Fused Silica
and
Other Transparent Window Materials

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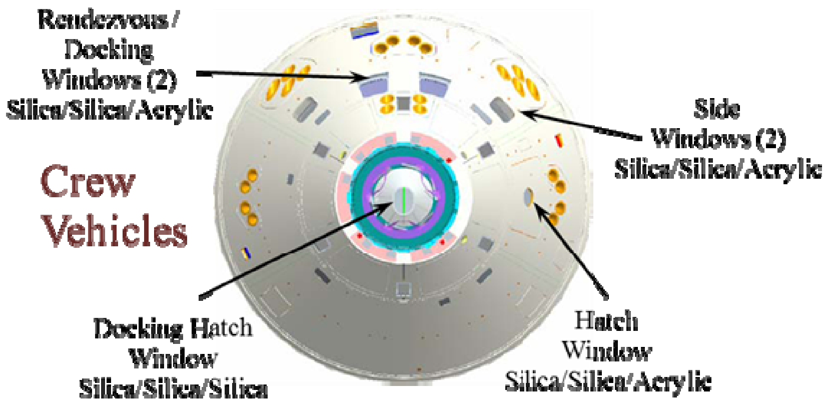
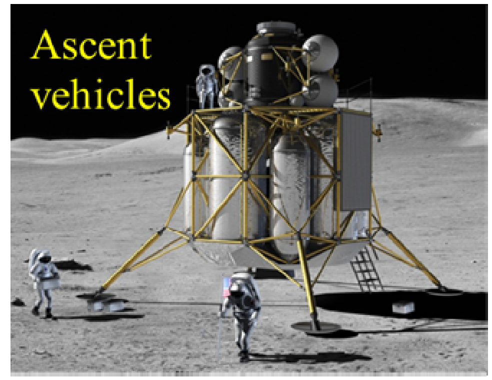
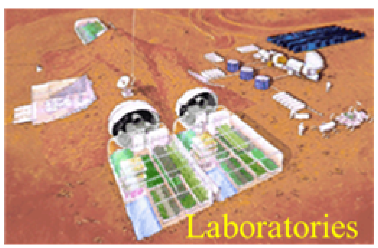
Outline

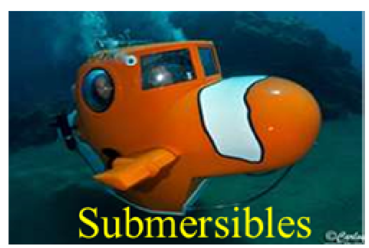
- ❑ Window Applications and Requirements
- ❑ Historical Material
- ❑ New Materials and Mechanical Properties
- ❑ ISS Windows and Damage
- ❑ Anomalous Behavior of Silica
- ❑ Comparison to Published Literature
- ❑ Conclusions

Some NASA Window Applications









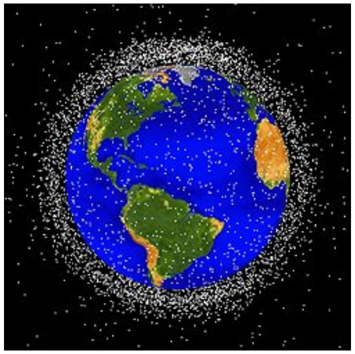
Fused Silica – Workhorse Material

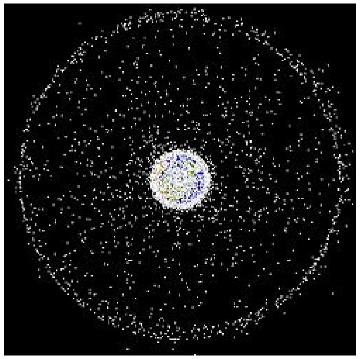
- Fused silica has been the historical material of choice:
  - Apollo
  - SkyLab (73-74) , Mir…
  - ISS (98-xxxx)
  - Shuttle
  - Orion

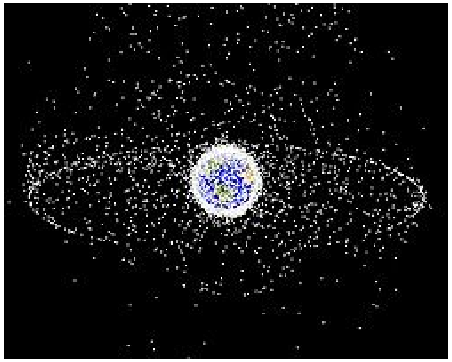
- Only one unexpected failure during an Apollo window proof test.

Window Requirements

- Thermal shock
- Mechanical (crack growth)
- Optical (haze, transmittance…..imagery, piloting)
- Chemical (atomic oxygen, radiation..)
- Impact residual strength (handling, hyper)



