

## Impact and Fracture Mechanics Assessment of a Fused Silica Window

**Objective:** Determine the survival probability of a fused silica window subjected to a large particle impact event within a hypersonic wind tunnel using numerical methods (LS-DYNA) and fracture mechanics theories for brittle solids. If damage is predicted, provide an assessment of the windows' service life under repetitive pressure cycling of 14 psi.

**Modeling Assumptions and Details:** A finite element (FE) solid model of a 18" diameter, 1.5" thick disk was constructed based on information provided by the engineering team at Arnolds AFB (see Appendix). The FE model idealized a fused silica window that was potted into a steel frame using Ultracal 60 cement. The window is subjected to a differential pressure of 14 psi during hypersonic wind tunnel operation. This pressure tends to bow the window outward into the wind tunnel (internal side).

It is hypothesized that there exists a potential, during a specific wind tunnel test, for large particle debris (Pyroceram) to impact the window at high velocities (12.27 ft/s tangential and 10.18 ft/s normal to the window). A nominal particle size was determined (see Appendix) and idealized as a sphere with a diameter of 42.90 mm.

Mechanical property data for fused silica and Pyroceram 9606 is presented in the Appendix. It should also be noted that the mechanical properties for fused silica are similar at 25 and 176C. Data for Pyroceram 9606 at 176 C was not available but is believed to follow a similar trend as that for fused silica.

The analysis approach consists of model validation, impact simulation and interpretation of the results using fracture mechanics for brittle solids. Auxiliary static stress models are also used to provide additional substantiation of the fracture mechanics predictions.

The FE model was built using Femap v10.02 and statically analyzed using NX Nastran v6.1. The transient dynamic impact analyses were performed using LS-DYNA v971 R4.2 for the Win64 platform.

### Summary:

(i) Determine stress state in the fused silica window during and subsequent to the impact event using LS-DYNA.

A LS-Dyna model was constructed of the impact event using two simulated particle sizes (42.90 mm (nominal size) and 12.7 mm). Stresses were calculated during and subsequent to the impact event. Impact stresses were found to be highly localized and the overall stress state of the window remains unchanged during and following impact. This result indicates that the particle can hit anywhere on the window and have approximately the same impact response (i.e., impact force on window and stress state within the window). Since fracture is dominantly initiated by tensile stresses, the following key results were determined: (a) the steady-state tensile stress in the window is ~4.0 MPa (580 psi); (b) the nominal particle created a peak tensile stress of ~17 MPa (2,466 psi) and the smaller particle created a peak tensile stress of ~6.3 MPa (910 psi).

(ii) Evaluate the window for its toughness or resistance to impact damage based on standard fracture mechanics principles.

Results from the LS-DYNA model show impact forces of 9,400 N (2,113 lbf) for the nominal particle size (42.90 mm diameter) and 1,060 N (238.3 lbf) for the smaller particle of 12.7 mm. Crack formation on the surface of the window is a function of impact force and sharpness of the contacting particle. A conservative approach was chosen for this analysis where the particle was assumed to be spherical and therefore presents a smooth contacting surface against the window. This allows a direct correlation with experimental fracture mechanics work conducted on fused silica where a spherical indenter having a diameter of 12.7 mm was pressed against a fused silica plate. In this experimental work, small surface cracks were noted at loads greater than 600 N (134.9 lbf). Since the smaller spherical particle is shown to cause surface cracking on the window, fracture mechanics principles would then predict that for sharper particles the probability of surface cracking is even greater. Moreover, as the particles become larger (42.90 mm), the probability of crack formation would likewise scale. This allows one to conclusively state that if particles between the sizes of 12.7 to 42.90 mm impact the fused silica window at the stated velocities, surface cracking will appear on the window.

### Summary: (continued)

*(iii) Provide an engineering assessment of the probability of the window surviving the impact event and if damaged, the largest flaw it could withstand and maintain its structural integrity*

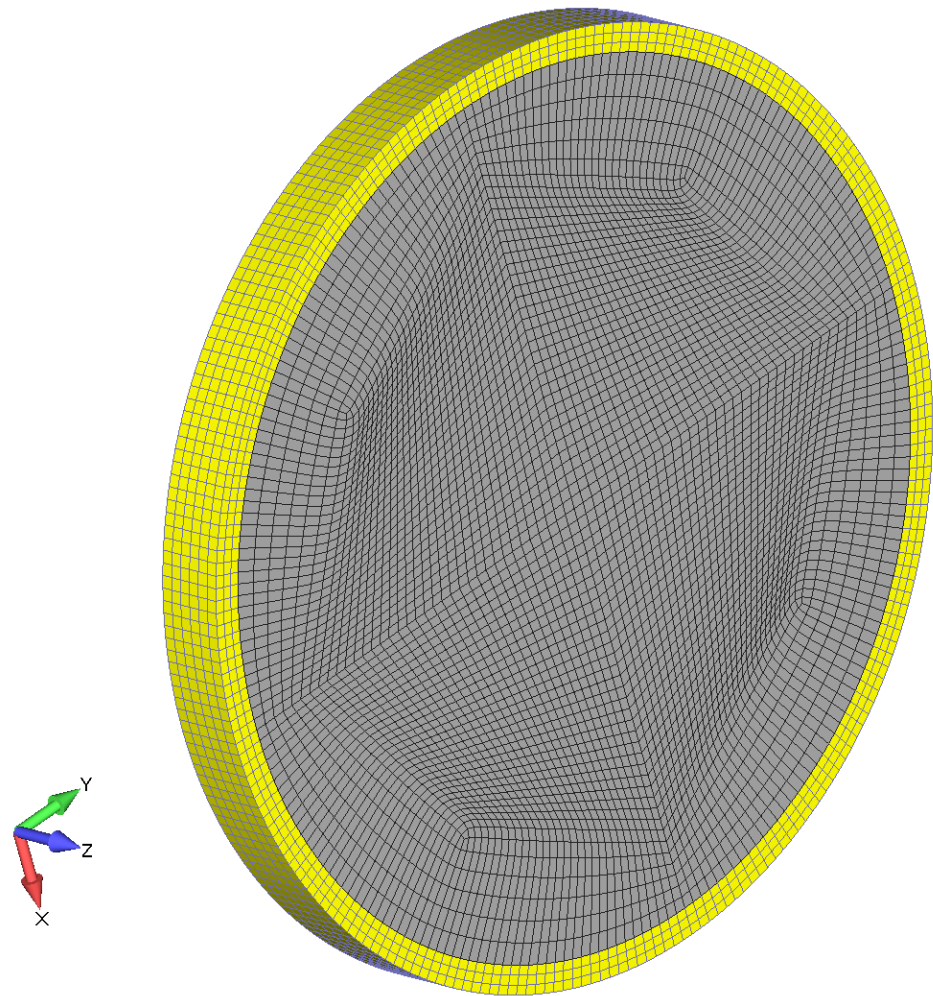
A detailed FEA contact model of the sphere/window system was created to determine the contact stresses due to the particle debris impact. The load for this model was the maximum contact force of 9,400 N (2,113 lbf). Stress results from this model were then used to drive the fracture mechanics calculations. In this work, it was argued that a crack of 5.7 mm (0.226") deep would form during the impact event. Given a fused silica fracture toughness of  $0.75 \text{ Mpa}\cdot\text{m}^{0.5}$ , calculations show that the window is able to withstand this flaw size and remain stable. That is, the catastrophic flaw size for the window under a differential pressure of 14 psi is 8.4 mm (0.331"). Therefore, the window should not fail during impact from Pyroceram debris.

The probability of window failure during the impact event is based on engineering judgment since no direct calculations exist. In this work, the worst possible particle configuration was assumed, that is, spherical. This assumption provides the absolute maximum impact force. From this analysis, the impact event was predicted to create a 5.74 mm deep crack. However, the propagation of this crack into the window for catastrophic failure is driven by the windows' steady-state tensile stress field due to the differential pressure load and is decoupled from the impact event. Hence, if the particle hits away from the center of the window (i.e., outer radial impact), the impact induced crack will be more stable (lower tensile stress in the window) and less likely to cause failure of the window. Overall, given the conservative nature of this analysis and that the particle would have to hit near the center of the window, the probability of the window failing in a catastrophic manner is highly unlikely.

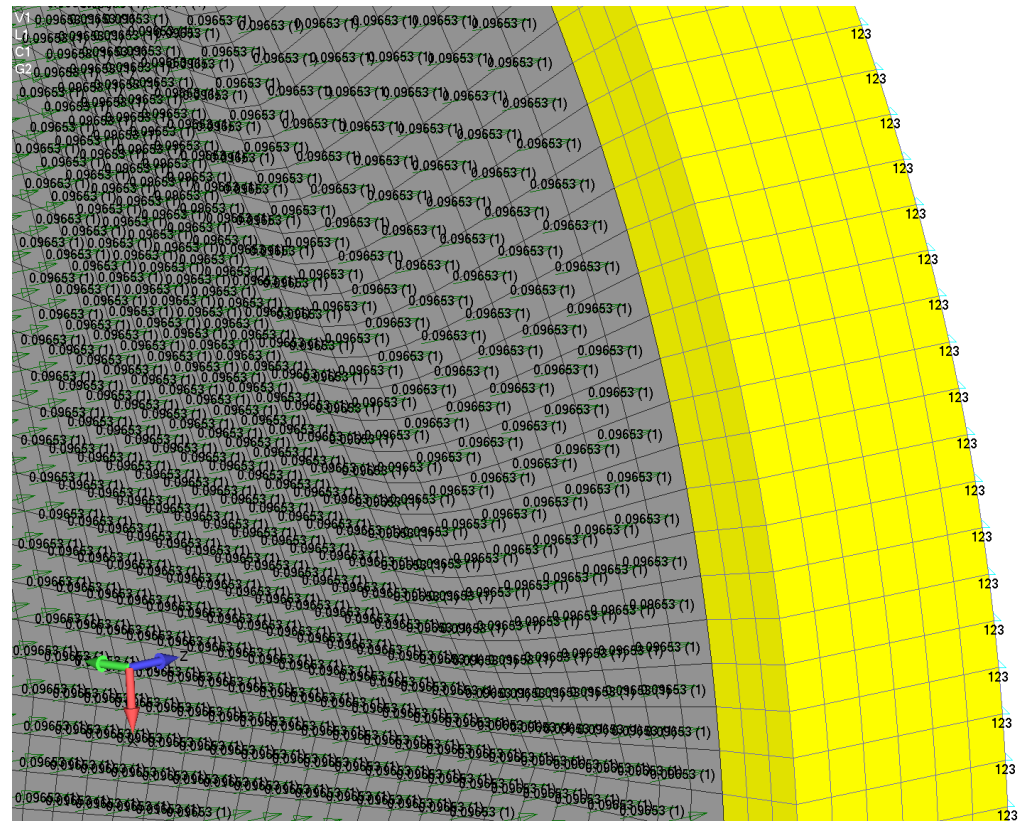
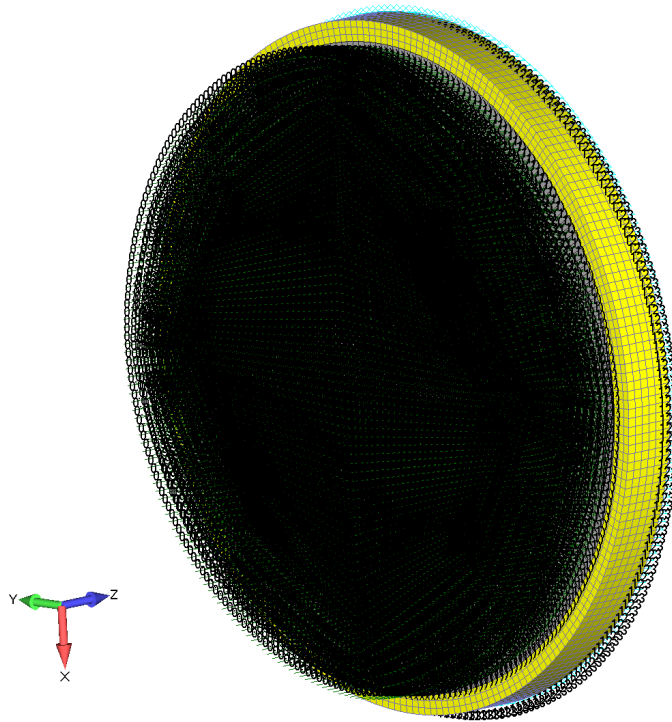
Long term stability of the window is difficult to predict since fused silica (glass) will tend to weaken due to moisture exposure. If the wind tunnel remains a dry environment then the impact induced crack should remain stable and not propagate during wind tunnel pressure cycling. It should be noted that the tolerable crack size is 8.4 mm (0.331") and visual inspection should be able to detect a crack that is larger than 1/4<sup>th</sup> of an inch.



