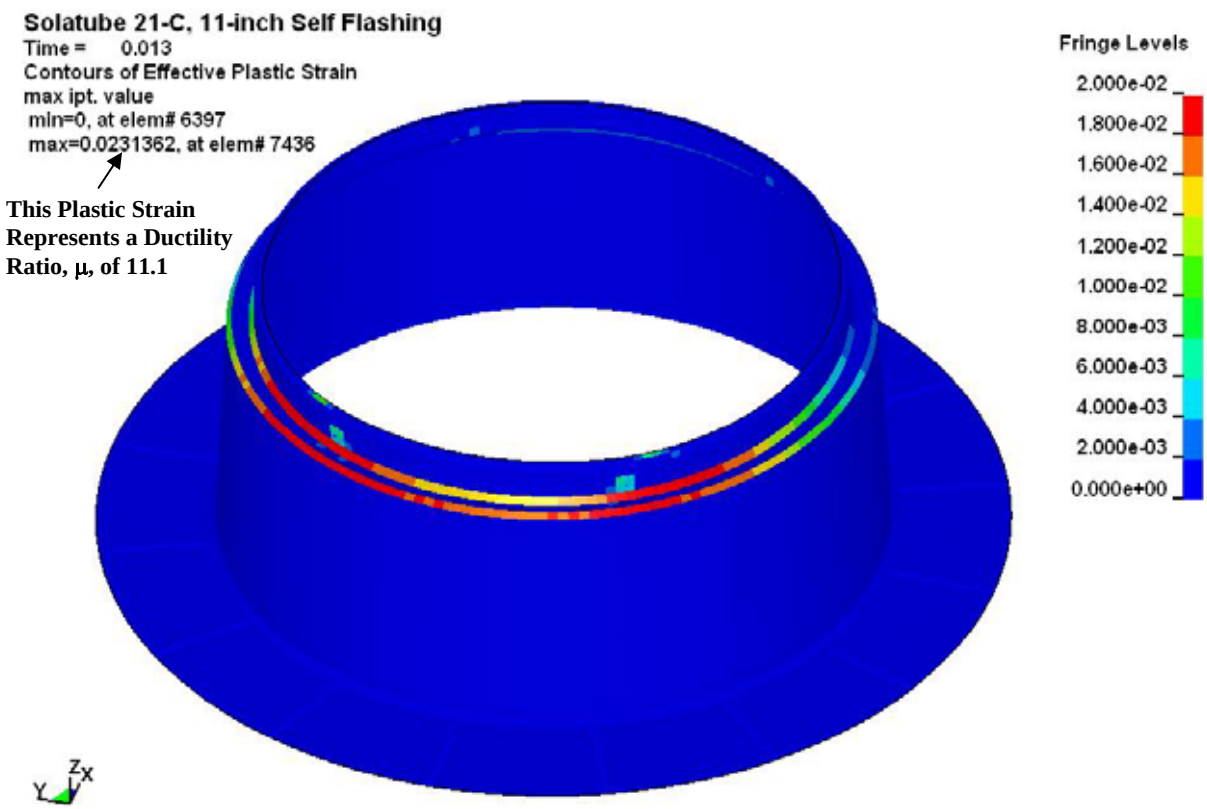

Figure 26. Plastic Strain in the Steel Flashing at 13 ms (End of Positive Phase)

