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Proof Test Levels for Advanced LIGO Viewports

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1 Introduction

The "LIGO Generic Requirements & Standards for Detector Subsystems"[1] calls for inert environment, proof testing for all brittle, non-metallic materials on the vacuum envelope. The minimum proof test factor for pressurized brittle, non-metallic materials is 2.0. Better than proof testing at the minimum test factor is to proof test at a stress which guarantees the desired minimum lifetime[2,3]. In this memo the appropriate proof test levels, based on fracture mechanics, are calculated for each of the Advanced LIGO (aLIGO) viewports.

2 Fracture Mechanics for Glasses

2.1 Formulation

It is well established that subcritical crack growth, or slow crack growth (SCG), in glasses and ceramics, in environments containing water vapor, is caused by a tensile stress enhanced, chemical corrosion at the tip of pre-existing surface flaws[4]. This phenomenon is known as "delayed failure" or "static fatigue".

Weiderhorn et. al. found that some glasses exhibited subcritical crack growth in vacuum, whereas some other glasses did not (including two that had anomalous elastic behavior and an Ultra-Low Expansion (ULE) glass). I am unaware of any studies on subcritical crack growth for the optical materials that we use in our vacuum viewports. It is possible (even likely) that these materials do not exhibit subcritical crack growth (static fatigue) while under vacuum. However, it is important to consider the lifetime and strength due to static fatigue in this application, because (a) the viewports are cycled up to air multiple times and for significant durations during their lifetime and (b) there can be tensile stresses on the air side of the viewport windows (associated with the compressive loading of the seal or due to slight overpressure when venting).

Pre-existing flaws grow in size under the service load (stress) to a critical size at which a crack propagates quickly. The subcritical growth can be expressed as a power function of the stress intensity factor, K_I:

$$V = AK_I^N$$

where V is the crack velocity, A and N are constants that depend on the environment and material composition. From this equation it can be derived that the time to failure, t_f, under a constant tensile stress, σ_a, is:

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[1] D. Coyne, "LIGO Generic Requirements & Standards for Detector Subsystems", E010613, section 3.4.4.1.1. This section is based upon: "Structural Design and Test Factors of Safety for Spaceflight Hardware", NASA-STD-5001, 21 June 1996. *N.B.: The current version of the requirements document (E010613-v1), requires a minimum proof test load of 1.2 times the maximum in-service load with a minimum design factor of safety of 3. However, this is really only appropriate for non-pressurized applications. The document will be revised to call for a proof test factor of 2.0 for pressurized applications, such as viewports.*

[2] J. Ritter, D. Coyne, K. Jakus, "Failure Probability at the Predicted Minimum Lifetime After Proof Testing", Journal of the American Ceramic Society, Vol. 61, No.5-6, pp. 213-216

[3] K. Jakus, D. Coyne, J. Ritter, Analysis of fatigue data for lifetime predictions for ceramic materials, J. Materials Science, 13 (1978) 2071-2080.

[4].

$$t_f = BS_i^{N-2}\sigma_a^{-N}$$

where $B = 2/(AY^2(N-2)K_{IC}^{N-2})$, Y is a geometric constant ($\sqrt{\pi}$ for surface flaws), K_{IC} is the critical stress intensity factor and S_i is the fracture strength in an inert environment.

The probability distribution function for the inherent fracture strength is often well modeled by a Weibull function:

$$\ln\left(\ln\left(\frac{1}{1-F}\right)\right) = m\ln\left(\frac{S_i}{S_0}\right)$$

where F is the cumulative failure probability and m, S_0 are constants.

2.2 Material Properties

2.2.1 Fused Silica (SiO_2)

The strength and delayed failure properties of fused silica are discussed in the report[5] on the design, and stress analysis, of the elastomer sealed viewports for aLIGO. Here only a summary of the relevant parameters are restated for convenience.

E = 10.7 10^6 psi (73.6 GPa)

ν = 0.17

m = 4.4

S_0 = 156.5 MPa

N = 40.5

B = 5.1 x 10^{-4} MPa^2 s

A = 7.49 x 10^6 m/s (MPa $\sqrt{m}$)$^{-N}$

K_{Ic} = 0.722 MPa $\sqrt{m}$

2.2.2 Corning 7056 Alkali Borosilicate Glass

The elastic properties of Corning 7056[6] (a glass designed to have a coefficient of expansion matched to Kovar for sealing to glass) are:

E = 62.8 GPa

ν = 0.21

[5] D. Coyne, "Design of the Elastomeric Sealed, High Quality, Viewports", T1100346-v2, section 4.1. The KIc and A values are not reported in T1100346 but available from the principal source for fused silica delayed failure parameters: L. Braun et. al., "Fracture Mechanics and Mechanical Reliability Study: Comparison of Corning Code 7980 and 7940 Fused Silica", NIST, Nov 1998.