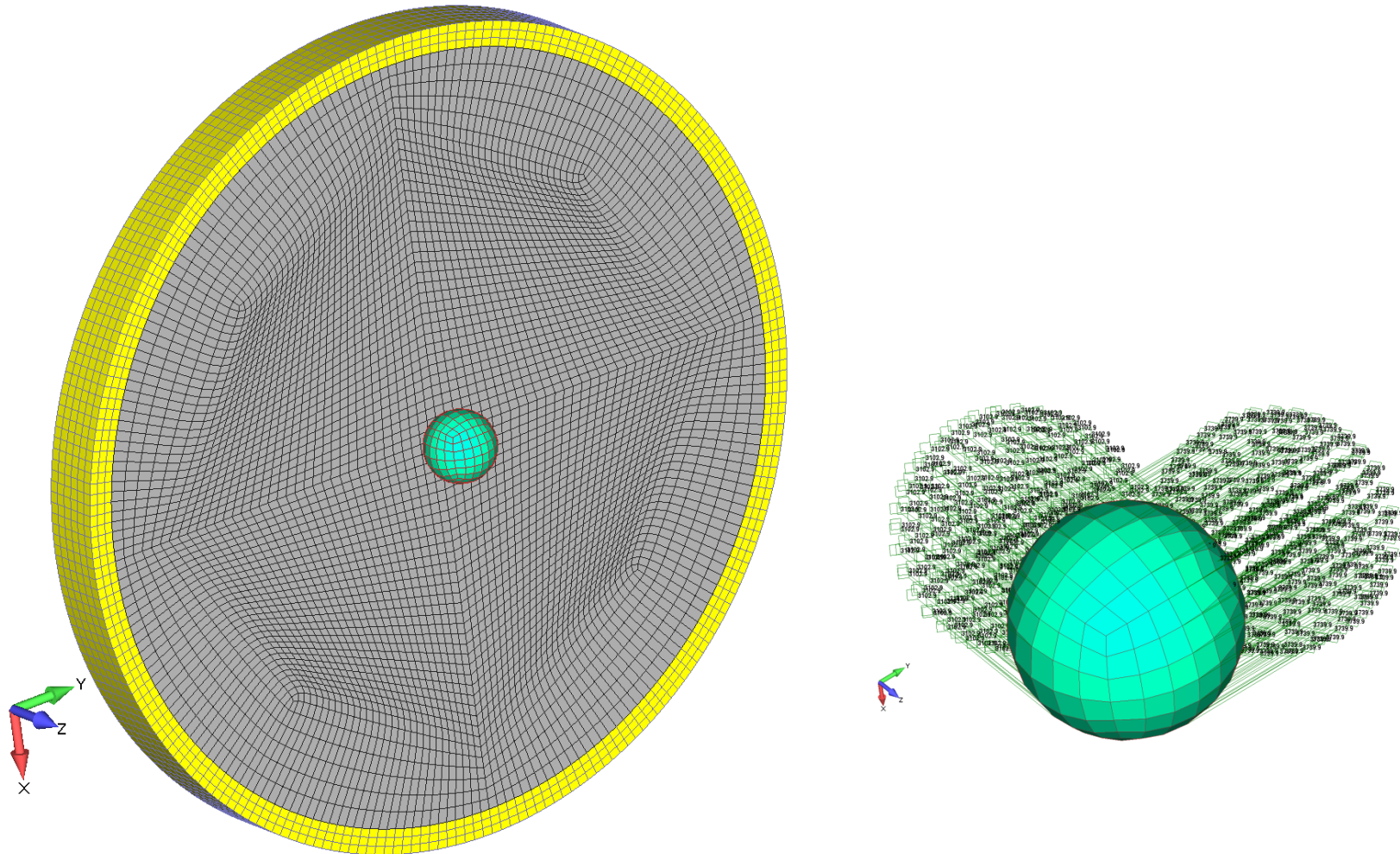
## Analysis Model and Boundary Conditions



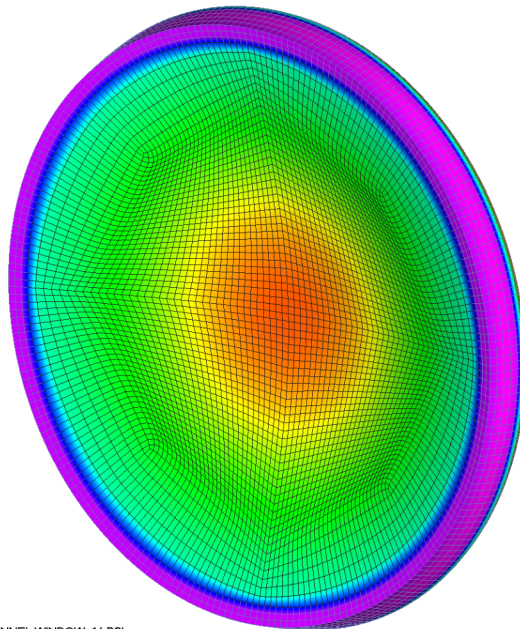
A finite element (FE) model was built of the 18" diameter, 1.5" thick fused silica wind tunnel observation window. The yellow band denotes the Ultracal 60 cement that was used to pot the window into the wind tunnel structure. It was included in the FE model to provide a more accurate boundary condition simulation.



A differential pressure of 14 psi was applied to the model (line symbols on the back surface of the window model (observer side)). Units for this analysis were N, mm, kg, second. As such, the differential pressure of 0.09653 N/mm<sup>2</sup> was applied. The model was constrained on the outer edge of the Ultracal 60 cement (the symbols 123).

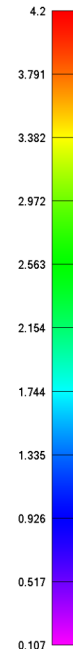


The particle debris (Pyroceram 9606) was idealized as a spherical particle. The weight of the particle was given as 0.24 lb (0.109 kg) with a material density of 161.6 lb/ft<sup>3</sup> (2.589x10<sup>-6</sup> kg/mm<sup>3</sup>). This data therefore defined the diameter of the particle as 42.9 mm. The impact velocity of the debris was provided as 12.27 ft/s (3739.9 mm/s) tangential and 10.18 ft/s (3102.9 mm/s) normal to the window. Note: see Appendix for additional details.



Output Set: ARNOLD AFB FUSED SILICA WIND TUNNEL WINDOW: 14 PSI  
Deformed(0.0503): Total Translation  
Contour: Solid Von Mises Stress

4.2 MPa (599.2) psi



### Wind Tunnel Viewport Window

$$\text{Pressure}_{\text{Load}} := 14 \frac{\text{lbf}}{\text{in}^2}$$

$$\text{Fused}_{\text{SilicaPoissons}} := 0.17$$

$$\text{Window}_{\text{Radius}} := 9 \text{ in}$$

$$\text{Window}_{\text{Thickness}} := 1.5 \text{ in}$$

$$\text{Disk}_{\text{Stress}} := \frac{3 \cdot (3 + \text{Fused}_{\text{SilicaPoissons}}) \cdot \text{Pressure}_{\text{Load}} \cdot \text{Window}_{\text{Radius}}^2}{8 \cdot \text{Window}_{\text{Thickness}}^2}$$

$$\text{Disk}_{\text{Stress}} = 599 \frac{\text{lbf}}{\text{in}^2}$$

$$\text{Disk}_{\text{Stress}} = 4.131 \frac{\text{N}}{\text{mm}^2}$$

A stress analysis was performed on the FE model using the given pressure differential of 14 psi. The resulting maximum stress of 4.2 MPa (610 psi) correlated well with the analytical calculation of 4.131 N/mm<sup>2</sup> (MPa) (599.2 psi) using the formula for simply supported disk under a uniform pressure (Timoshenko, Theory of Plates and Shells, 1959).



