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Long Term Reliability of Large ULE™ Mirror Blanks

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ABSTRACT

ULE™, the titania-silica binary glass with zero expansion coefficient, is an ideal material for large telescope mirror blanks due to the unique combination of its optical, thermal and mechanical properties-together with the ease of fabrication-which help meet performance and durability requirements in a cost-effective manner. Indeed, the 8m class Subaru and Gemini telescope mirror blanks have been fabricated successfully from ULE glass and will be in full operation in the not too distant future.

This paper will focus on the stringent reliability requirements which the mirror blank must meet during fabrication, transportation, installation and operation atop high mountains with extreme environmental fluctuations. In particular, the paper will present strength and fatigue data for ULE glass as a function of surface finish. Such data are critical for selecting the appropriate surface finish to ensure mechanical reliability of the mirror blank at various stages of fabrication and during transportation. The use of Weibull statistical distribution for surface flaws combined with Power Law fatigue model helps arrive at a safe stress level which should not be exceeded to ensure the mechanical reliability of the mirror blanks. The safe stress level is verified through independent static fatigue tests on ULE discs with surface finish identical to that of the mirror blank. In this manner the mechanical reliability of large ULE mirror blanks can be ascertained at extremely low failure probabilities. The successful application of reliability model to both Subaru and Gemini mirror blanks will be illustrated.

Keywords: 8-m mirror, mechanical reliability, ULE™, safe allowable stress, strength and fatigue.

1. INTRODUCTION

ULE, a binary titania-silica glass made by Corning,* offers dimensional stability due to its essentially zero thermal expansion coefficient over a wide temperature range representative of operating ambient conditions[1]. This glass is manufactured by the flame hydrolysis process which introduces chemical vapors into gas-oxygen burners at approximately 1700°C. The combustion reaction forms sub-micron size molten titania-silica particles. The burners are aligned over a rotating table where the particles are collected and fused into a large dense solid boule of ULE, typically 1.5 m in diameter by 15 cm thick. Homogeneity is ensured through strict process control and by utilizing high-purity chemicals that are not subject to the ordinary compositional variations and contaminants of sand and other raw materials of conventional glass melting processes. The coefficient of thermal expansion (CTE) of ULE is dependent on the glass composition and is therefore subject to tight process control and minimal process variation. ULE is an amorphous, binary glass with no crystalline phases present. This differentiates it from other low expansion materials, such as the glass-ceramics Zerodur®† and AstroSitall‡ whose properties are dependent on controlled crystal growth in a glassy matrix. ULE is isotropic, meaning that its properties are the same in all directions, at any given location in a mirror or structure. This is critical for the predictability and preservation of optical figure.

2. MIRROR FABRICATION TECHNIQUES

Solid mirror blanks of virtually any diameter, thickness, and shape can be manufactured from ULE using Corning's fusion sealing processes. Single boules can be made into blanks up to 1.4 m diameter. Single or multiple boules can be flowed out to produce blanks from 1.4 to 2.7 m diameter. Flowout is a Corning process in which a boule or a stack of boules is heated under controlled conditions and the molten glass is flowed to the required diameter. In addition, plano discs of ULE

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*ULE™ is a trademark of Corning Incorporated ULE is available as Corning Code 7971 Corning is currently in the process of developing an alternate process using different raw materials to produce ULE, which will be marketed as Corning Code 7972 glass can be sagged to form contoured parts. This results in lower material cost and reduced grinding time. The plano blank is placed on a refractory sagform (convex mold) and heated above the softening point allowing the glass to sag under its own weight to take the shape of the sagform; see Figure 1.