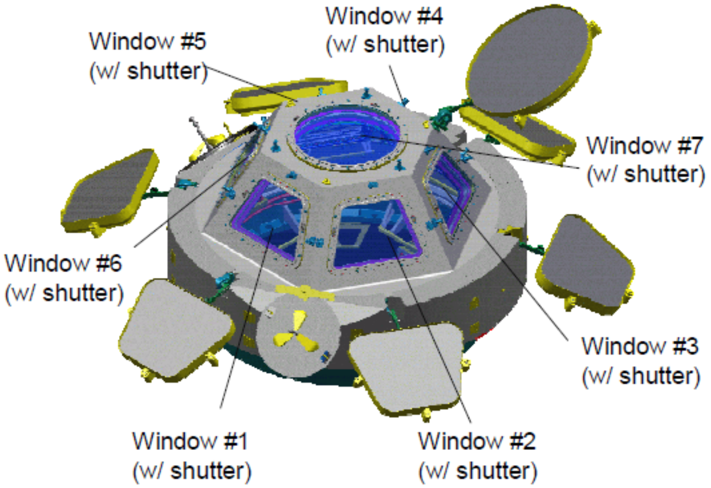




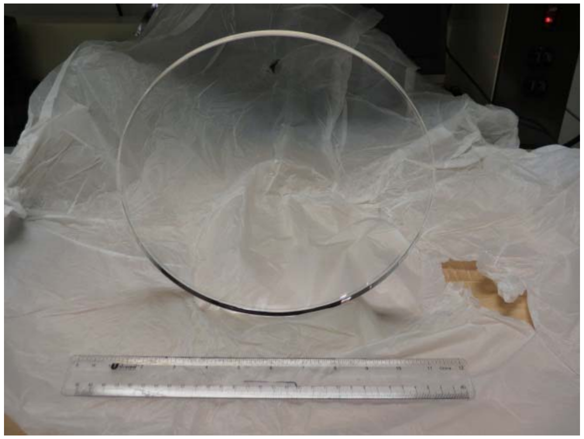
- Big advantages are optical and thermal.
- But why windows at all?! Psychological.

Windows in Use - ISS

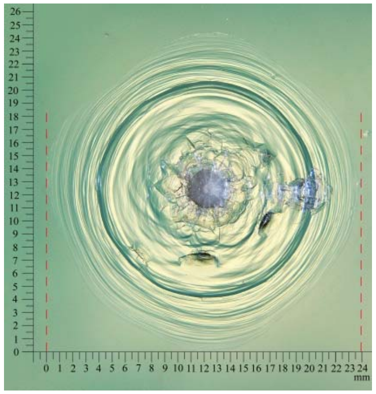
- Most famous are the Cupola windows, which are shuttered:



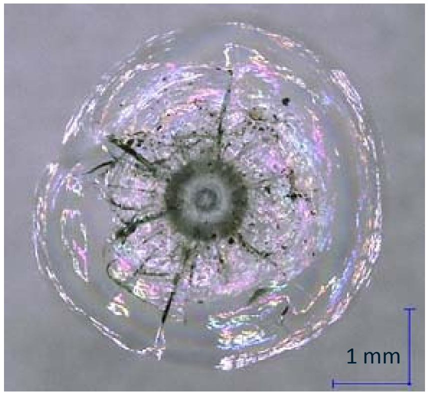
- More typical widow (10”ϕ):



HITF White Sands



STS-84 Atlantis

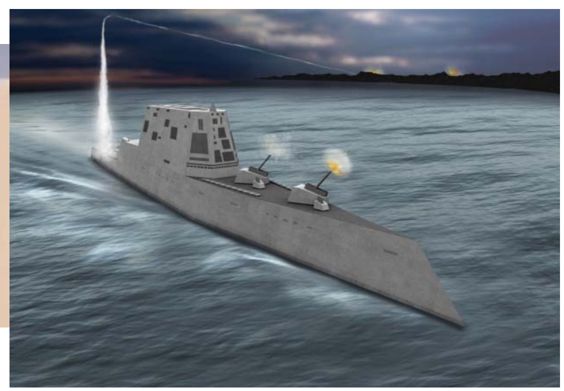


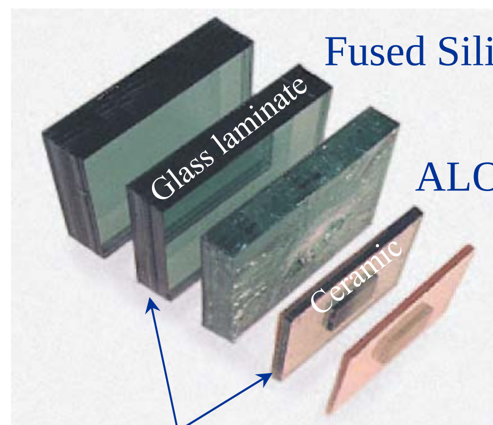
- Some windows are not shuttered and can be damaged by MMOD….

New, Impact Resistant Materials

- A variety of “new” materials have been developed or re-developed:
  - AlON
  - Spinel
  - MgO, Alumina, glass-ceramics

- One driving force has been military armor:





- Might these materials work for spacecraft windows?

Property Comparison

- Thermals shock related: $R^{"} = \frac{(1-v)\lambda\sigma_c}{\alpha E \rho C_p}$

Material	Young's Modulus GPa	Fracture Strength (MPa)	CTE x $10^{-6}/^{o}C$ α	Thermal Conductivity (W/mK) λ	Heat Capacity (J/gK)	R (K)	R" (Wcm^2 /gK)
Silica	72	80	0.5	14	0.77	1733	143
Spinel (coarse grain)	270	80	6	15	0.88	73	3.5
Spinel (fine grain)	270	160	6	15	0.88	73	3.5
AlON	314	210	5	13	0.92	99	3.8

- Positive: similar thermal conductivity.
- Negative: new materials have higher CTE.
  - ➢ Poor thermal shock.