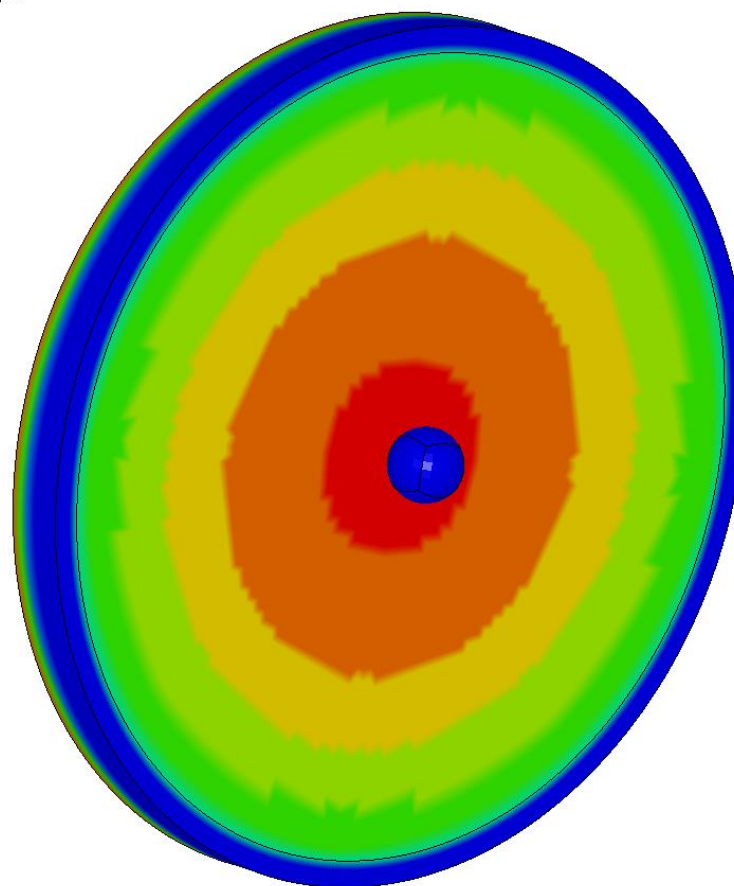
## Impact Analysis of Particle Debris

Analysis Notes: The debris particle (Sphere with 42.90 mm (1.689") diameter) was impacted against the fused silica window at a velocity of 3739.9 mm/s tangential and 3102.9 mm/s normal. The model was used to provide an idea of the peak stress during impact but more importantly, a peak contact force. It is this peak contact force that was leveraged for subsequent fracture mechanics analysis.

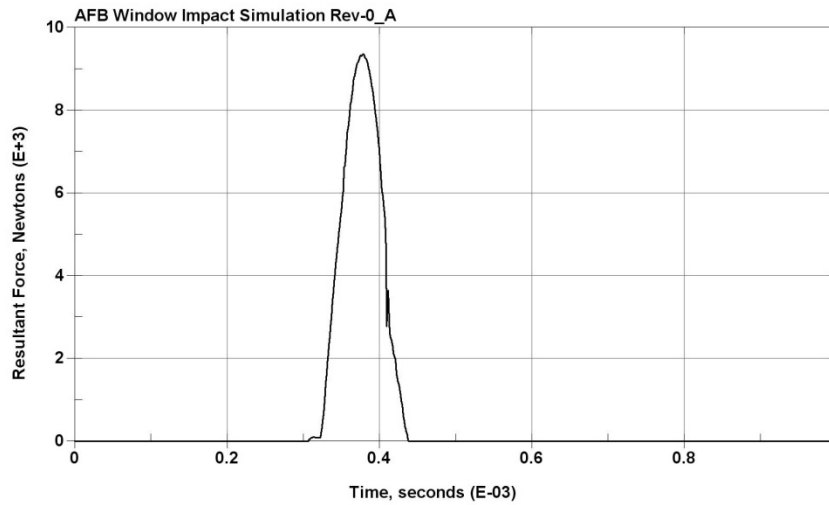
Stresses are presented in N/mm<sup>2</sup> (MPa). Deflections when given are in mm.

**AFB Window Impact Simulation Rev-0\_A**

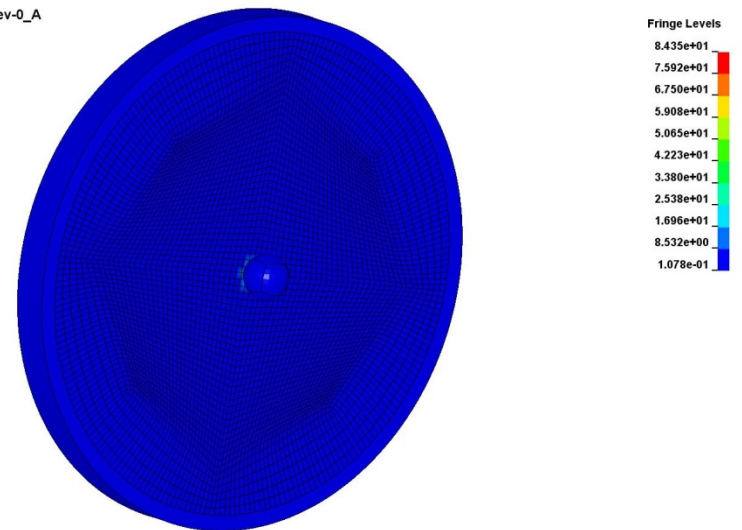
Time = 0  
 Contours of Maximum Principal Stress  
 max ipt. value  
 min=-0.0930296, at elem# 14776  
 max=3.96737, at elem# 100209



At the start of the impact simulation, the window has a maximum tensile stress of 3.967 MPa (575.4 psi) due to the differential pressure of 14 psi between the observer side and the wind tunnel side. This stress result corresponds well to that calculated with the static stress model at 4.2 MPa (610 psi).



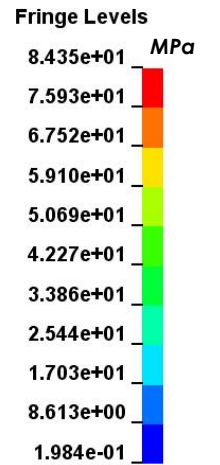
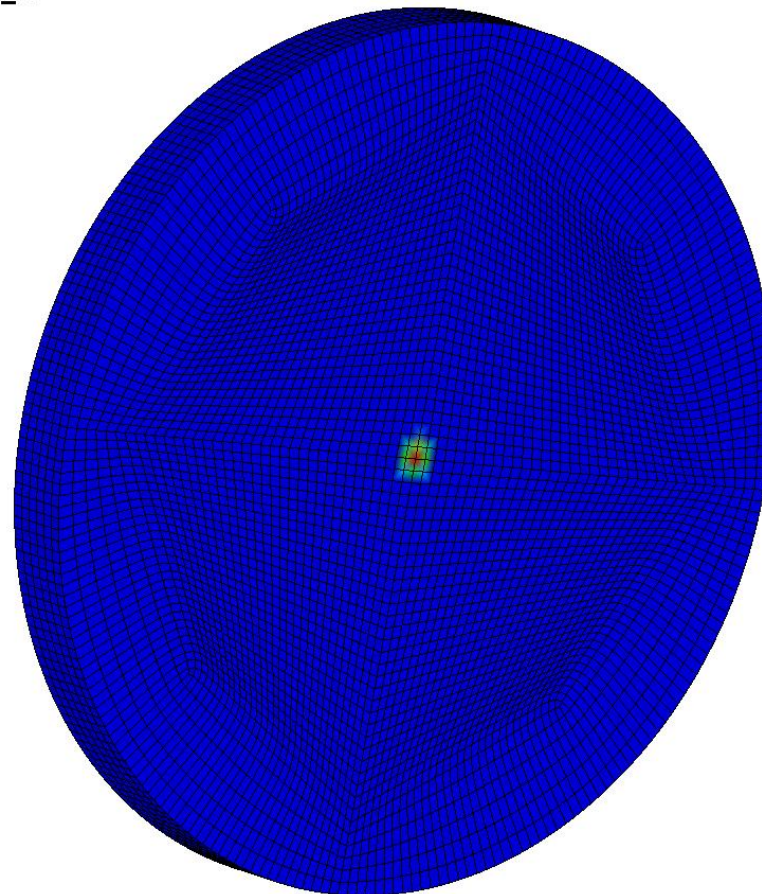
AFB Window Impact Simulation Rev-0\_A  
Time = 0.00037977  
Contours of Effective Stress (v-m)  
max ipt. value  
min=0.107821, at elem# 53257  
max=84.3485, at elem# 21018



The peak contact force during impact is 9,400 N (2,100 lbf). The maximum von Mises stress at peak deceleration is 84.35 MPa (12,230 psi). This stress is compressive and is located under the impacting sphere .

**AFB Window Impact Simulation Rev-0\_A**

Time = 0.00037977  
 Contours of Effective Stress (v-m)  
 max ipt. value  
 min=0.198438, at elem# 40204  
 max=84.3485, at elem# 21018



The maximum von Mises stress at peak deceleration is 84.35 MPa (12,230 psi). This stress is compressive and is located at the point of contact. The overall stress state in the window is only affected locally by the impact. This would indicate that off-center impacts would be identical to the stress state shown here. In other words, the particle can hit anywhere on the window with the same result.

**AFB Window Impact Simulation Rev-0\_A**

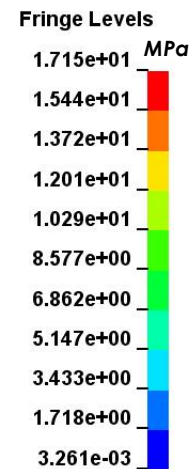
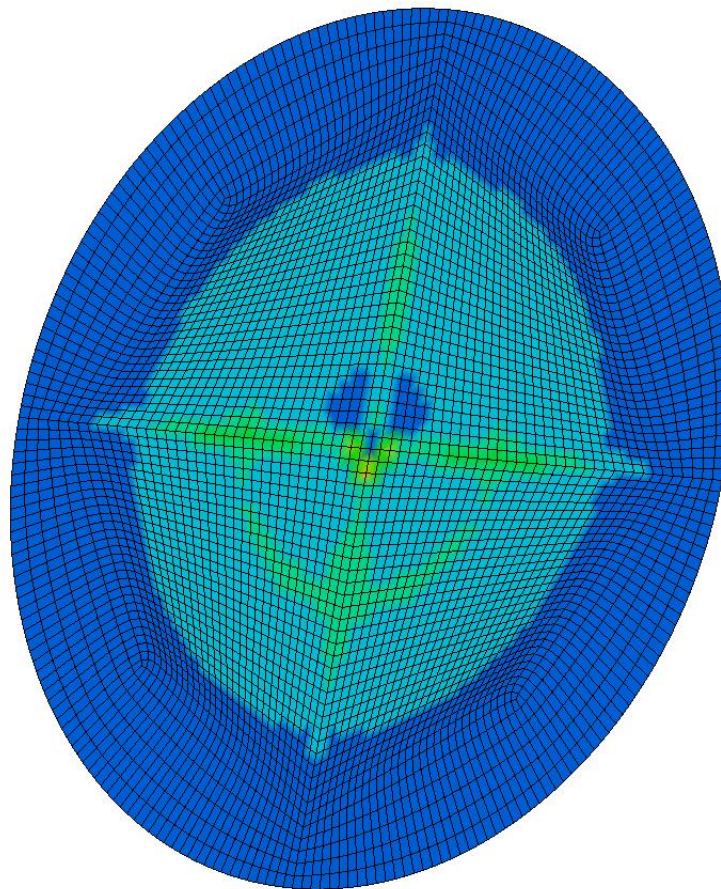
Time = 0.00037977