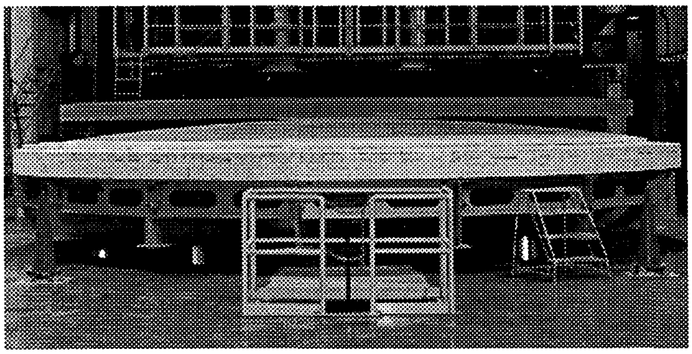

Figure 1. Sagging of 8 m Plano ULE Mirror Blank on Refractory Sagform

For mirrors larger than 2.7 m, Corning's hex seal process can be used.[2,3] The hex seal technique uses high temperature to fusion seal hexagonal-shaped ULE or fused silica building blocks into one monolithic piece. The hex seal process has been used successfully to produce three 8-m class meniscus mirror blanks: the 8.3 m mirror blank for the National Astronomical Observatory of Japan's SUBARU telescope and the two 8.1 m mirror blanks for the Gemini 8-m Telescopes Project. Because ULE glass can be fused with no loss in quality or strength at fusion seams, it is an ideal building block material. The hex seal process involves wire-sawing and grinding disks into hexagons, fitting together full and partial hexagons, and then fusing them at high temperature to form the mirror blank. Specifically, the manufacturing of sagged 8-m mirror blanks, depicted in Figure 2, involves the following steps:

i) fabrication of 1.5 m diameter x 15 cm thick ULE boules;
ii) stacking and fusing of two boules in a furnace to form a 30 cm thick disc;
iii) wire-sawing and grinding of above discs into hexagons of final dimensions;
iv) assemblage of full and partial hexagons in a prescribed pattern on the turntable;
v) fusing of above assembly on a rotating turntable in a furnace to form a circular blank of required diameter;
vi) grinding of the top surface using the turntable and a computer controlled grinding wheel mounted on a vertical spindle affixed to a gantry crane;
vii) turnover of the blank, using specially designed equipment, for grinding the bottom surface;
viii) removal of the blank from the turntable for placement onto a refractory sag form for sagging in a furnace to the prescribed concave shape;
ix) controlled cooling of the sagged blank to room temperature followed by packing and shipping to the mirror polisher.

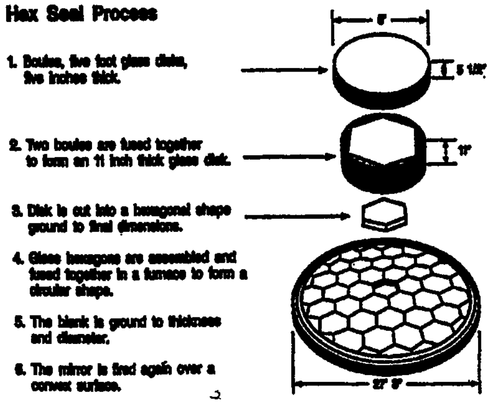

Figure 2. Corning's Hex Seal Process

These large solid mirror blank fabrication processes can also be applied to the manufacture of individual components for large lightweight mirrors. Examples of mechanical reliability analyses conducted during the 8 m blank manufacture will be discussed next.

3. MECHANICAL RELIABILITY

As noted in the preceding sections the fabrication of large monolithic ULE mirror blanks involves multiple processing steps. Each of these steps induces mechanical stresses in the mirror blank over a finite period of time. To ensure mechanical reliability of the blank, it is critical to control the stress/time history via design and process parameters thereby minimizing the growth of subsurface damage during the manufacturing process[4]. Alternatively, the subsurface damage associated with grinding and polishing can be minimized via finer grit size, slower removal rate, or acid etching, all of which impose economic penalty on the fabrication cost. However, such measures enhance the mechanical reliability of mirror blanks during fabrication, coating, transportation, installation, and operation.