Mechanical Property Comparison

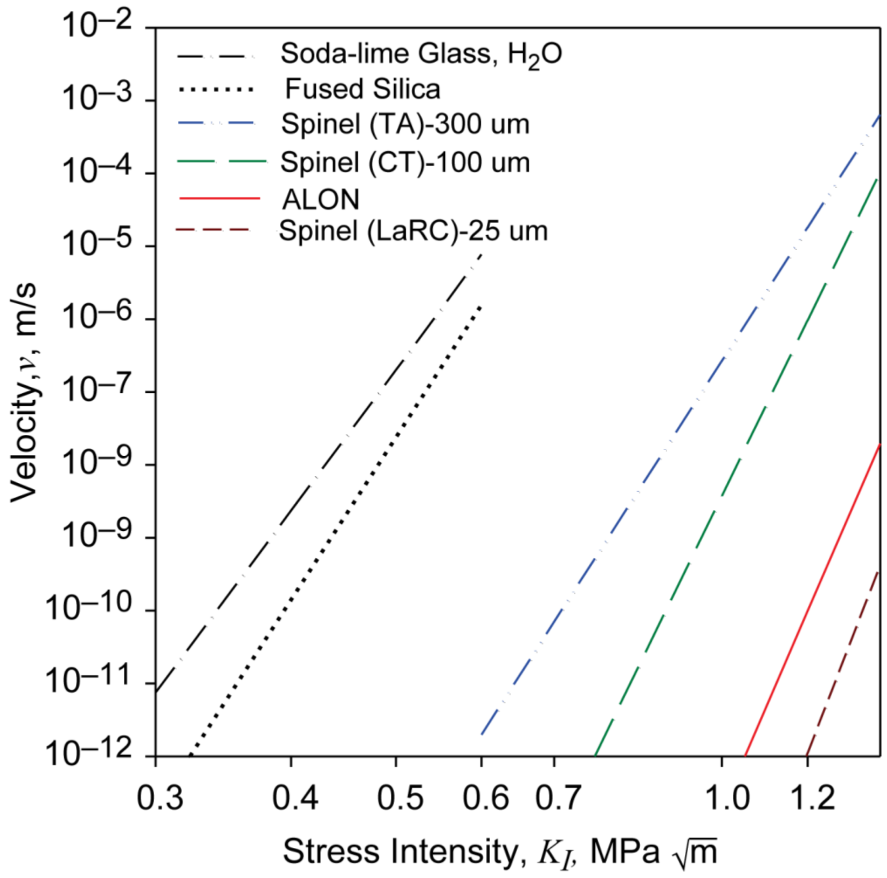
- Crack growth related:

Material	Density (g/cc)	Young's Modulus (GPa)	Fracture Toughness (MPa√m)	Crack Growth Exponent, n	Fracture Strength MPa
Silica	2.2	72	0.75	24	80
Spinel (coarse grain)	3.6	270	1.5	22	80
Spinel (fine grain)	3.6	270	2.0	50	160
AlON	3.7	314	2.2	35 - 50	210

- Positive: New materials are tougher and SCG resistant.
- Negative: New materials are denser and stiffer.

Slow Crack Growth Curve

- The SCG curve captures much of the mechanicals:



Material	Density (g/cc)
Silica	2.2
Spinel	3.6
Spinel	3.6
AlON	3.7

- Does not account for weight…….

Launch Weight is Expensive.

- Can Mass be Reduced? -

- Slow crack growth life function: $t_{f\,min} = B\sigma_{proof}^{n-2}\sigma_{applied}^{-n}$

- Combine with – Window mass: $m = \dfrac{\rho\pi D^2 t}{4}$

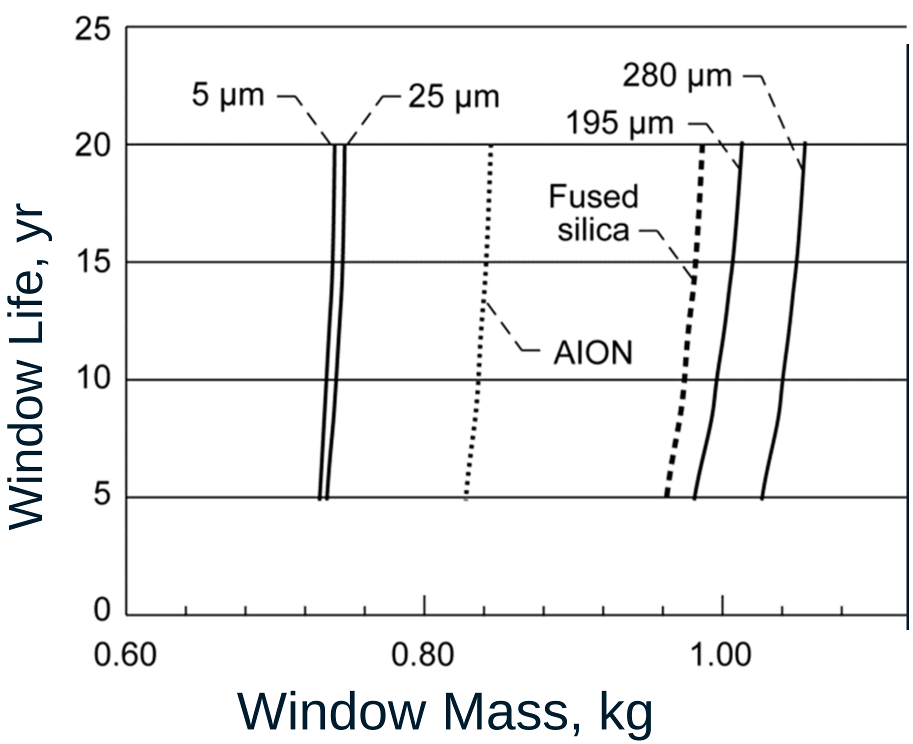
  – Window stress: $\sigma_{max} = \dfrac{3PD^2}{32t^2}(3+v)$

  – Proof stress: $\sigma_{proof} = \left(\dfrac{K_{Ic}}{Y\sqrt{a_{max}}}\right)$

- Mass for a lifetime: $m = \left(\dfrac{t_{f\,min}}{B}\right)^{\frac{1}{2n}}\left(\dfrac{K_{Ic}}{Y\sqrt{a_{max}}}\right)^{\frac{2-n}{2n}}\left(\dfrac{3\pi^2 P\rho^2 D^6}{512}(3+v)\right)^{\frac{1}{2}}$