Contours of Maximum Principal Stress

max ipt. value

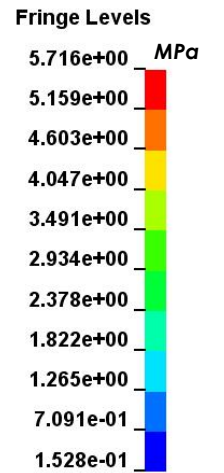
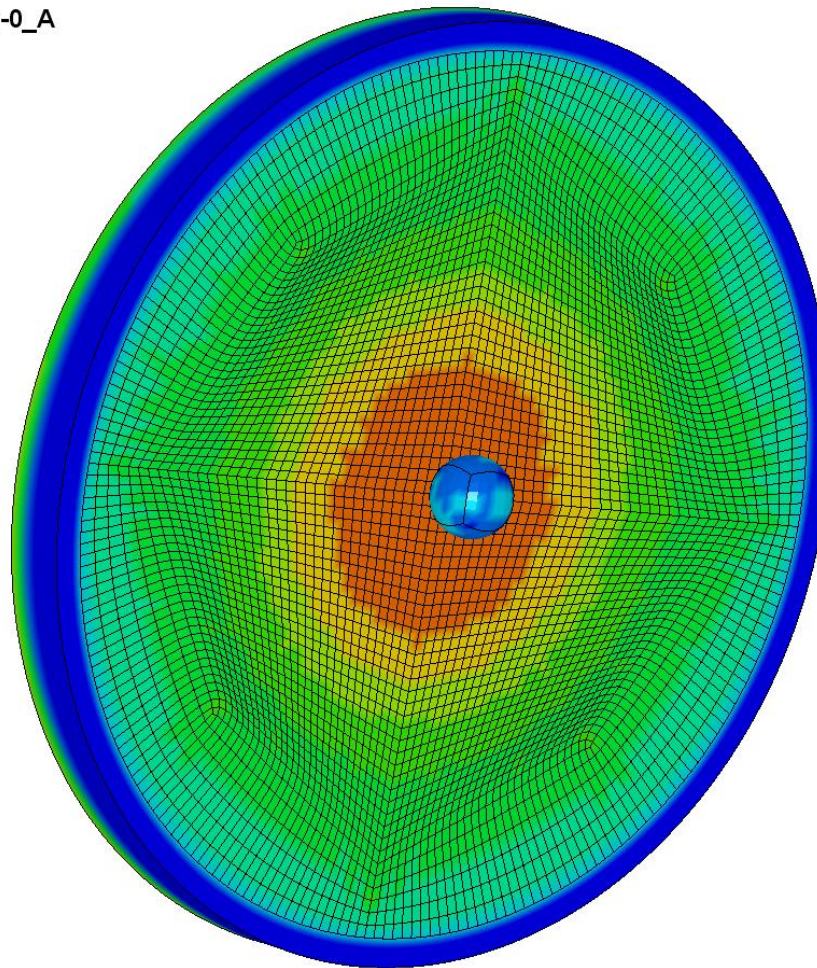
min=0.00326101, at elem# 101469

max=17.1499, at elem# 104168



**AFB Window Impact Simulation Rev-0\_A**

Time = 0.0010001  
Contours of Effective Stress (v-m)  
max ipt. value  
min=0.152805, at elem# 51856  
max=5.7157, at elem# 100385



At the end of the simulation (0.001 second) the stress in the fused silica window is 5.716 Mpa (829.0 psi). Given the static stress state of ~4 Mpa, the disk is noted to settle to its static stress condition very quickly.

## Impact Analysis of Small Particle Debris (diameter of 12.7 mm)

Analysis Notes: A small debris particle (sphere with 12.70 mm (0.50") diameter) was impacted against the fused silica window at a velocity of 3739.9 mm/s tangential and 3102.9 mm/s normal. The rationale for this additional work was driven by the discovery of an article Swain, et al. in *J. Mater. Sci.*, vol. 8, p1153 (1973) where a 12.7 mm tungsten carbide sphere was pressed into a block of fused silica. In their work, it was determined that cone cracks would form in the fused silica at loads greater than 600 N (135 lbf). This work provides a direct method to determine if cracks may form in the wind tunnel window during particle debris impact. That is, if the impact force exceeds 600 N for a 12.7 mm diameter sphere, then there is a high probability that surface cracking will occur in the fused silica wind tunnel window.

Stresses are presented in  $\text{N/mm}^2$  (MPa). Deflections when given are in mm.

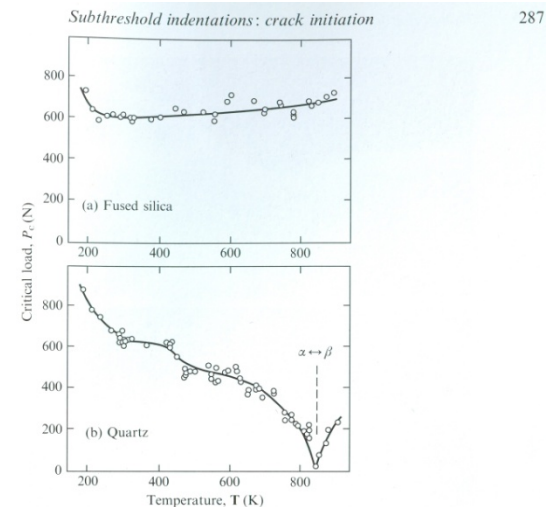
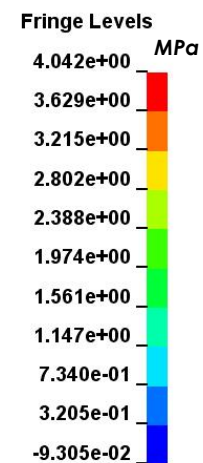
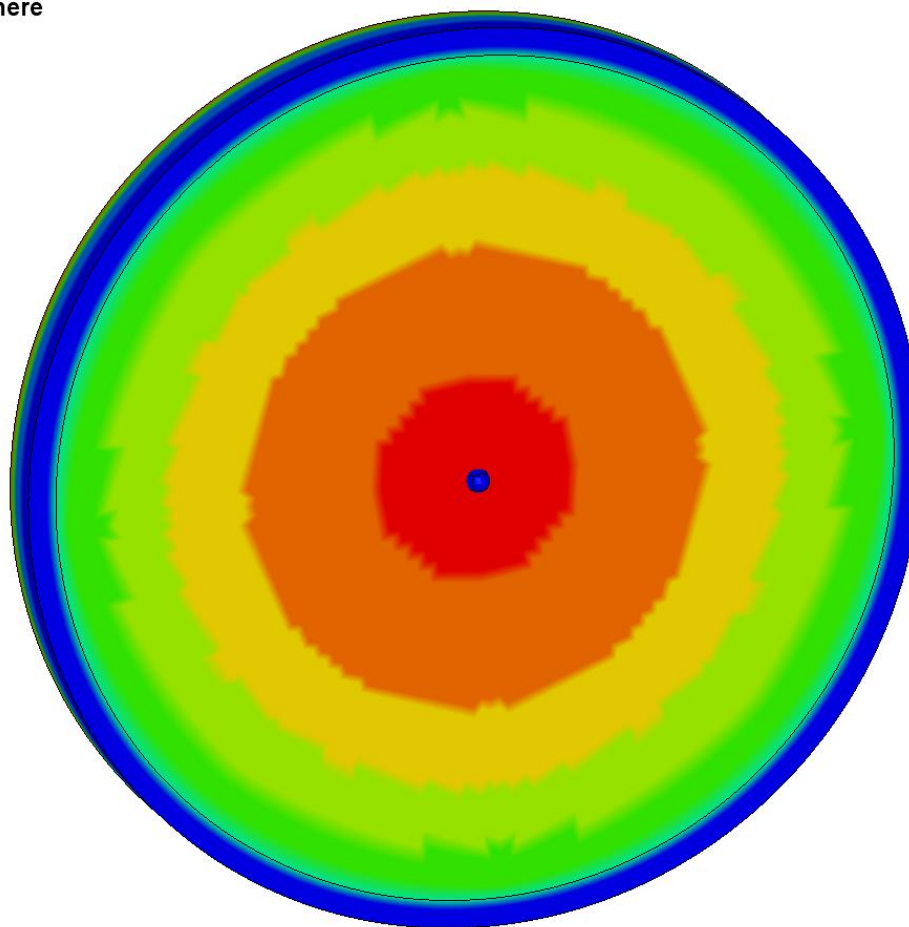


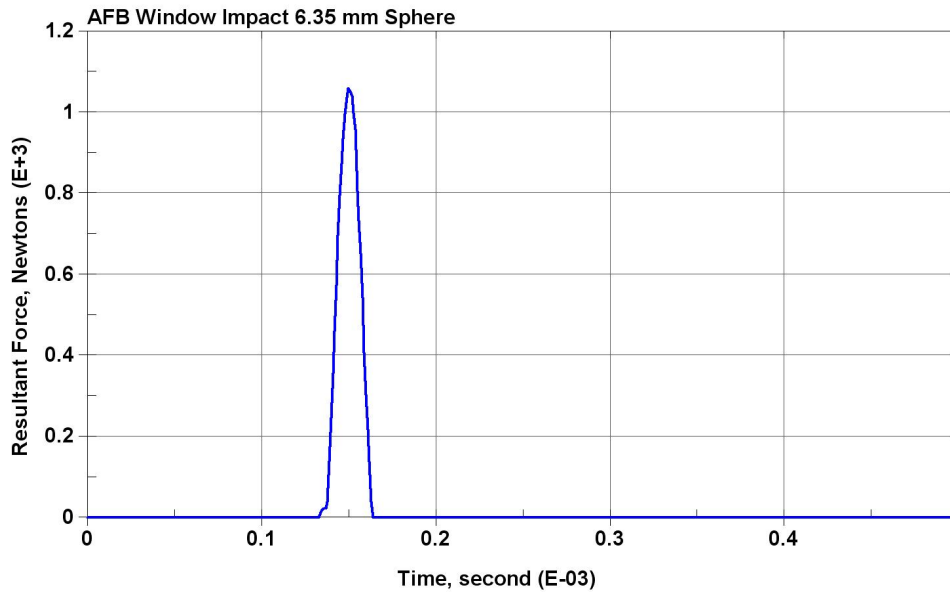
Fig. 8.33. Critical load for cone-crack initiation in (a) fused silica and (b) quartz as function of temperature. Vacuum data on abraded surfaces, tungsten carbide sphere,  $r = 6.35$  mm. (Each data point mean of at least ten tests.) (After Swain, M. V., Williams, J. S., Lawn, B. R. & Beek, J. J. H. (1973) *J. Mater. Sci.* **8** 1153.)