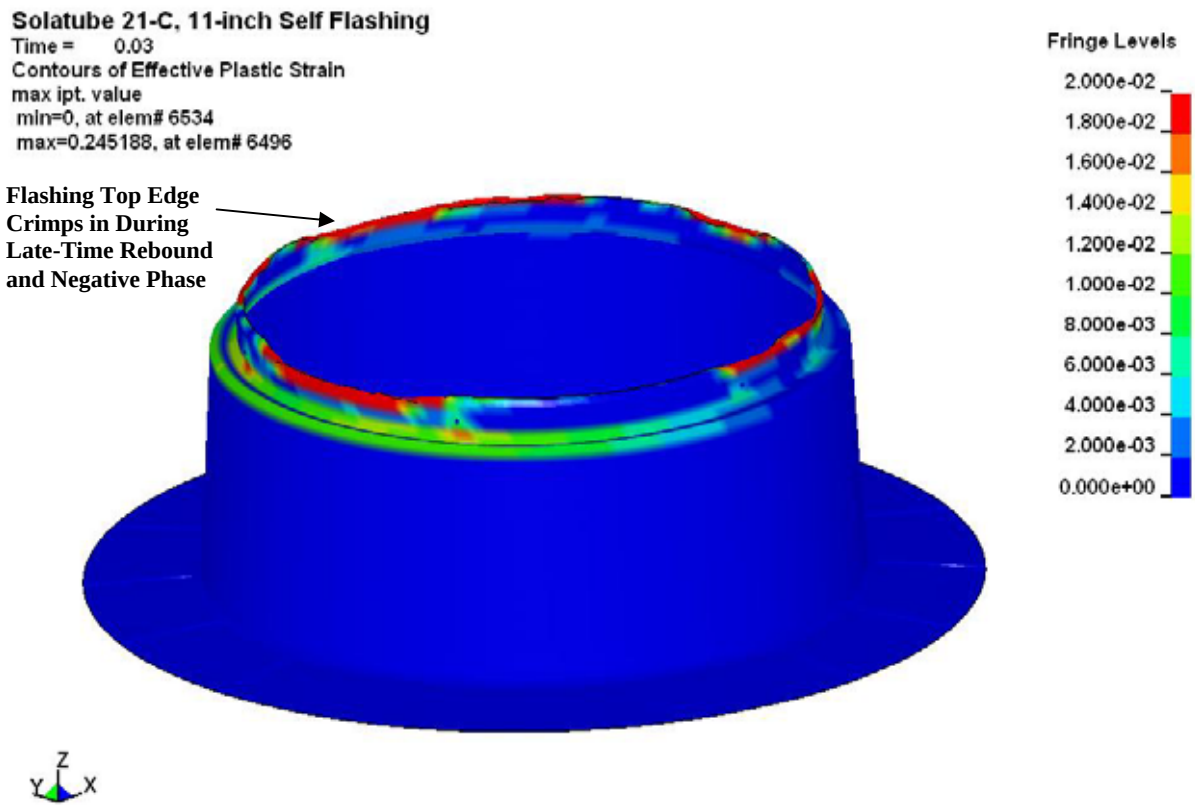

Figure 27. Plastic Strain in the Steel Flashing at 30 ms (End of Negative Phase and Rebound)

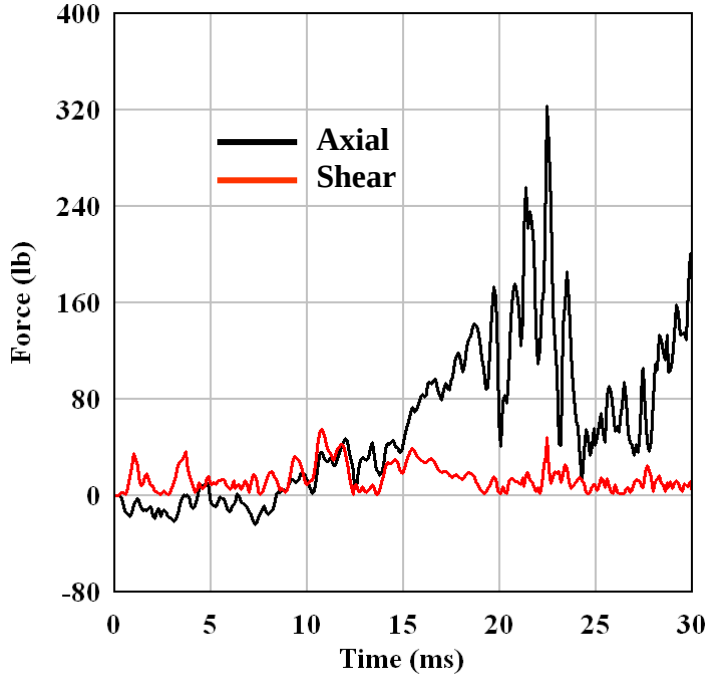

Figure 28. Dome Forward Fastener Forces (30 Degrees Off Centerline)