Relative Mass

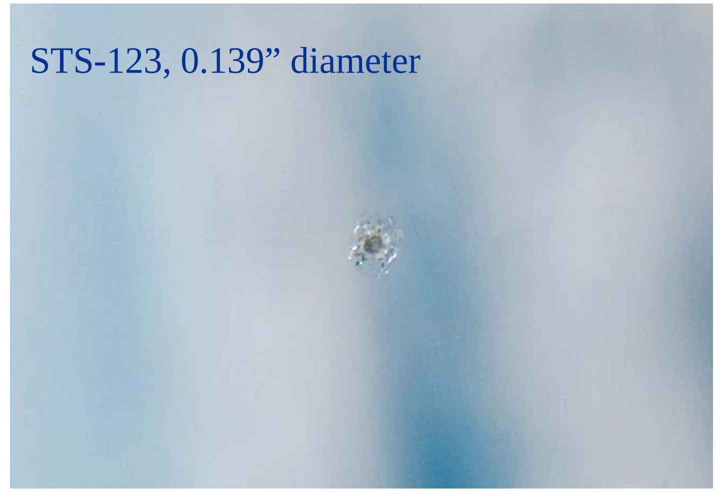
Material	Grain Size, μm	Relative Mass
Spinel (TA)	300	1.14
Spinel (AL)	180	1.04
Spinel (CT)	110	.97
Spinel (LaRC)	25	.74
Spinel (Julich)	5	.73
AlON	245	.83
Fused Silica	------	1



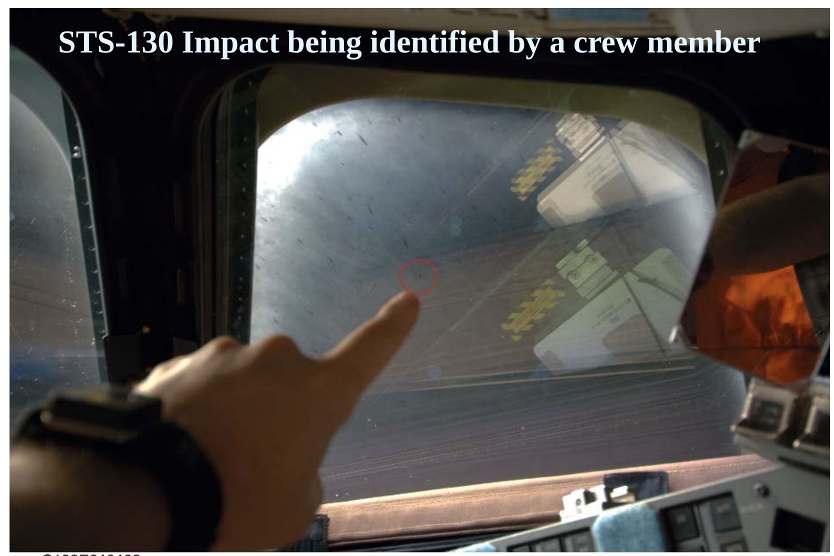
- Yes, mass can be reduced from a SCG Perspective!
- For spinel, the grain size needs to be small……..

Impact: Shuttle Examples


STS-113 W11 HVI, .095” diameter


STS-123, 0.139” diameter

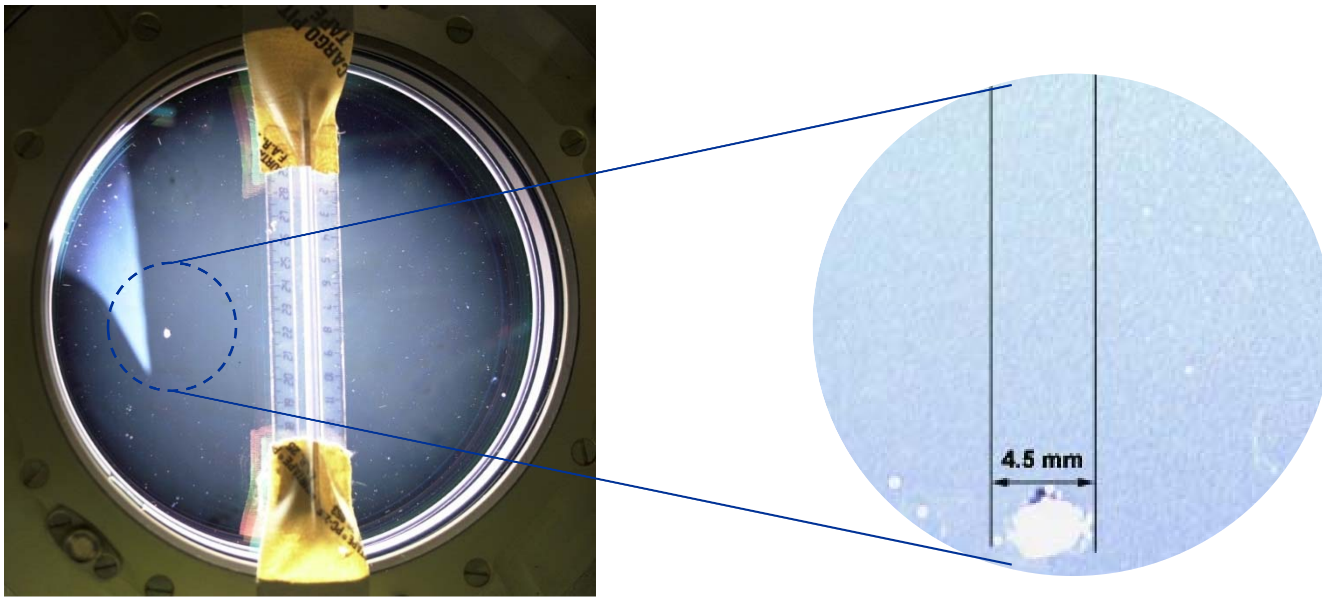

STS-126 HVI, the largest natural HVI incurred by an Orbiter window (~.5” dia)