**AFB Window Impact 6.35 mm Sphere**

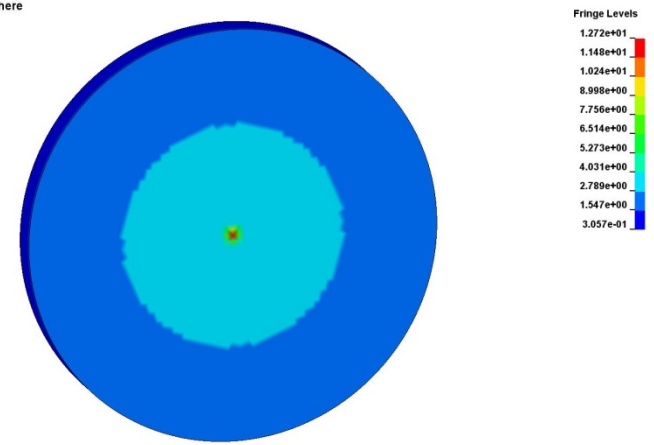
Time = 0  
 Contours of Maximum Principal Stress  
 max ipt. value  
 min=-0.0930489, at elem# 14776  
 max=4.04204, at elem# 100209



At the start of the impact simulation, the window has a maximum tensile stress of 4.042 MPa (586.2 lbf) due to the differential pressure of 14 psi between the observer side and the internal side. This stress result corresponds well to that calculated with the static stress model at 4.2 MPa (610 lbf).



AFB Window Impact 6.35 mm Sphere  
Time = 0.00015  
Contours of Effective Stress (v-m)  
max ipL value  
min=0.305654, at elem# 26231  
max=12.723, at elem# 21018



The peak contact force during impact is 1,060 N (238 lbf). The maximum von Mises stress at peak deceleration is 12.72 MPa (1,845 psi). This stress is compressive and is located under the impacting sphere. What is most important is that the peak contact force exceeds the experimentally measured fracture threshold of 600 N for a 12.7 mm diameter sphere. This result indicates that small surface cracks would form due to debris impact.

**AFB Window Impact 6.35 mm Sphere**

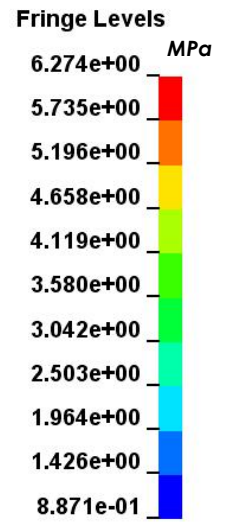
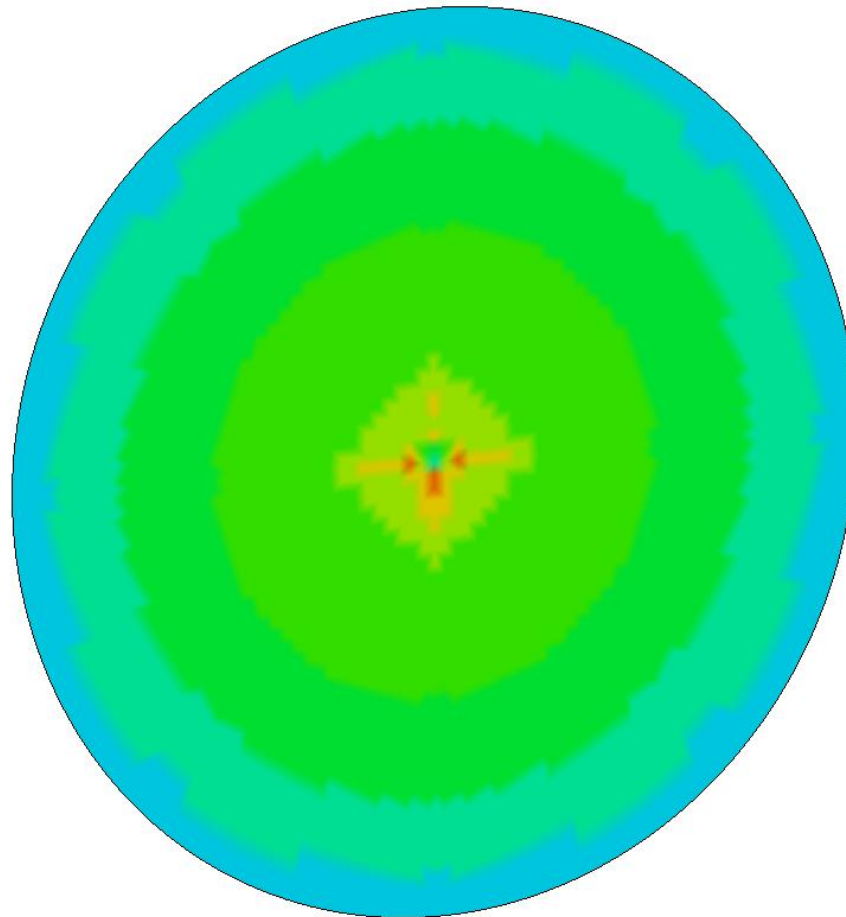
Time = 0.00015

Contours of Maximum Principal Stress

max ipt. value

min=0.887067, at elem# 101469

max=6.27361, at elem# 104168



**AFB Window Impact 6.35 mm Sphere**

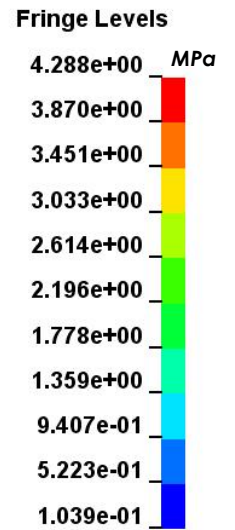
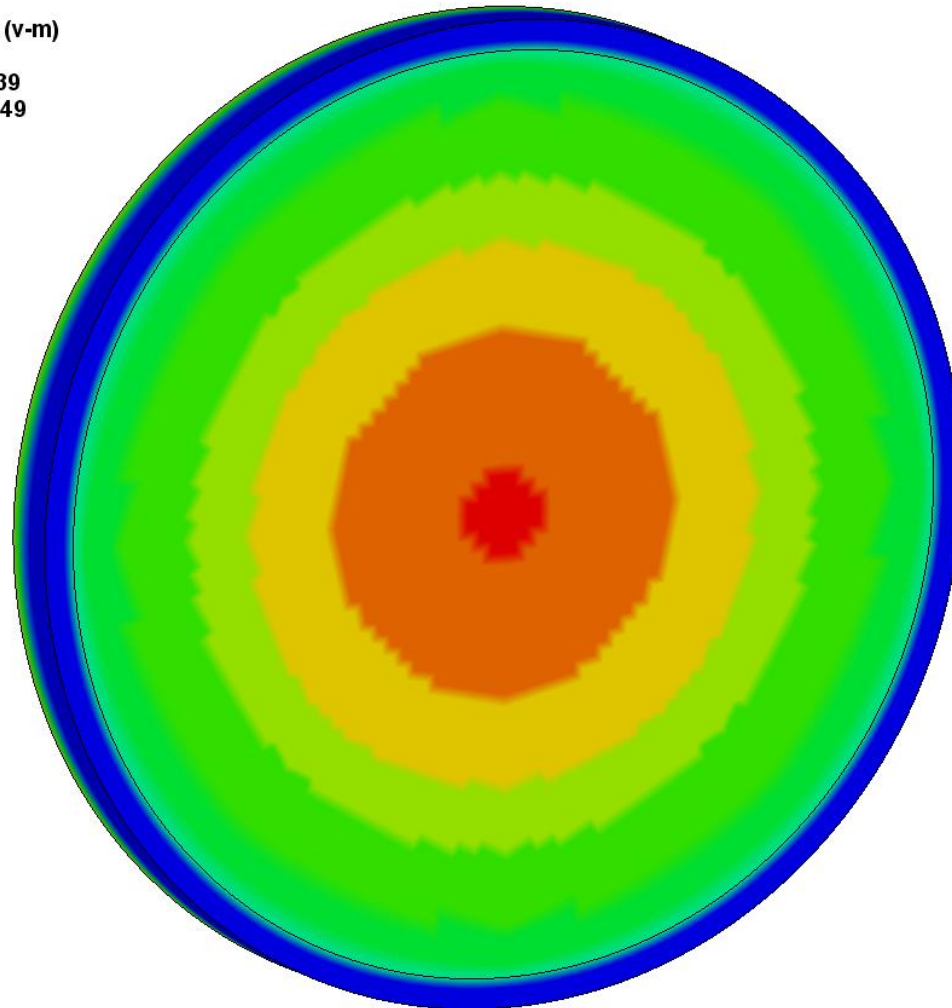
Time = 0.0005

Contours of Effective Stress (v-m)

max ipt. value

min=0.103864, at elem# 52339

max=4.28819, at elem# 102549





## Fracture Mechanics Assessment

Analysis Notes: Crack growth from an impact induced flaw will be assessed based on fracture mechanics principals.

Subthreshold indentations: crack initiation

287

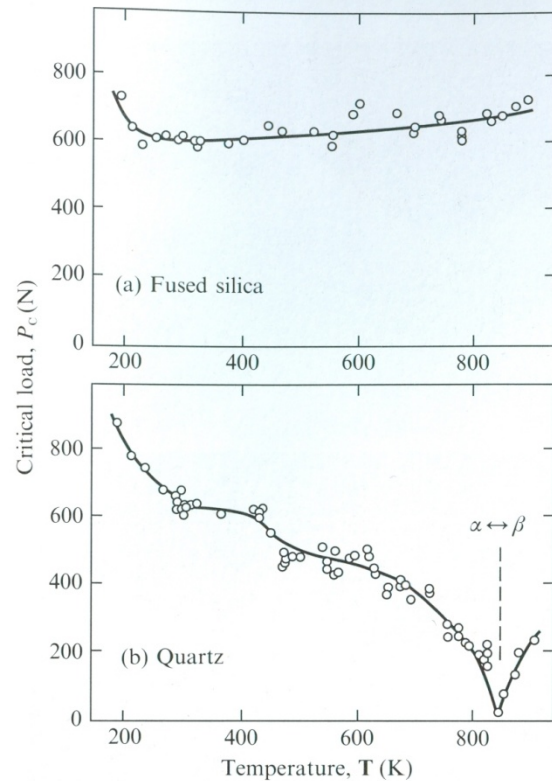


Fig. 8.33. Critical load for cone-crack initiation in (a) fused silica and (b) quartz as function of temperature. Vacuum data on abraded surfaces, tungsten carbide sphere,  $r = 6.35$  mm. (Each data point mean of at least ten tests.) (After Swain, M. V., Williams, J. S., Lawn, B. R. & Beek, J. J. H. (1973) *J. Mater. Sci.* **8** 1153.)

254 Indentation fracture

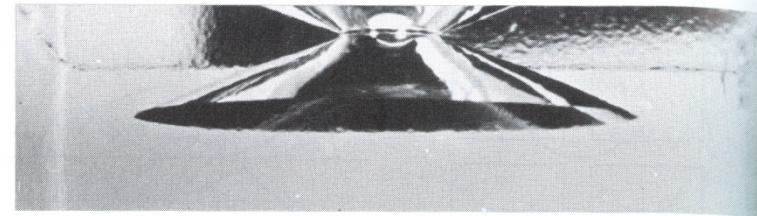


Fig. 8.3. Cone crack in soda-lime glass. Photographed under load ( $P = 40$  kN) from cylindrical punch, optical micrograph (block edge length 50 mm). Crack makes angle  $\simeq 22^\circ$  to free surface. (After Roesler, F. C. (1956) *Proc. Phys. Soc. Lond.* **B69** 981.)