[6] MatWeb, Corning 7056 Alkali Borosilicate Crushed/Powdered Glass

I have been unable to find any delayed failure (static fatigue) data in the literature[7] for Corning 7056 glass, or more generally for borosilicate glass. As a consequence, the proof test factor for this glass will default to 2.0.

2.2.3 Zinc Selenide (ZnSe)

The elastic properties of chemical-vapor-deposited (CVD) ZnSe windows are[8]:

$E = 74.3$ GPa

$\nu = 0.31$

and the Weibull distribution parameters for the equibiaxial fracture strength (determined by the maximum likelihood estimator) are:

$m = 9.6$

$S_0 = 60.6$ MPa

With a failure probability of $F = 10^{-5}$ and a lifetime, $t_f = 20$ years:

$S_i = 18.3$ MPa

$\sigma_f = 7.86$ MPa

A NASA report[9] on slow crack growth properties of CVD ZnSe windows showed a remarkably large variation in slow crack growth properties from (or derived from) data in the literature. In my opinion[10] the most appropriate slow crack growth parameters are:

$N = 39.6$

$B = 6.74 \times 10^{-4}$ MPa^2-s

$A = 1.09 \times 10^3$ m/s (MPa $\sqrt{m}$)$^{-N}$

$K_{Ic} = 0.9$ MPa $\sqrt{m}$

However it should be noted that there is a great deal of uncertainty in these values (despite reporting 3 significant digits). The interested reader should consult the source references.

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[7] albeit with a very limited search.

[8] J. A. Salem, "Mechanical Characterization of ZnSe Windows for Use With the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS) Module", NASA/TM-2006-214100, Feb 2006

[9] J. A. Salem, "Estimation of ZnSe Slow-Crack-Growth Properties for Design of the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS) Windows", NASA/TM-2005-213359, Apr 2005

[10] The SCG properties reported in Ref. 9 are derived principally from two other references, which are referred to in Ref. 9 as Ref. 1 and Ref. 2. The Ref. 2 data has large scatter, or was fitted after truncating some of the data for a better fit. For these reasons the Ref. 2 data is suspect in my opinion. The Ref. 1 data set which has the least scatter and has an N value which is consistent with most other data cited in Ref. 9, including Ref. 2, seems the best choice for N and A values. In order to derive a B value, one must use an appropriate K_{Ic} value. In Ref. 9 the K_{Ic} value for small cracks of intergranular or transgranular nature is recommended as conservative. However this value is so conservative that the aLIGO ZnSe viewport would not be predicted to sustain even 1 atm. Consequently, the less conservative, but more realistic K_{Ic} value reported for a dry nitrogen environment is used in my recommended SCG property set.

2.2.4 Calcium Flouride (CaF2)

CaF2 is being considered for use with a laser heater system for transient attenuation on the Input Test Mass (ITM) front surface to be installed as part of the O5 upgrades. This system will utilize quantum cascade lasers (QCLs) operating at 4.65 µm. The system will be known as Central Heater for Transient Attenuation (CHETA). CHETA requires 60 mm clear view, double-glass, In-sealed, AR coated (1064nm, 4650 nm), viewports. CaF2 has high transmission from the UV to the Mid-Wave Infrared (MWIR) with low absorption and high laser damage threshold. However, CaF2 is brittle and subject to slow crack growth.

Material and fracture mechanics property data[11],[12] for CaF2 is as follows:

E = 108 GPa

ν = 0.30

m = 6

S_0 = 70 MPa

N = 33

B = 1.22 MPa^2 s

A = 1.89 x 10^{12} m/s (MPa $\sqrt{m}$)$^{-N}$

K_{Ic} = 0.35 MPa $\sqrt{m}$

3 Stress

3.1 Stress due to the Pressure Load

The response (deflection and stress) of the window/optic due to one atmosphere of load can be estimated by the response of a circular flat plate of constant thickness loaded with a uniform pressure on one side and simply supported at its perimeter[13]:

$$y_c = \frac{-qa^4(5+\nu)}{64D(1+\nu)}$$, the deflection of the plate (window) at the center

$$\sigma_c = \frac{3qa^2(3+\nu)}{8t^2}$$, the stress at the face of the plate (window) at the center

where

a = radius to the simple support (taken as the compressed o-ring I.D.)