STS-130 Impact being identified by a crew member

S130E010103

Impact: ISS Example

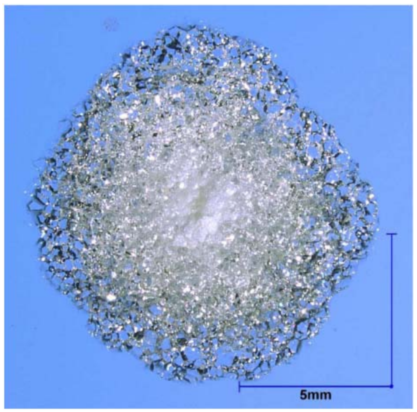
- Russian fused silica window (not shuttered):

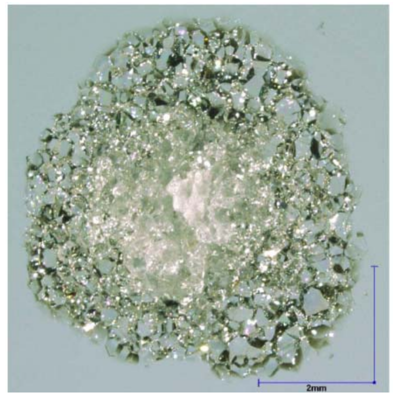


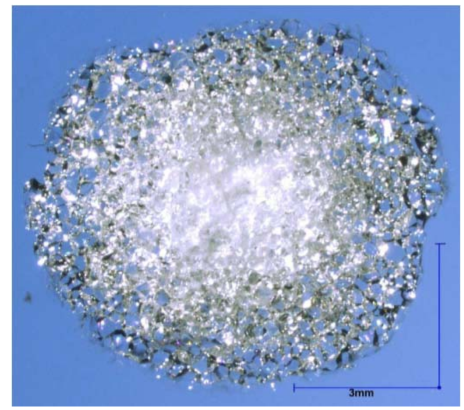
- Window sealed.

Hyper Velocity Impact of Spinel vs Silica

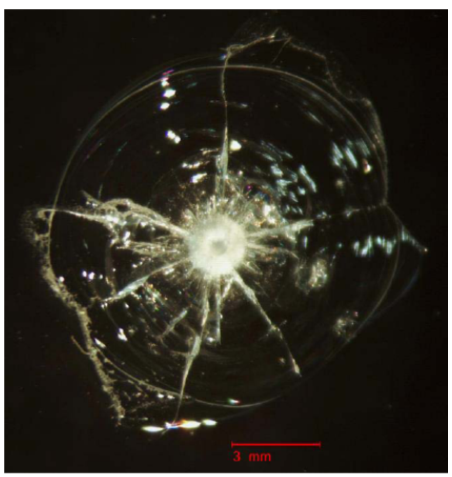
- Similar sizes but very different morphologies:

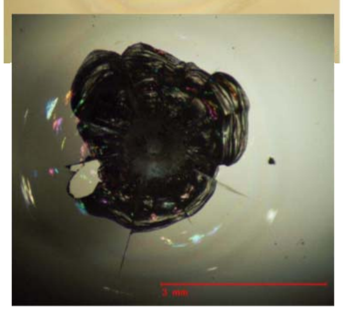


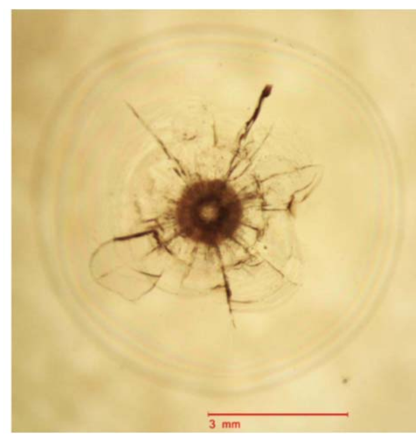




Large pit with gain boundary cracking.







Central pit with radial and circumferential cracks.

Summary

- Spinel and AlON exhibit better fracture toughness and crack growth as compared to glasses, and thus have potential in window systems.
- They can reduce weight from a crack growth perspective.
- Thermal shock resistance metrics are poor - component level testing to qualify.
- Impact size is similar, however, the morphology is very different; residual strength needs to be measured……….
- Are the post impact residual strengths similar?

Fused Silica

Observations and Anomalies

Macro-crack Fracture Toughness

Russian Quartz-Silica

Fracture Toughness (MPa√m)		
Method	Air (75°F, 45% RH)	Dry N_2
SEPB	0.71 ± 0.05	0.73 ± 0.02
VB	0.71 ± 0.04	0.77 ± 0.01

Shuttle Fused Silica (7980)

Fracture Toughness (MPa√m)		
Method	Air (75°F, 45% RH)	Dry N_2
SEPB	0.71 ± 0.04	0.74 ± 0.03
VB	0.73 ± 0.04	0.77 ± 0.02