In Figure 8.33 (a), a 12.7 mm diameter indenter is pressed against a flat surface of fused silica. At loads greater than 600 N (135 lbf), cone cracks are noted to form. This effect is unchanged between temperature from 250 to 800 C. At lower temperatures (150 C), the fused silica is more crack resistant but still fails at loads of around 700 N (157 lbf). An example of a cone crack is shown on the right.

286 Indentation fracture

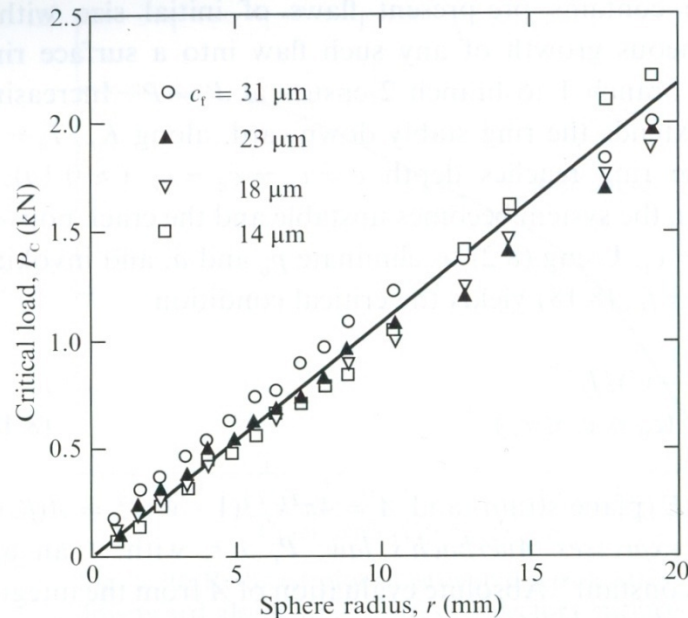
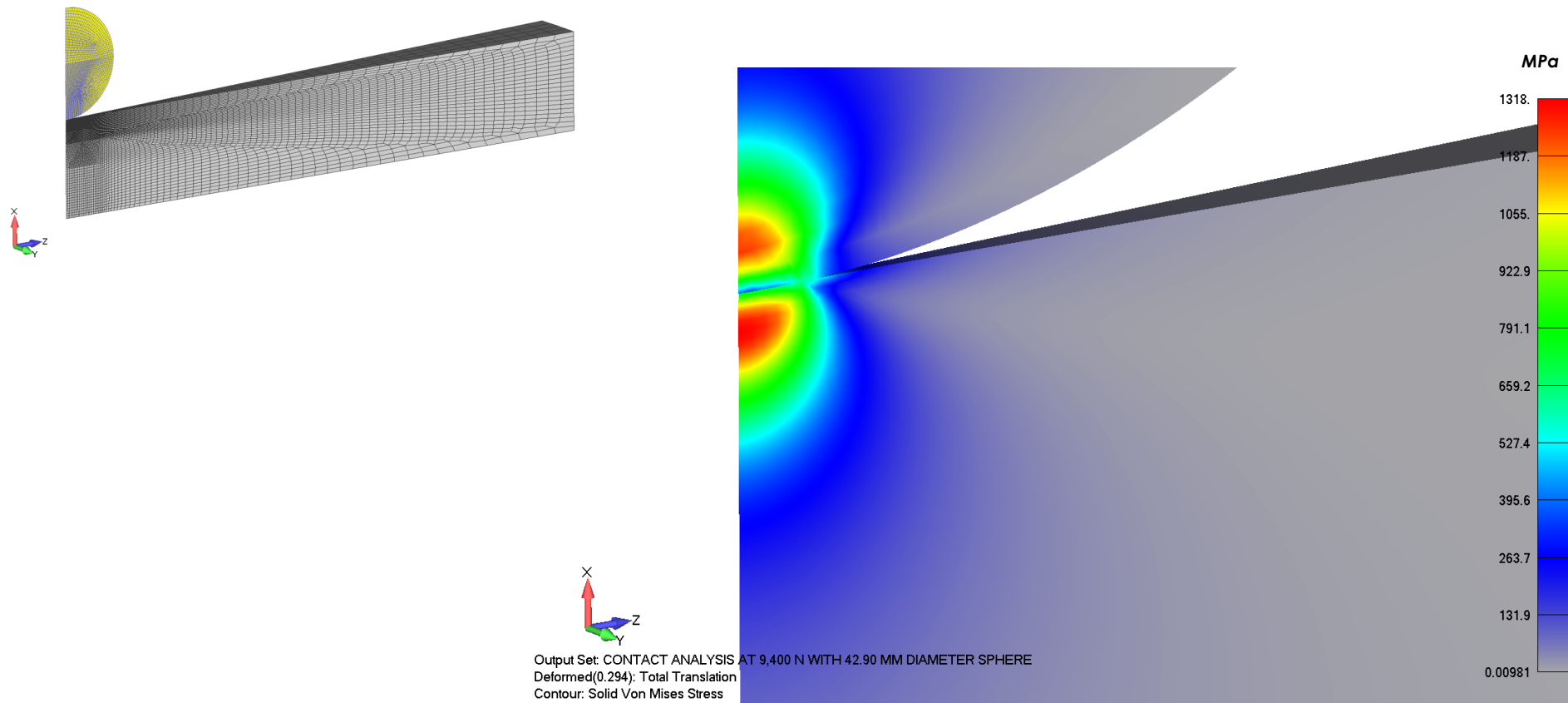
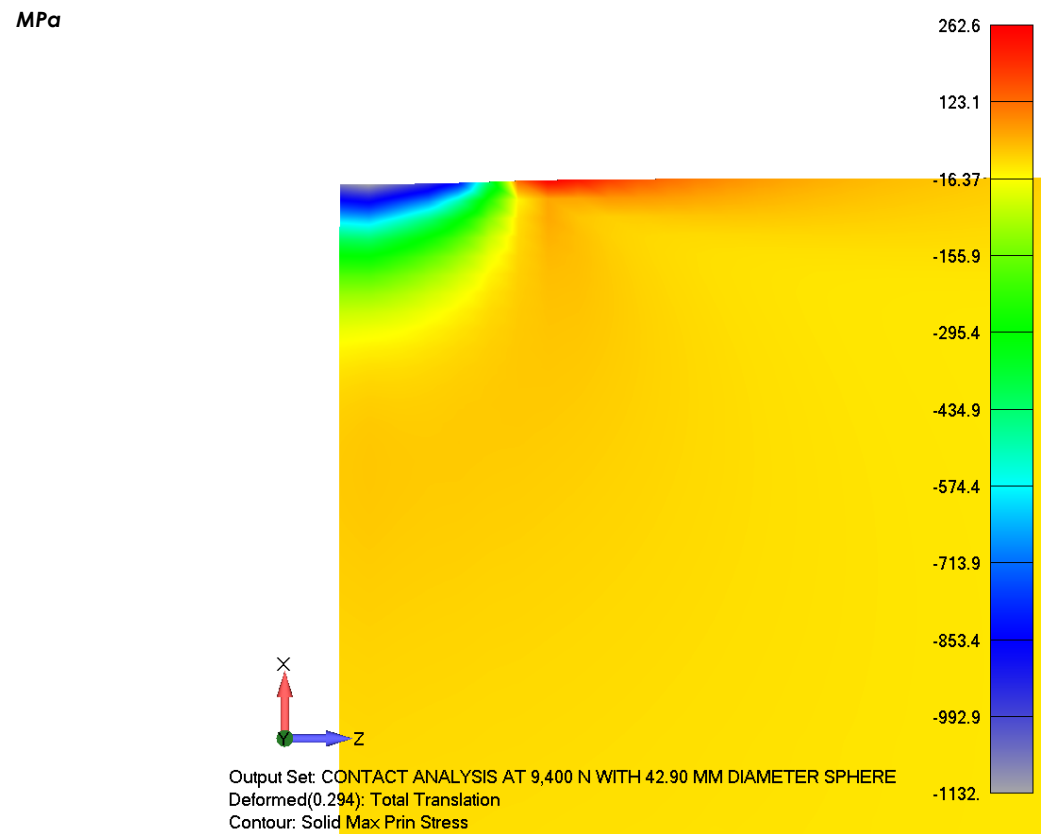
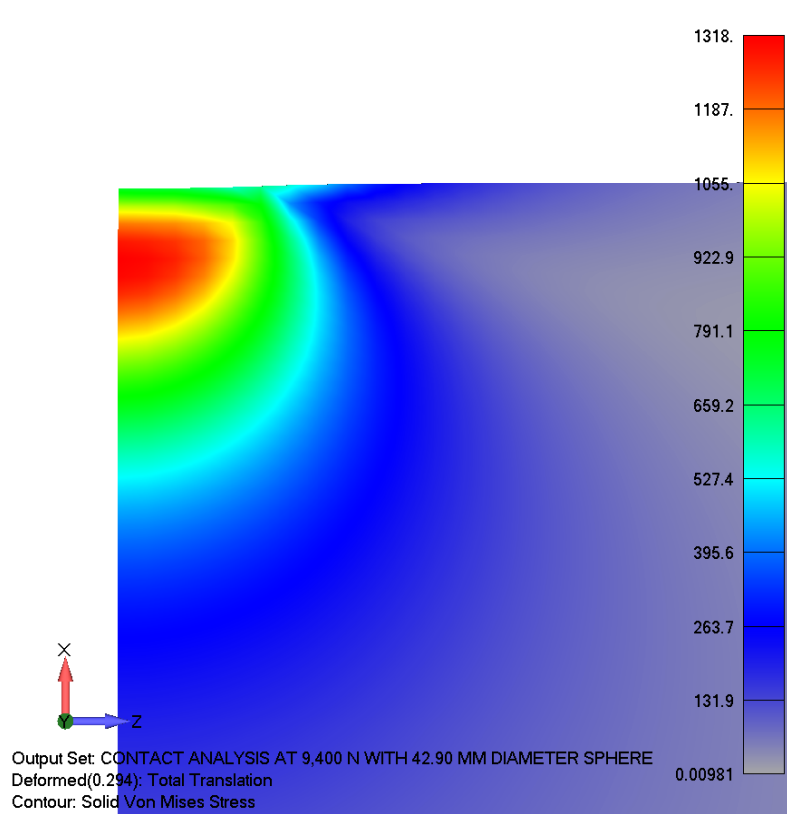


Fig. 8.32. Critical load for cone-crack initiation, as function of indenter radius on soda-lime glass. Glass surfaces pre-abraded to produce controlled flaws, sizes  $c_f$  indicated. (Each data point mean of at least ten tests.) Note Auerbach's law,  $P_c \propto r$ , insensitive to initial flaw size. (After Langitan, F. B. & Lawn, B. R. (1969) *J. Appl. Phys.* **40** 4009.)