The process of enhancing mechanical reliability begins with the analysis of stress/time histories the blank experiences during manufacturing and shipping. Several critical processing steps must be analyzed including rough grinding, turnover, fine grinding, acid etching, sagging, contour grinding, and packing and shipping of sagged and generated blanks. This is followed by mechanical characterization of ULE glass, involving concentric ring flexure tests on a large sample of glass discs, with different surface finishes representative of various manufacturing steps[2]. The Weibull analyses of biaxial strength and fatigue data obtained from these tests help determine the minimum strength and fatigue constant corresponding to an acceptable level of failure probability[5]. The minimum strength is further discounted to allow for large surface area of the mirror blank compared with that of disc specimens. Similarly, the Power law fatigue model helps account for finite stress duration the blank is exposed to during manufacturing by adjusting the minimum strength further[3]. In this manner, the safe stress/time history is deduced for the 8-m class blank using disc data generated in the laboratory. By safe stress we mean a stress value that will limit the failure probability of the mirror blank during its manufacture to an acceptably low level, e.g. 1×10^{-6}. Verification of safe stress/time history is carried out by subjecting several groups of discs to different biaxial static stresses in 100% relative humidity for extended periods of time, representative of different manufacturing steps, and re-measuring their strength at the end of static tests. If there is no indication of strength degradation following static tests, then there is no subsurface crack growth and the recommended stress/time history for a given surface finish is indeed a safe one[4]. Conversely, the above approach helps optimize the surface finish and control subsurface damage via grinding, polishing and etching, if necessary, to sustain specified stress/time histories during the manufacture of large mirror blanks. Additional control of subsurface damage during processing also facilitates subsequent handling, packaging, and transportation of generated blanks to the polisher.

4. STRENGTH AND FATIGUE CHARACTERISTICS

The design strength of annealed bulk glass is customarily taken as 1000 psi[4]. This is the maximum value of static value of static tensile stress which the designer of glass components may allow in service. It is based on many years of design experience, laboratory tests, customer feedback and the glass manufacturer's goal of ensuring long-term reliability. It is derived as follows.

> The sandblast abrasion yields a strength value of about 6000 psi for most glasses[6,7]. However, real-life abrasion (due to excessive handling) based on strength tests on glass components which have been in service for several years tends to be twice as severe—thereby reducing the strength to 3000 psi. Such a strength value is the amount of stress which the glass can support for short time (1 to 2 secs.). To ensure long-term reliability over a service life of 40 years or more, the short-term abraded strength must be discounted further by a factor of 3. This reduces the strength from 3000 to 1000 psi, commonly known as the threshold value, and is taken as the design strength. Since crack growth at this stress level is negligibly small, glass designs based on 1000 psi service stress fall in the category of subthreshold design.

Most of the bulk glass products, as noted above, are designed and manufactured to limit the static service stress to below the threshold level. Such a subthreshold designensures safe operation of the article throughout its lifetime and minimizes product liability cost for the glass manufacturer. In the case of telescope mirror blanks, their 8^{+}meter diameter translates into an order of magnitude larger surface area than most bulk products with higher probability of encountering critical flaws. Furthermore, their orders of magnitude greater weight poses the risk of inflicting surface damage each time they are handled during manufacturing and transportation. Finally, the acceptable failure probability for such unique, high cost, structures must be kept several orders of magnitude lower than that of most bulk glass products. These considerations reduce the design strength of ULE mirror blanks to 750 psi assuming two orders of magnitude lower failure probability than that of other bulk products.

ULE glass contains silica as a continuous phase whose titania content is adjusted to achieve the ultra low thermal expansion coefficient. The Si-O-Si bond is the strongest oxide bond and renders these materials super strong, at least theoretically. However, when subjected to tensile stress in humid environment, it becomes highly reactive and transforms to Si-OH bond through a series of chemical reactions involving exchange of protons and electrons[8]; see Figure 3. The weak Si-OH bond cannot support much stress and severs easily resulting in flaw growth and gradual loss of strength. This phenomenon, known as stress corrosion cracking or static fatigue, has received much attention over the last three decades and is often used to estimate the safe allowable stress for glass structures like large telescope mirrors[9-11]. Since chemical reactions are activated processes, static fatigue in silicate glasses is also an activated process in which the activation energy is stress-dependent and the reaction rate is governed by both the stress field and environmental conditions at the flaw tip[12].