Tosoh

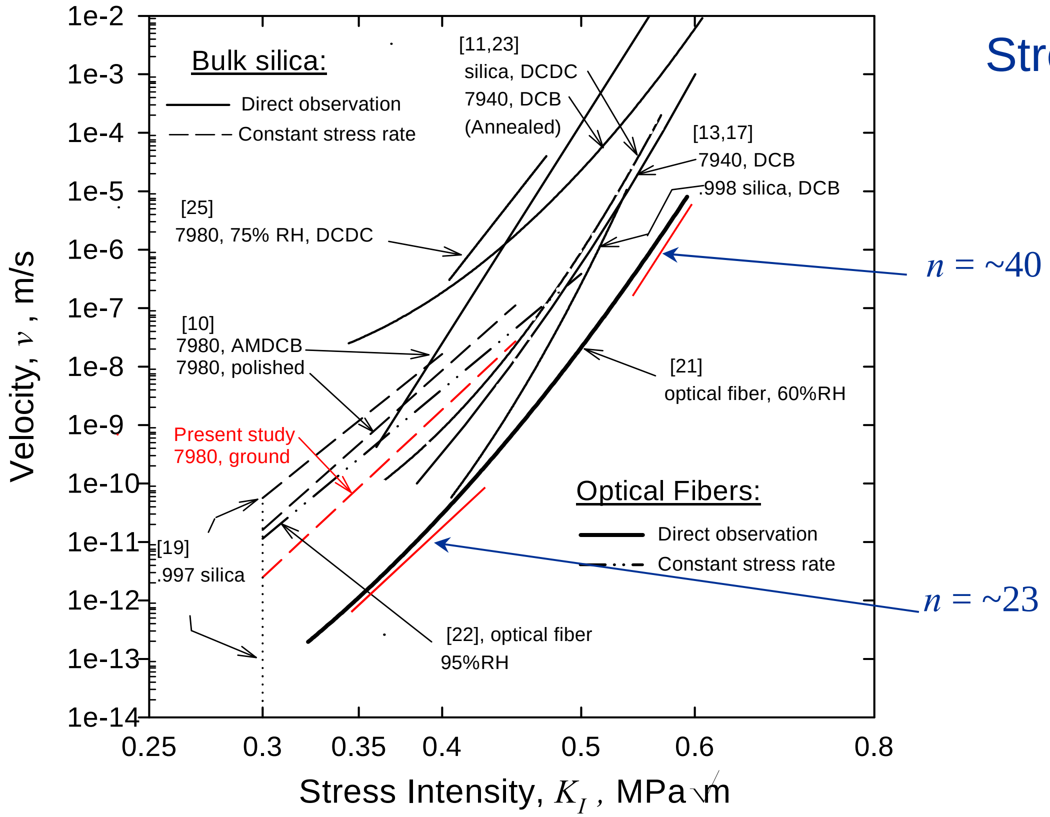
Fracture Toughness (MPa√m)	
Configuration	Air (75°F, 25% RH)
VB	0.73 ± 0.08

Literature on 7940 & 7980

Fracture Toughness (MPa√m)				
Method	Vacuum	Vacuum/ Dried	Dry N_2	Source
AMDCB			0.72 ± 0.01	NIST (LB)
DCB	0.74 ± 0.03	0.73 ± 0.02		NIST (SW)
3-Pt	0.75 ± 0.03		0.76	NIST (SW)
DCDC	0.73 to 0.76			Sandia

- Silicas have identical fracture toughness at the macro-scale.
- Insensitive to test method, test material, or researcher.

Crack Growth Data for 7940/7980 and Optical Fiber



Strength data fit via the Power Law
or
as directly observed

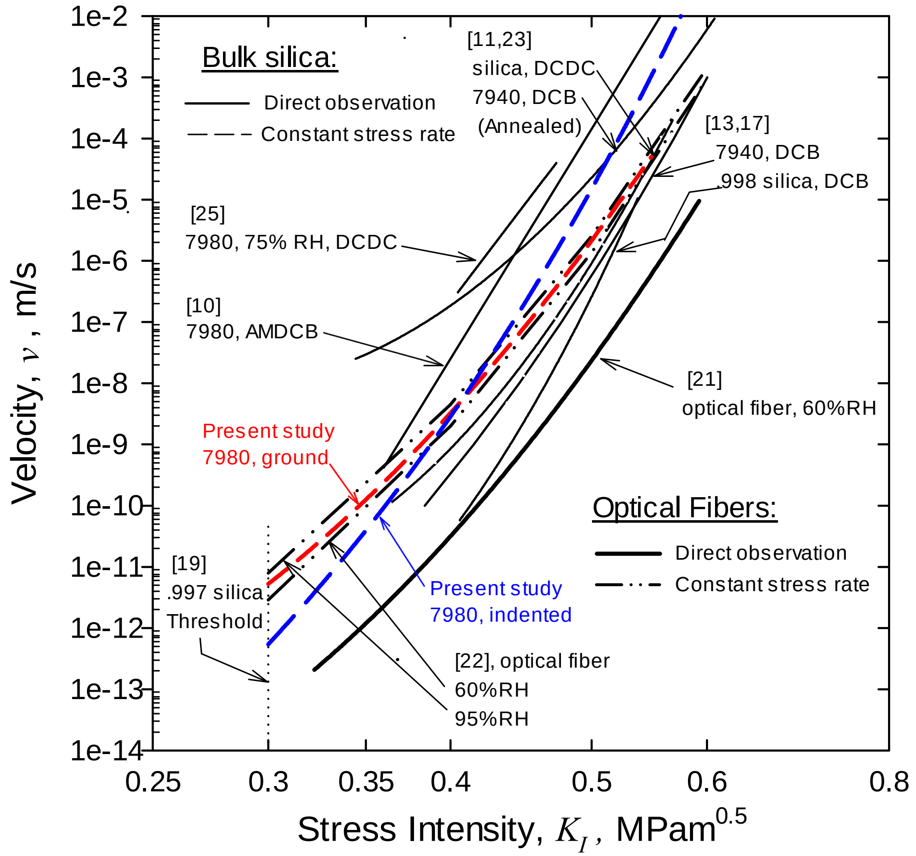
$$v = \frac{da}{dt} = A_I K_I^{n_I} = A_I^* \left[\frac{K_I}{K_{IC}} \right]^{n_I}$$

- Large variance.
- Strength methods (small cracks) give a low n.
- Directly observed macrocracks give high n.