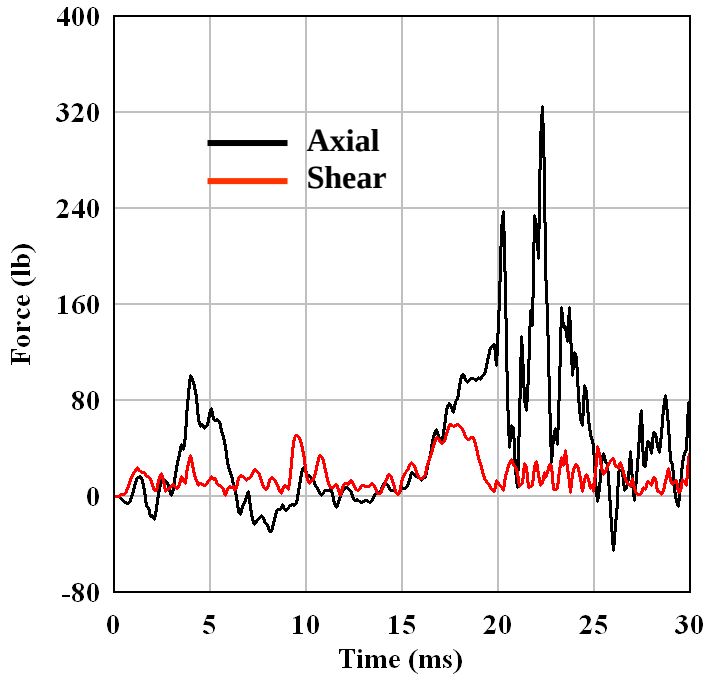

Figure 29. Dome Side Fastener Forces

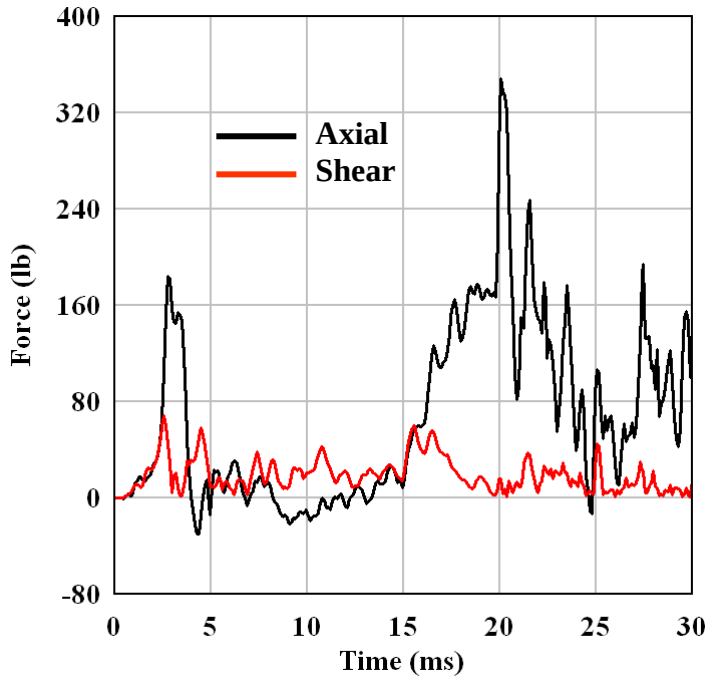

Figure 30. Dome Rear Fastener Forces (30 Degrees Off Centerline)