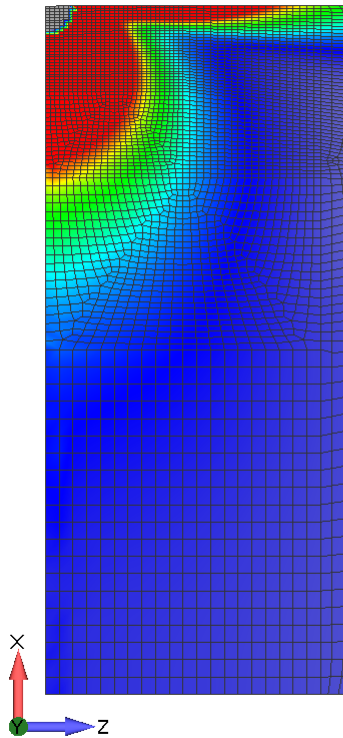
This figure presents data for cone cracking as a function of load (kN) and indenter radius in soda-lime glass. It can be assumed that the same trend would hold for fused silica. Data at a sphere radius of 20 mm is approximately close to the nominal particle size of 21.45 mm (42.90 mm diameter) to be of engineering use. At the figure's maximum sphere radius, the maximum normal load is 2,100 N (472 lbf) for cone-crack formation. LS-DYNA results calculate a maximum normal load of 9,400 N (2,110 lbf). This value exceeds the limit shown in the above figure and a high probability of cone-crack initiation is predicted for the wind tunnel impact event.



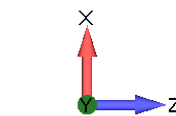
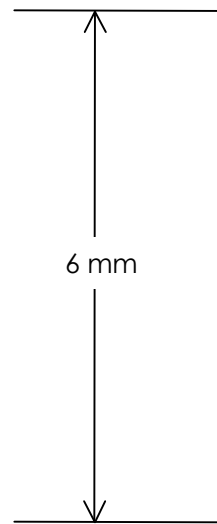
A contact analysis was performed using a 42.90 mm sphere under a load of 9,400 N (2,110 lbf). The maximum von Mises stress (dominantly compressive) is 1,318 MPa (191,200 psi).



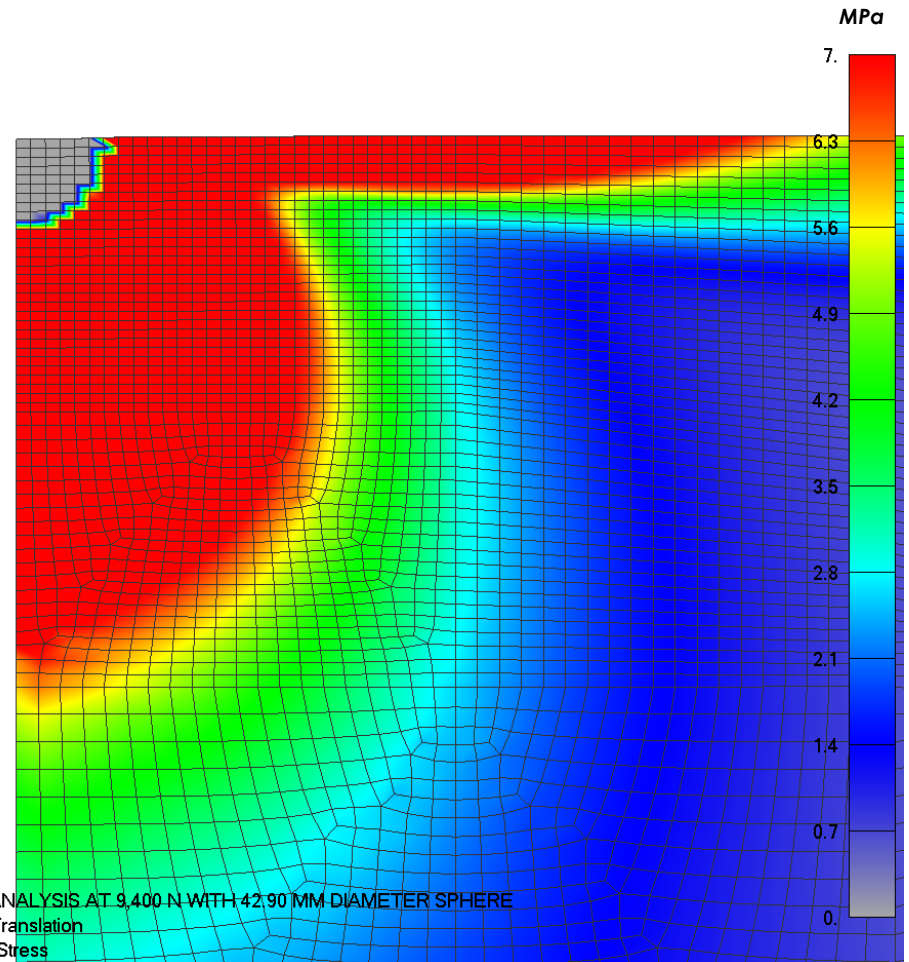
Although high compressive stresses are developed directly beneath the indenter (sphere), tensile stresses (image on the right) are much less with a maximum at 262.6 MPa (38,090 psi). It should be noted that the contact tensile stress of 38,000 psi is more than sufficient to create a crack in fused silica.



A section of the FEA model of the fused silica window under impact from the 42.90 mm particle. Tensile stresses are formed due to the contact behavior.



Output Set: CONTACT ANALYSIS AT 9,400 N WITH 42.90 MM DIAMETER SPHERE  
Deformed(0.294): Total Translation  
Contour: Solid Max Prin Stress



The Solid Max Prin Stress (maximum principal stress) is contoured over the fused silica section. This stress component is dominantly tensile. In this view, the stress legend is capped at 7 MPa (1,000 psi) to bracket the extent of the 7+ MPa tensile field. The tensile stress field extends about 6 mm (0.236") into the 1.5" thick fused silica window.

260 Indentation fracture

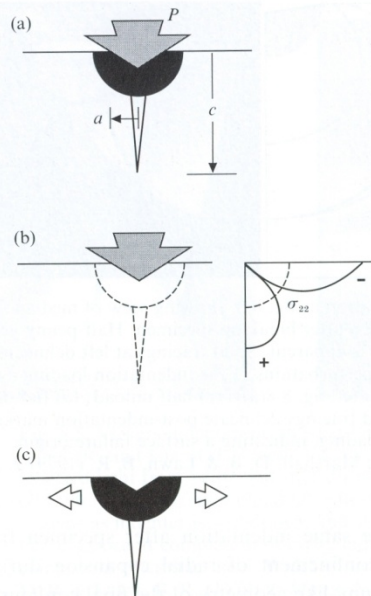


Fig. 8.10. Radial–median crack system. (a) Elastic–plastic configuration at full load, composed of superposable (b) reversible (elastic) in-plane ( $\sigma_{22}$ ) stress and (c) residual (plastic) centre-opening force components. (After Lawn, B. R., Evans, A. G. & Marshall, D. B. (1980) *J. Amer. Ceram. Soc.* **63** 574.)

## Fracture Mechanics of Fused Silica

Fracture toughness of fused silica (approximate):

$$K_{Ic\_FS} := 0.75 \cdot 10^6 \cdot \frac{N}{m^2} \cdot m^{\frac{1}{2}}$$

Governing fracture mechanics equation for a crack in an infinite plate:

$$K_{Ic} := \sigma \cdot \sqrt{\pi \cdot \text{CrackSize}}$$

Process for determining the maximum allowable flaw size at a stress level of 10 MPa

$$\sigma_{\text{DiffPress}} := 7 \cdot \frac{N}{mm^2}$$

$$\text{FlawSizeMax} := \frac{\left( \frac{K_{Ic\_FS}}{\sigma_{\text{DiffPress}}} \right)^2}{2}$$

$$\text{FlawSizeMax} = 5.74 \text{ mm}$$

At this stage of the analysis, it is probable that a crack has formed on the surface of the window from the impact of a Pyroceram particle. Having a small crack in the window does not necessarily mean that the window will catastrophically fail. What determines the survivability of the window is how deep this crack penetrates. Analytical formulas for crack length prediction from an impact event are not available leading to a more general inference of crack penetration. From the prior page, a tensile stress field of greater than 7 MPa exists up to 6 mm deep into the window due the large particle impact (42.90 mm diameter). This tensile stress field would initiate and propagate a crack size to a length of 5.74 mm (0.226"). This logic would conclude that the large particle impact would initiate and propagate a crack 5.74 mm deep into the window. This then provides a starting point to determine if the fused silica window will be stable or catastrophically fail under the applied differential pressure of 14 psi.

Table 8.1. Hardness  $H$ , toughness  $T_0$  and brittleness  $H/T_0$  (descending order), plus threshold contact size  $a_c$  and load  $P_c$ , for selected monocrystalline (mc) and polycrystalline (pc) solids.

Material	$H$ (GPa)	$T_0$ (MPa m <sup>1/2</sup> )	$H/T_0$ (μm <sup>-1/2</sup> )	$a_c$ (μm)	$P_c$ (N)
Diamond (mc)	80	4	20	0.3	
Silicon (mc)	10	0.7	14	0.6	0.004
Magnesium oxide (mc)	9	0.9	10	1.2	0.01
Silica (glass)	6	0.75	8	2	0.02
Silicon carbide (mc)	19	2.5	8	2	0.1
Sapphire (mc)	20	3	7	3	0.2
Silicon nitride (pc)	16	4	4	8	1
Zirconia (pc)	12	3	4	8	0.8
Tungsten carbide (pc)	20	13	1.5	50	60
Zinc selenide (pc)	1.1	0.9	1.2	80	8
Steel (pc)	5	50	0.1	12000	800000

$T_0$  for polycrystalline solids is short-crack (indentation) toughness.

#### 42 FRACTURE AND FATIGUE CONTROL IN STRUCTURES

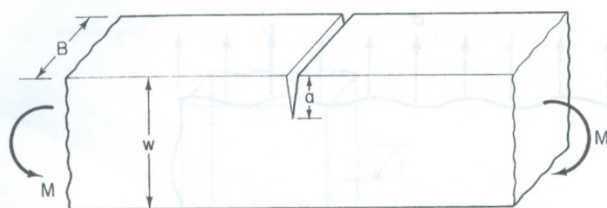


FIG. 2.10 Edge-notched beam in bending.

TABLE 2.3. Stress-intensity-factor Coefficients for Notched Beams (Ref. 5).