} *Cracks size or test method effect??*

- Wide range, directly observed data is nonlinear – *exponential law!*

Literature Values for 7940/7980 and Optical Fiber



Exponential law

or

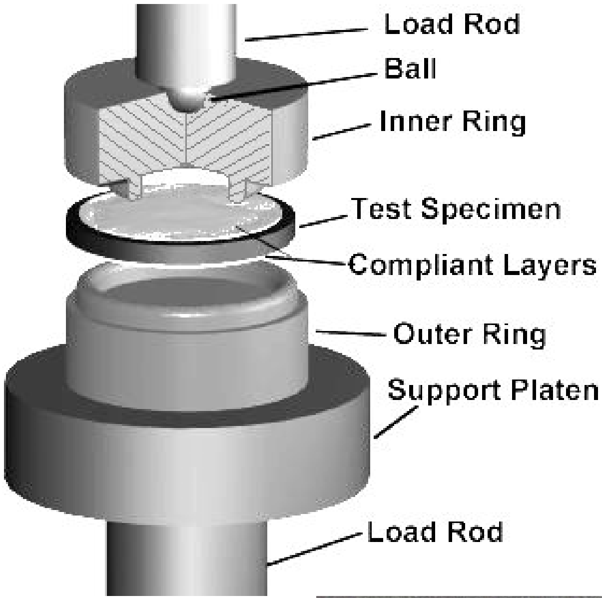
as directly observed:

$$v = \frac{da}{dt} = A_2 \exp\left(n_2 \frac{K_I}{K_{Ic}} \right)$$

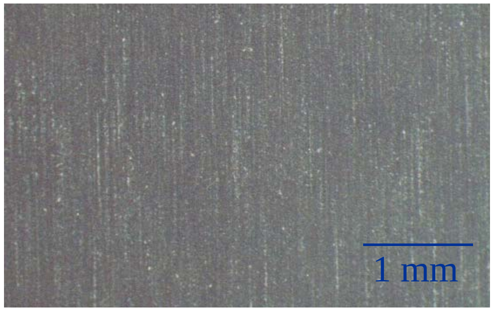
- The exponential law provides better agreement between directly observed macrocracks and strength based velocity estimates (blends).
- Still some difference between larger and smaller cracks…..

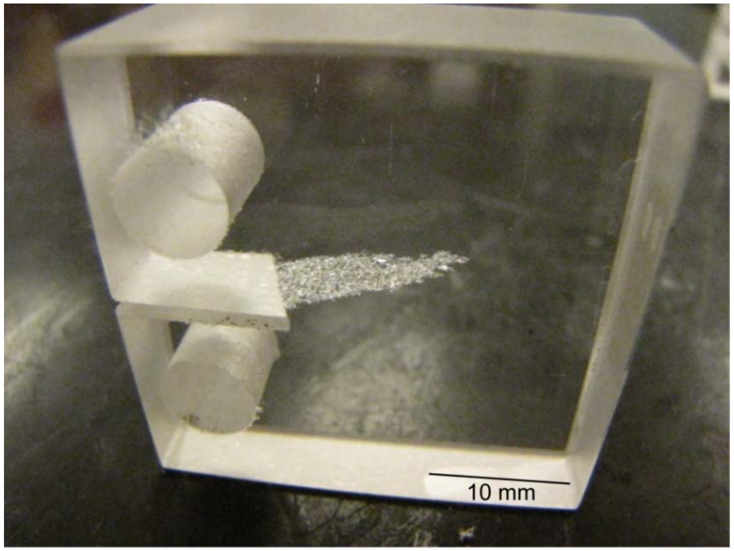
What is Different?

- Crack size and observation method used:



Strength method – estimate from strength



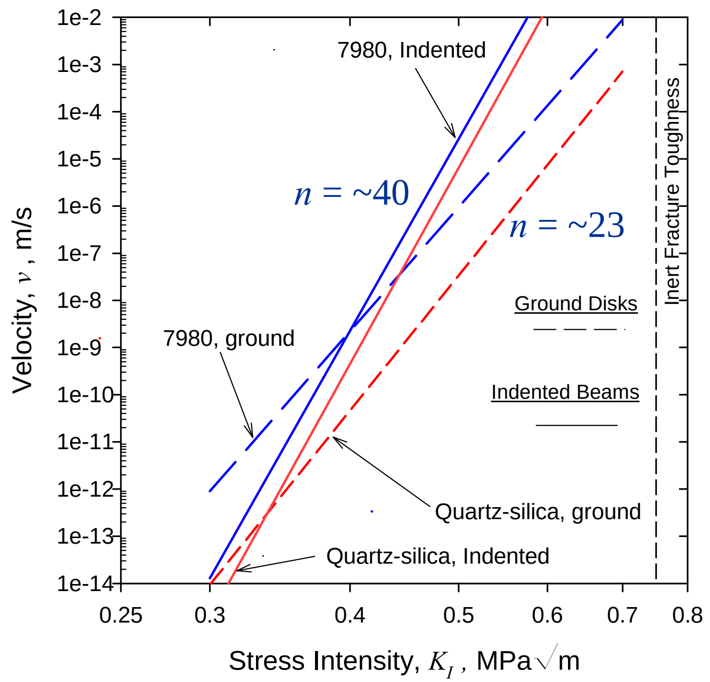


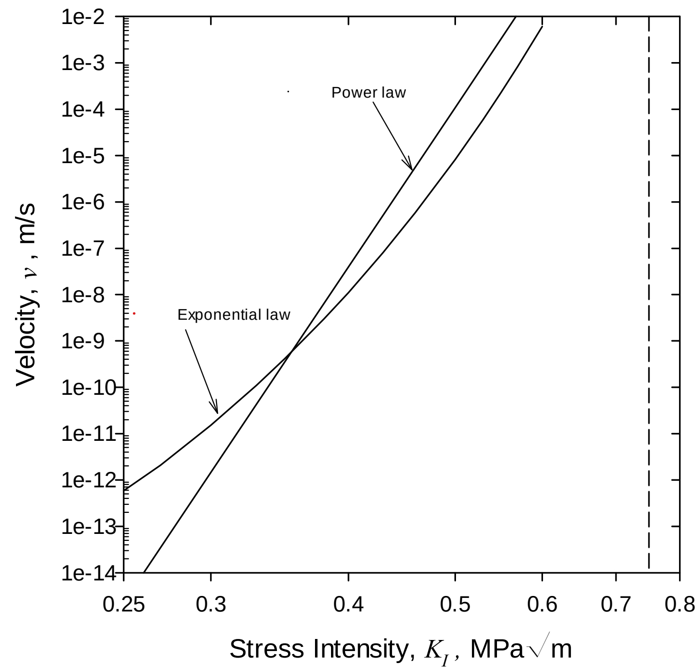
Macro-crack method: direct observation of the crack.