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[11] J.A. Salem, "Crack propagation in calcium fluoride single crystals", Proceedings Volume PC13134, Optical Manufacturing and Testing, 1-Oct-2024, Optical Engineering + Applications, 2024, San Diego, CA, USA PC1313409 (2024) https://www.spiedigitallibrary.org/conference-proceedings-of-spie/PC13134/PC1313409/Crack-propagation-in-calcium-fluoride-single-crystals/10.1117/12.3031867.full

[12] J. Salem, R. Rogers, and C. Heb, "Crack propagation in calcium fluoride single crystals", Optical Engineering, July 2023, Vol. 62(7) https://www.spiedigitallibrary.org/journals/optical-engineering/volume-62/issue-7/077102/Crack-propagation-in-calcium-fluoride-single-crystals/10.1117/1.OE.62.7.077102.full

[13] W.C. Young, Roark's Formulas for Stress & Strain, 6th ed., Mc-Graw-Hill, 1989, Table 24, case 10a with r_0=0

q = applied pressure load
t = window thickness
$D = \frac{Et^3}{12(1-\nu^2)}$ is the "plate constant", or stiffness
E = modulus of elasticity
ν = Poisson's ratio

This approximate calculation is reasonably close to finite element results, indicating that the response is primarily plate-like bending[14]. The finite element analysis for the non-wedged, 6 inch, high quality viewport windows[15] is documented in T1100346. The finite element analysis for the TCS viewport ZnSe window[16] is documented in E1100379. In both of these cases the approximate plate bending formulation given above yields a higher (conservative) stress. The approximate plate bending formulae is used for all other viewport designs in section 4.

3.2 Thermal Stress

The only viewports which have some thermal loading are the following:

- PSL injection viewports
- TCS injection viewports

As shown in E1100379, with nominal (low) surface and bulk absorption, the small amount of absorption in the TCS viewport window causes very little temperature increase and insignificant stress. Both of these high power injection viewports (PSL and TCS) have an outer, secondary, window which does not have a differential pressure across it. This window prevents significant surface contaminants (e.g. bugs) from causing increased absorption on the pressurized window.

4 Proof Test

The proof test should have the same stress field as the service stress, except amplified. Since the in-service stress is principally due to differential pressure, the proof stress can be accomplished by simply applying a higher differential pressure.

The minimum lifetime after proof testing is given by:

$$t_{min} = B\sigma_p^{N-2}\sigma_a^{-N}$$

where σ_p is the proof stress, σ_a is the applied, or service, stress and N and B are fracture mechanics material parameters defined above. The applied/service stress is the result of 1 atmosphere of differential pressure load. A proof test would impose a higher differential pressure in order to get the same stress field response except at higher amplitude. Due to the linear elastic response of the window, the proof stress can be expressed as a multiple of the applied/service stress:

$$\sigma_p = x\sigma_a$$

[14] Even though the window is quite thick, its response is dominated by the plate stiffness, D (i.e. the elastic modulus, E, and Poisson's ratio, ν), as opposed to the bulk modulus, K.

[15] D. Coyne, "Design of the Elastomeric Sealed, High Quality, Viewports", T1100346-v2.

[16] M. Jacobson, "Analysis Report of ZnSe Viewports for aLIGO TCS", E1100379-v3. *N.B.: The –v3 version has an error in the finite element analysis under pressure load and will be corrected.*

where x is the number of atmospheres of load to be used in the proof test and σ_a is the applied stress in service.

However the proof test load can be high enough to cause unintended damage if not careful. The viewport is either sealed with an o-ring or a glass-to-metal fused bellows/flexure seal. In the case of the o-ring seal, the proof pressure is generally high enough that the gap between the glass and the viewport flange will close and cause contact between the glass and metal, which can initiate surface flaws that lead to failure, i.e. without proper precaution the proof test can lead to premature failure. As a consequence either (a) a protective thin shim of soft material is placed between the glass and the metal (e.g. kapton), or (b) the window is proof tested separately from the viewport assembly and care is taken not to compromise the glass surface is subsequent handling and assembly. We have chosen the former approach.