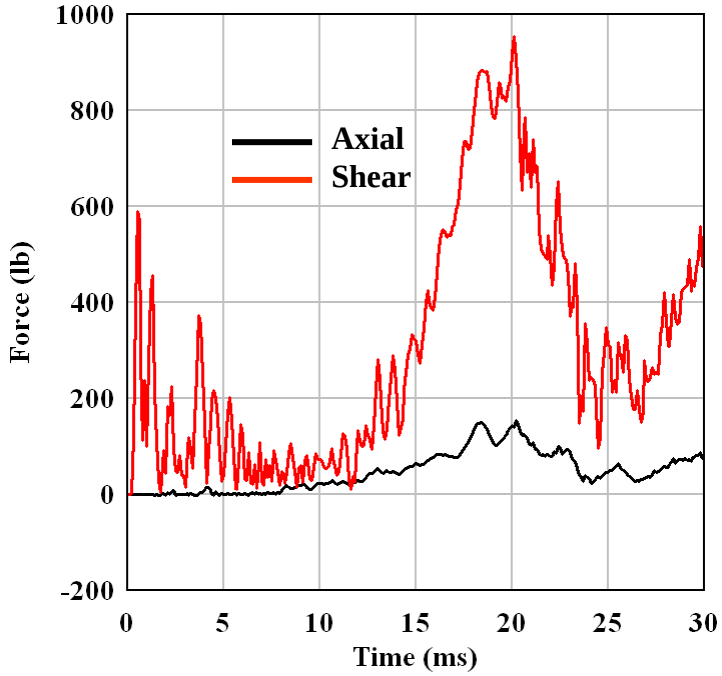

Figure 31. Roof Front Fastener (6 Degrees Off Centerline)