$a/W$	0.05	0.1	0.2	0.3	0.4	0.5	0.6 (and
$g(a/W)$	0.36	0.49	0.60	0.66	0.69	0.72	0.73

### Fracture Mechanics of Fused Silica

Fracture toughness of fused silica (approximate):

$$K_{Ic\_FS} := 0.75 \cdot 10^6 \cdot \frac{N}{m^2} \cdot \frac{1}{m}$$

Governing fracture mechanics equation for a crack in an infinite plate subjected to a bending moment is given in Barsom and Rolfe "Fracture and Fatigue Control in Structures", 1999:

$$K_I = \frac{6 \cdot \text{BeamMoment}}{\text{Width} \cdot (\text{WindowThickness} - \text{CrackAllowable})^{\frac{3}{2}}} \cdot \text{GeometryFunction}$$

At the applied differential pressure, the maximum disk moment can be determined from a formula for a simply supported disk as:

$$\text{BeamMoment} := \frac{(3 + \text{FusedSilicaPoissons}) \cdot (\text{DifferentialPressure} \cdot \text{WindowRadius}^2) \cdot \text{in}}{16}$$

$$\text{BeamMoment} = 2.538 \times 10^4 \text{ N}\cdot\text{mm}$$

The following constants can be determined as:

$$\text{Width} = 1 \text{ in} \quad \text{WindowThickness} = 1.5 \text{ in}$$

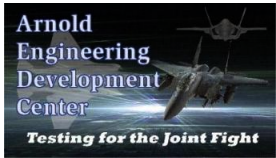
$$\text{GeometryFunction} = 0.64$$

Process for determining the maximum allowable flaw size under bending is:

$$\text{CrackAllowable} := \text{WindowThickness} - \left[ \frac{(6 \cdot \text{BeamMoment}) \cdot \text{GeometryFunction}}{K_{Ic\_FS} \cdot \text{Width}} \right]^{\frac{2}{3}}$$

$$\text{CrackAllowable} = 8.4 \text{ mm}$$

From the prior arguments, it is reasoned that a crack of 5.74 mm (0.226") exists in the fused silica window from the impact of a large particle. Further crack propagation is driven by the tensile stresses state due to the applied differential pressure (14 psi). The stress intensity for a edge crack under bending (which approximates the window bending due to the pressure load) is given by Barsom and Rolfe. Performing some basic algebra, the allowable crack size to prevent catastrophic failure is 8.4 mm or 0.331". This analysis indicates that the window would be stable with an embedded 5.74 mm deep crack.



## Appendix

Engineering Guidance

Mechanical Property Data

Engineering Calculations

Cited and Recommend References

Certifying Engineer



## Engineering Guidance

- 1) The total velocity of the debris fragment is 16.8 ft/sec. The fragment will hit the middle of the window at an angle of 39.7 deg. The fragment velocity normal to the window is 10.18 ft/sec and the velocity of the fragment parallel to the window is 12.27 ft/sec.
- 2) The debris fragment is 3-in x 3-in x 0.24-in. = 0.00146 ft<sup>3</sup>. The density of the material is 161.6 lb/ft<sup>3</sup> so the weight of the fragment is 0.24 lb.
- 3) The fragment material is Pyroceram 9606.
- 4) The wind tunnel window is 18-in diameter x 1.5-in thick with bevels on the inside and outside edges. The window is potted in a steel frame with ULTRACAL 60 cement.
- 5) The window does not have structural loading. The pressure differential across the window at the time of impact is 14.2 psia outside - 0.2 psia inside = 14.0 psi. The temperature of the window will be 350 deg F.
- 6) The window material is fused silica that has been annealed, homogenized and polished to within 0.1 wavelength of sodium light. Since the windows are used for shadowgraphs, we know the residual stresses through the window are very low.

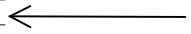


## Mechanical Property Data

**Mechanical and Thermal Properties:**

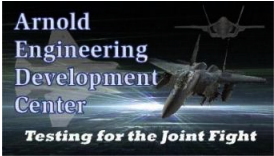
Unless otherwise stated, all values @ 25°C

Elastic (Young's) Modulus	72.7 GPa	Softening Point	1585 °C (10 <sup>7.6</sup> poises)	
Shear Modulus	31.4 GPa	Annealing Point	1042 °C (10 <sup>13</sup> poises)	
Modulus of Rupture, abraded	52.4 MPa	Strain Point	893 °C (10 <sup>14.5</sup> poises)	
Bulk Modulus	35.4 GPa	Thermal Conductivity	1.30 W/m K	
Poisson's Ratio	0.16	Thermal Diffusivity	0.0075 cm <sup>2</sup> /s	
Density	2.201 g/cm <sup>3</sup>	Average C.T.E.	0.52 ppm/K	5 °C-35 °C
Knoop Hardness (100 g load)	522 kg/mm <sup>2</sup>		0.57 ppm/K	0 °C-200 °C
			0.48 ppm/K	-100 °C-200 °C



Shear Modulus	31 GPa at 25°C
Rupture Modulus	50 MPa at 25°C
Bulk Modulus	36.9 GPa at 25°C
Apparent Elastic Limit	55MPa (7980 psi)
Compressive Strength	1.1 GPa
Tensile Strength	50 MPa
Poisson Ratio	0.17 at 25°C
Knoop Hardness	500 kg/mm <sup>2</sup>
Molecular Weight	28.09
Class/Structure	Amorphous glass
Chemical Stability	High resistance to water and acids (except hydrofluoric).

Mechanical property data is provided for fused silica. For the impact simulation, the most important mechanical property is the Elastic Modulus of 72.7 GPa. Although this data is provided at 25 C, the annealing point of clear fused silica is 1042 C with a softening point at 1585 C. These high temperatures would assure that the Elastic Modulus would remain unchanged at the tunnel's operation temperature of 176 C.



## NIST Property Data Summaries

### Pyroceram 9606 ( Unknown Composition )

Reference: [NIST Technical Note](#)

Reference: [NIST Structural Ceramics Database](#)

Note: [About Property Data Summaries](#).

Note: [Abbreviations and Other Notes](#)

Note: [Other Materials](#)

**Material Summary:**

[Ref. 1,2,3,4,5,6]  
 Manufacturer.....: Corning Glass  
 Material Designation: Pyroceram 9606  
 Material Form.....: Polycrystal  
 Composition.....: Unknown  
 Processing.....:

Grain Size [μm]	Porosity [%]	Fracture Toughness [MPa·m <sup>1/2</sup> ]	Fracture Energy [J/m <sup>2</sup> ]	Measurement Method	Measurement Environment	Comments
		2.5		DCB	air	Ref. 1; E = 108 GPa E = 120 GPa E = 120 GPa
		3.17		ICS		
		2.69		IS		
		2.14		CNB	air	Ref. 2
		2.07		CNDC	dry N2	Ref. 3
		2.8		ICS	air	Ref. 4
		2.5		IS		
2			24.8	SENB	air	Ref. 5; E = 114 GPa
		2.25		SCF	air	Ref. 6; E = 132 GPa; density = 2.59 g/cm <sup>3</sup>

Typical Physical Properties

Product	Use Consistency (lb. water per 100 lb. gypsum cement)	Setting Range min. (Vicat)	% Setting Expansion final	Minimum Compressive Strength (lb. per sq. in., dry <sup>(1)</sup> )	pH Reaction
ULTRACAL 30 Gypsum Cement	38	25-35	0.080	6,000	Alkaline
ULTRACAL 60 Gypsum Cement	39	75-90	0.065	5,000	Alkaline
HYDROCAL A-11 Gypsum Cement	42	16-20	0.080	5,500	Alkaline
HYDROCAL B-11 Gypsum Cement	44	25-35	0.080	4,500	Alkaline
Medium High-Expansion HYRDOCAL Gypsum Cement	48-50 44-45	25-35	1/8"/ft. 3/8"/ft.	—	Slightly acid
HYDRO-STONE Cement	32	17-20	0.240 (maximum)	10,000	Alkaline
Industrial White HYDROCAL Cement	45	25-35	0.390 (maximum)	5,000	Neutral
Industrial Moulding Plaster	70	27-37	0.200 (maximum)	2,000	Neutral

(1) Wet strength is about half that for dry strength.



## Engineering Calculations

### Wind Tunnel Viewport Window

$$\text{Pressure}_{\text{Load}} := 14 \frac{\text{lbf}}{\text{in}^2}$$

$$\text{Fused}_{\text{SilicaPoissons}} := 0.17$$

$$\text{Window}_{\text{Radius}} := 9 \text{ in}$$

$$\text{Window}_{\text{Thickness}} := 1.5 \text{ in}$$

$$\text{Disk}_{\text{Stress}} := \frac{3 \cdot (3 + \text{Fused}_{\text{SilicaPoissons}}) \cdot \text{Pressure}_{\text{Load}} \cdot \text{Window}_{\text{Radius}}^2}{8 \cdot \text{Window}_{\text{Thickness}}^2}$$

$$\text{Disk}_{\text{Stress}} = 599 \frac{\text{lbf}}{\text{in}^2}$$

$$\text{Disk}_{\text{Stress}} = 4.131 \frac{\text{N}}{\text{mm}^2}$$

$$\text{SphereVolume} = \frac{4 \cdot \pi \cdot \text{SphereRadius}^3}{3}$$

$$\text{SphereVol} := 0.00146 \cdot \text{ft}^3$$

$$\text{SphereDensity} := 161.6 \cdot \frac{\text{lb}}{\text{ft}^3}$$

$$\text{SphereRadius} := \left[ \frac{(3 \cdot \text{SphereVol})}{4 \cdot \pi} \right]^{\frac{1}{3}}$$

$$\text{SphereDensity} = 2.589 \times 10^{-6} \frac{\text{kg}}{\text{mm}^3}$$

$$\text{SphereRadius} = 21.45 \text{ mm}$$



## Cited and Recommend References

### **Review of Literature Used in this Report:**

1. B. Lawn, *Fracture of Brittle Solids, Second Edition, 1993*

An outstanding book on the fracture of brittle solids and in particular glass. It was invaluable in the development of this engineering report.

2. J.E. Gordon, *The New Science of Strong Materials or why you don't fall through the floor, 2006*

A laypersons introduction to engineering fracture mechanics. Good background on why glass is weak and prone to catastrophic failure. A good reference for all engineers.

3. A.P. Parker, *The Mechanics of Fracture and Fatigue, 1981*

The standard introduction to fracture mechanics and very useful to put the "nuts and bolts" together for a fracture mechanics prediction.

4. J.M. Barsom and S.T. Rolfe, *Fracture and Fatigue Control of Structures, 1999*

For the interested reader that would like to more about fracture mechanics from an application viewpoint. Several excellent case studies are detailed within their work.

5. S. Timoshenko and S. Woinowsky-Krieger, *Theory of Plates and Shells, Second Edition, 1987*

Whenever you need the direct source for plate formulas. This work was used to calculate the stress and bending moment values used within the report.



Certifying Engineer



Work within this report was done under best industry practices and was executed by George Laird, Ph.D., P.E.