In the case of a glass-to-metal fused seal, the proof test load is high enough to cause permanent deflection of the bellows/flexure. In this case the proof test apparatus must provide a soft landing to support the edge of the glass before the bellows/flexure exceeds the elastic limit. In the aLIGO viewport proof tester (D1101939) this is accomplished with a PEEK ring which contacts the outer radius of the face of the window, just inside the o-ring gland, which approximates the boundary condition afforded by the bellows/flexure reasonably well (though of course not exactly).

The proof test values, as well as other relevant parameters, for each of the aLIGO viewport windows is given in Table 1. The proof test levels are based on a 20 year lifetime.

Note that the TCS viewport includes two windows, one comprised of fused silica and the other comprised of zinc selenide. Both of the windows are exposed to the same proof pressure at the same time. Consequently the larger of the two proof pressures should be used (to ensure a 20 year minimum lifetime). This is possible only because the proof test levels for both windows are so similar.

For the commercial viewports which have a metal-to-glass, fused seal, the outer radius of the glass window is assumed to be .25" larger than the clear aperture, based on measurements for one design.

Note that for the large aperture (7.8” diameter) commercial viewports, the Factor of Safety (FS) is only 1.5 with a failure probability, F, of 10^{-2}, whereas for all other windows FS = 3.0 and F = 10^{-5}.

5 Internal Overpressure Limit

If the nominal pressure differential across the viewport is reversed (i.e. the vacuum system is overpressured by the vent/purge-air system), then the outer surface of the window will be placed into tensile stress. The proof test defined in this document does not subject the outer surface of the window to a tensile stress. Nonetheless, we need to set a practical limit on the maximum allowed internal pressure level from the perspective of potential viewport failure. Some background information/references:

- Document T080145-v1, "Viewport Safety Protocols", states that "Volume backfill procedures and equipment should limit internal transient overpressure to 2 psi (10 kPa) [TBR] or less above ambient."
- Document E1200293-v4, "Venting Isolatable Vacuum Volumes at LHO", sets a 1.5 psig limit for operation (not a design limit).

- It has been recently noted at the LHO facility that the pressure regulator on the clean air skid is rated at 1-2 psig and the pressure relief valve next to it is 1.75 psig. The pressure relief valves on the flex tubes are set to 1/3 psig.
- The Advanced Light Source (ALS) project vacuum policy limits overpressure for viewports to 0.5 psi based on a recommendation from Varian[17].

Using the fracture mechanics formalism, and glass material properties, defined in this document, suggests that a 2 psig internal overpressure (reverse pressure) would have a minimum Safety Factor of 14.7 at a cumulative failure probability of .00001 (for all viewport types) based on the allowable stress for a 20 year lifetime, with the following assumptions and caveat (see Table 2):

1. The vacuum-side surface is similar to the air-side surface, i.e. the surface flaw distribution on the vacuum side, which has been proof-tested in a tensile stress state, is statistically similar to the air-side surface, which has not been subjected to a tensile proof stress. This is only true if the same care and handling is applied to both sides. Given our careful inspections, care in handling and requirements to cover all viewports, I think that this is a reasonable assumption.
2. The boundary conditions of the window are not significantly altered by the reversal of the pressure difference. This is certainly the case for the custom viewports with o-ring sealed windows (symmetric design). The covar sealed, commercial viewports used by LIGO (MDC/Larson) have an asymmetric flexure attachment to the glass window. Under vacuum there is a small stress riser in the glass at the edge of the flexure which is covar bonded to the glass[18]. With reversed pressure, the stress in this area is likely in compression; The stress should certainly not be at a higher tensile stress value.
3. For the large commercial viewports (7.8" diameter) is SF = 2.6 for F = .00001 and F = 11.4 for F = .01 (See section 4 for motivation on why this particular viewport is evaluated at a higher failure probability.)

[17] section 5.9 of "Advanced Light Source Vacuum Policy and Vacuum Guidelines for Beamlines and Experiment Endstations", LBL-37713, UC-410, Aug 1995: https://inis.iaea.org/search/search.aspx?orig_q=RN:27031742

[18] A finite element stress analysis of a viewport similar to the nominal 6 inch diameter version used by LIGO was reported on pages 17-21 of the file "2008 07 18 SSV v1.6.ppt" filed in the LIGO DCC entry G080409-v1.