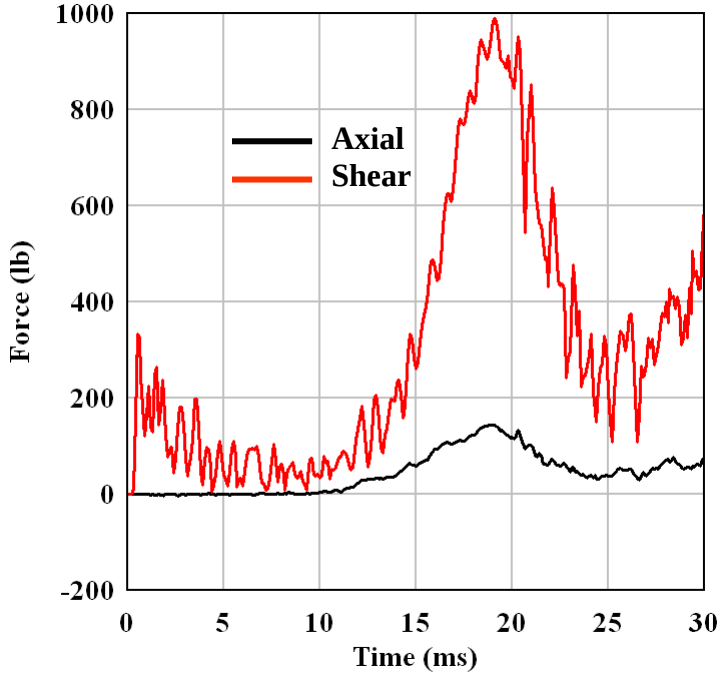

Figure 32. Roof Side Fastener

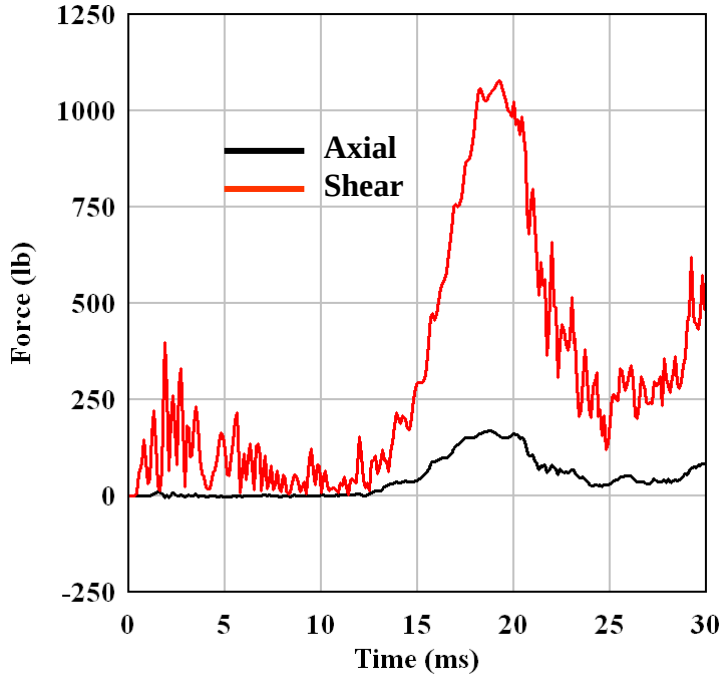

Figure 33. Roof Rear Fastener (6 Degrees Off Centerline)