How can we determine the source of the differences??

Crack Size Effect

- Use strength method to test ground specimen (small cracks) and larger cracks (indented specimens):

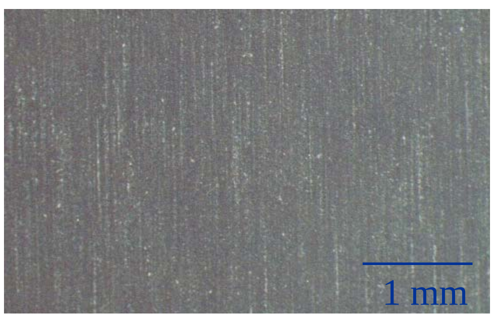


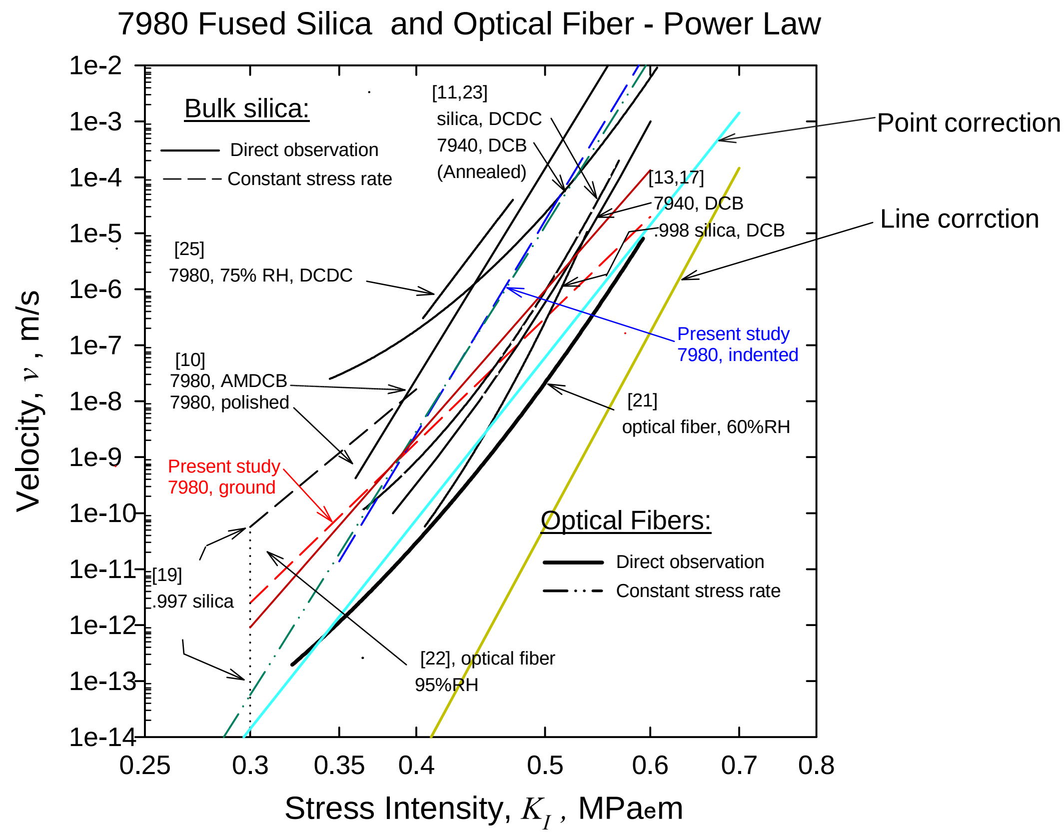


- Indented specimen give similar *n* as directly observed macrocracks – not a method effect. Crack size effect?

Other Influences Giving a Crack Size Effect

- Residual stress
  - Correction (Fuller's, et al.) generally increase the n value and shifts data too far…





Crack Growth of Various Fused Silicas

- Water content - need systematic measurements…….

Water Crack Growth Parameter	
Material	n
7980	39
Russian	43
Tosoh	35
GE	37

Same water content?

- Different silicas exhibit very similar n when test identically! Measure water content…….

Water Adsorption

- Near surface adsorption of water creates surface residual stresses (Wiederhorn) and higher *n* (Tomozawa).
- But does not explain the difference between small and large crack data:
  - Large cracks shouldn't be influenced, yet exhibit high *n*
  - Small cracks result in low *n* or high *n*
- Research is needed……..

Conclusions

- Fracture toughness of several fused silicas are identical regardless of technique, vintage or researcher.
- Slow crack growth parameters of several silica are very similar when tested identically.
- Yet, the reported slow crack growth parameters are quite varied, even for a single commercial silica.
- Use of the exponential function rationalizes some of the differences between large crack, small crack, and strength-based parameters, but…..future research.
- New materials exhibit better toughness and crack growth as compared to silica, and thus have potential in window systems. More work is needed to qualify these materials.

Acknowledgements

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- Thanks to Lynda Estes for many discussions.