Table 1: Proof Test Levels

										Weibull Parameters											
Type	Supplier	Model Number	Flange OD (in)	Optic material	View Dia (in)	window Radius (in)	Optic thick. (in)	E (GPa)	ν (--)	S0 (Mpa)	m	F	Inert Strength Si (Mpa)	Limit Stress sf (Mpa)	bending stress (MPa)	FEA stress (Mpa)	Factor of Safety	N (--)	B (Mpa^2-s)	proof pressure (atm)	GN2 pressure (psig)
AOS Commercial 6"	Norcal	ZV800	9.97	7056 glass	5.600	3.050	0.375	62.8	0.21						8.07	7.90	2.0			2.00	14.7
AOS Commercial 7.8"	MDC	9722012/450027	9.97	Quartz/ Fused Silica	7.780	4.140	0.375	73.8	0.17	156.60	4.40	1.E-02	55.05	22.71	14.68		1.5	40.5	5.10E-04	2.37	20.1
AOS Commercial 4.5"	MDC	450004	4.47	7056 glass	2.690	1.595	0.17	62.8	0.21						10.74		2.0			2.00	14.7
AOS High Quality 6"	LIGO	D1100999	9.97	Fused Silica	5.240	2.669	0.75	73.8	0.17	156.60	4.40	1.E-05	11.44	5.10	1.53	1.47	3.5	40.5	5.10E-04	2.10	16.2
AOS High Quality 6", wedged	LIGO	D1101000	9.97	Fused Silica	5.240	2.669	0.87	73.8	0.17	156.60	4.40	1.E-05	11.44	5.10	1.13		4.5	40.5	5.10E-04	2.07	15.8
AOS High Quality 6", septum	LIGO	D1101535	9.97	Fused Silica	5.240	2.669	0.75	73.8	0.17	156.60	4.40	1.E-05	11.44	5.10	1.53	1.47	3.5	40.5	5.10E-04	2.10	16.2
AOS High Quality 6", septum,	LIGO	D1101092	9.97	Fused Silica	5.240	2.669	0.87	73.8	0.17	156.60	4.40	1.E-05	11.44	5.10	1.13		4.5	40.5	5.10E-04	2.07	15.8
TCS Dual 3"	LIGO	D1003194	9.97	Fused Silica	2.250	1.306	0.5	73.8	0.17	156.60	4.40	1.E-05	11.44	5.10	0.82		6.2	40.5	5.10E-04	2.04	15.3
				ZnSe	2.250	1.306	0.5	74.3	0.31	60.60	9.60	1.E-05	18.27	7.86	0.86	0.76	10.3	39.6	6.74E-04	2.05	15.5
PSL High Power, 6" (non-wedged)	LIGO	D1101670	9.97	Fused Silica	5.240	2.669	0.75	73.8	0.17	156.60	4.40	1.E-05	11.44	5.10	1.53	1.47	3.5	40.5	5.10E-04	2.10	16.2
PSL High Power, 6", wedged	LIGO	D1101714	9.97	Fused Silica	5.240	2.669	0.87	73.8	0.17	156.60	4.40	1.E-05	11.44	5.10	1.13		4.5	40.5	5.10E-04	2.07	15.8
CaF2 CHETA	?	?	9.97	CaF2	2.362	1.378	0.5	108.0	0.30	70.00	6.00	1.E-05	10.27	4.86	0.95		5.1	33	1.22E+00	1.90	13.3

Table 2: Internal Overpressure Limits

					2.00	reverse pressure (psig)
Type	Supplier	Model Number	Flange OD (in)	Optic material	bending stress (Mpa)	Factor of Safety
AOS Commercial 6"	Norcal	ZV800	9.97	7056 glass	1.10	14.7
AOS Commercial 7.8"	MDC	9722012/450027	9.97	Quartz/ Fused Silica	2.00	11.4
AOS Commercial 4.5"	MDC	450004	4.47	7056 glass	1.46	14.7
AOS High Quality 6"	LIGO	D1100999	9.97	Fused Silica	0.21	24.6
AOS High Quality 6", wedged	LIGO	D1101000	9.97	Fused Silica	0.15	33.1
AOS High Quality 6", septum	LIGO	D1101535	9.97	Fused Silica	0.21	24.6
AOS High Quality 6", septum,	LIGO	D1101092	9.97	Fused Silica	0.15	33.1
TCS Dual 3"	LIGO	D1003194	9.97	Fused Silica	0.11	45.6
				ZnSe	0.12	67.4
PSL High Power, 6" (non-wedged)	LIGO	D1101670	9.97	Fused Silica	0.21	24.6
PSL High Power, 6", wedged	LIGO	D1101714	9.97	Fused Silica	0.15	33.1
CaF2 CHETA	?	?	9.97	CaF2	0.13	37.5