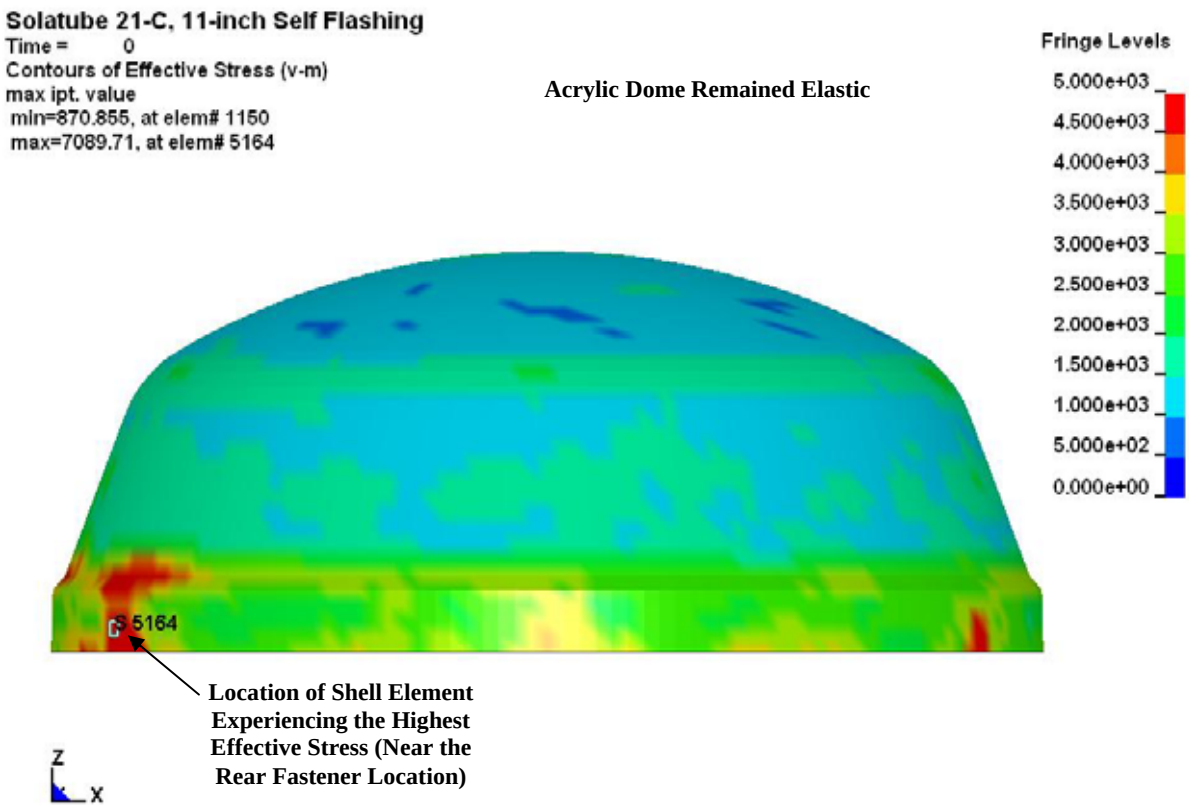

Figure 34. Contours of Peak Von-Mises Stress in the Acrylic Dome

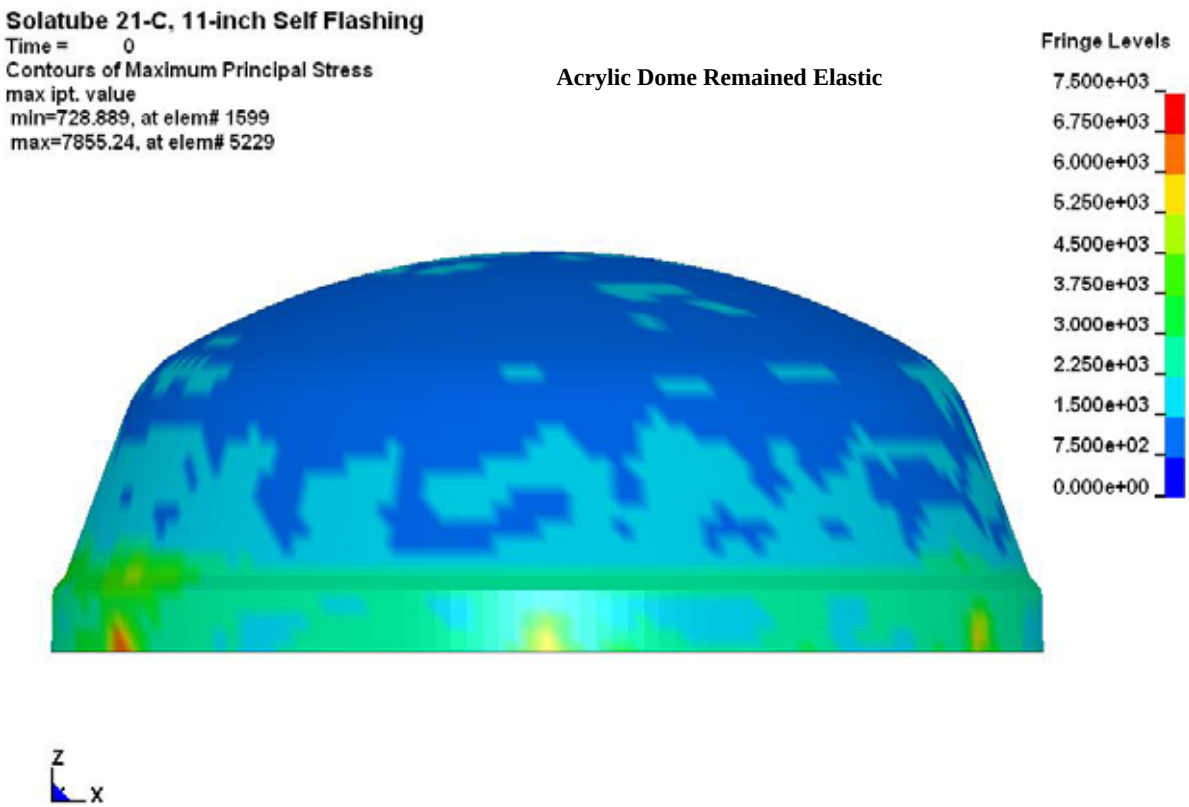

Figure 35. Contours of Peak First Principal Stress in the Acrylic Dome

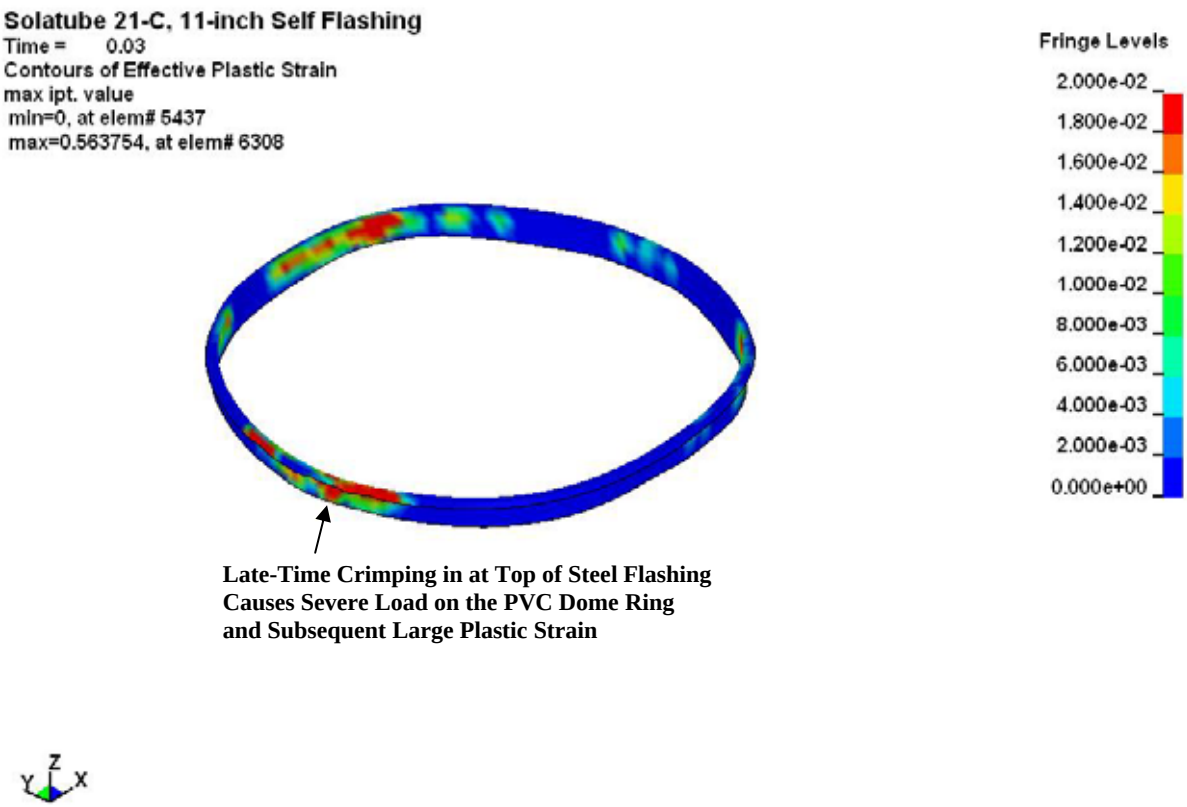

Figure 36. Contours of Plastic Strain in the PVC Dome Ring at Late Time

7.0 SUMMARY

This report summarizes BakerRisk's assessment of the blast capacities for the Solatube 21-C with 11-inch self flashing. Blast evaluations are presented in the form of finite element analysis in response to two blast load cases. The first is the design load case as specified by the United States Army Corp of Engineers. The design pressure load is a right triangular pulse with a peak pressure of 6.3 psi, impulse of 25.1 psi-ms, and load duration of 7.97 ms. In response to the design pressure load, the steel flashing reaches an equivalent localized ductility ratio, μ_{equiv}, equal to 5.8. Relating the equivalent ductility ratio, μ_{equiv}, to a maximum allowable ductility ratio, μ, of 6.0, the response is acceptable for design against blast. Also, the finite element simulation predicts that the skylight will survive the design environment without blowing in to the protected facility. The acrylic dome and the PVC dome ring remain elastic during all phases of response. The nonlinear dynamic finite element analysis confirms that the Solatube 21-C with 11-inch self flashing meets the UFC requirements for the design pressure load.

The six fasteners connecting the acrylic dome to the steel flashing should be #6 sheet metal screws. For connecting the flashing to 26 gage steel roof decking, 36 ¼-inch diameter sheet metal screws are required.

The second load case involves a more intense loading where the skylight is exposed through line of site to the design threat explosive source. For this condition, the exterior surface is loaded with a traveling blast pressure wave. Front surfaces of the skylight experience reflected pressure loads well above free field. In this case, the steel flashing reaches a higher equivalent localized ductility ratio, μ_{equiv}, of 11.1 during positive phase loading. The timing of the skylight rebound and negative pressure phase of the blast loading pushes the steel flashing to localized areas of severe plastic strain. The acrylic dome remains elastic during all phases of response.