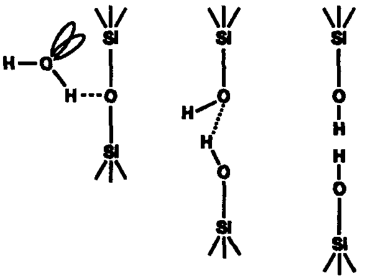

Figure 3. Stages of Stress Corrosion in Silicate Glass and Glass-ceramics

Stress corrosion in silicate glasses is commonly described by Power law[11] which relates the rate of crack growth, dc/dτ, to stress intensity, K_I, at the crack tip:

$$\frac{dc}{d\tau} = AK_I^n \tag{1}$$

In eqn. 1, A and n are constants, c is crack or flaw depth, τ is time and:

$$K_I = Y\sigma_a\sqrt{c} \tag{2}$$

in which Y is the flaw shape parameter and σ_a is the applied stress. The constant n is also called stress corrosion susceptibility constant, or simply fatigue constant, and is most conveniently determined by measuring the strength of glass, σ_f, as function of stress rate, $\dot{\sigma}$, in humid environment. Integration of eqn. 1 provides the following relationship:

$$\sigma_f = C(\dot{\sigma})^{1/(n+1)} \tag{3}$$

in which C is a constant. Thus, the strength of silicate glasses depends nonlinearly on the rate of stressing. Since the exponent 1/(n+1) is small for large values of n and large for small values of n, glasses with small values of n exhibit greater fatigue than those with large values of n. For example, if $n \rightarrow \infty$, the glass becomes insensitive to fatigue and its strength remains constant regardless of stressing rate.

Application of eqn. 3 to strength data at two different stress rates provides the n value:

$$n = \left(\frac{\ln \dot{\sigma}_1 - \ln \dot{\sigma}_2}{\ln \sigma_1 - \ln \sigma_2} \right) - 1 \tag{4}$$

Dynamic fatigue tests for ULE glass were carried out on 15cm diameter x 6mm thick discs with 240 grit surface finish using the concentric ring fixture and 100% relative humidity (both the 240 grit grinding media and 100% RH were selected to provide a conservative value of n). Approximately 8 discs were tested at each of the four stress rates, namely 220, 22, 2 and 0.1 psi/sec. The strength vs. stress rate data are plotted on log-log scale in Figure 4. The slope of the best fit line through these data provides a measure of stress corrosion constant n per eqn. 4. A mean value of n = 41.3 is obtained from this plot with a 95% confidence interval of 24.1 to 135.1. The low end of this interval will be used for a conservative estimate of safe allowable stress during manufacturing, handling, shipping and installation of the mirror as well as in service.

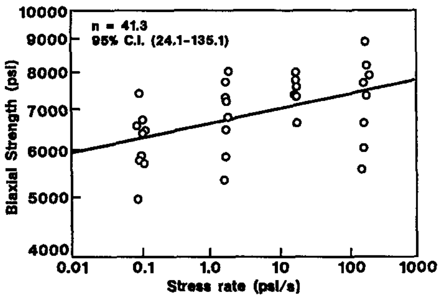

Figure 4. Dynamic Fatigue Data for ULE Discs with 240 Grit Surface in 100% RH

To assess the mechanical reliability of the mirror during the various manufacturing steps, we examine the impact of stress corrosion on design stress for ULE glass. The design stress, σ_d, is dictated by both the stressed area of mirror, A_m, relative to that of disc specimens, A_d, and the stress duration of critical manufacturing step, τ_s:

$$\sigma_d = \sigma_f \left(\frac{A_d}{A_m} \right)^{1/m} \left[\frac{(\sigma_f / \dot{\sigma}) / (n+1)}{\tau_s} \right]^{1/n} \tag{5}$$

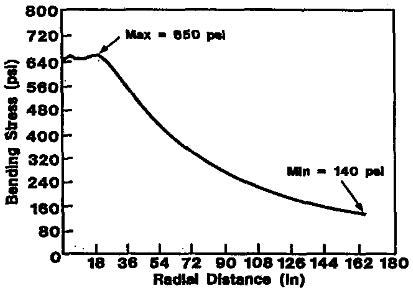

Figure 5. Bending Stress Profile on Sagform

In eqn. 5, σ_f denotes the specimen strength corresponding to an acceptable level of failure probability, $\dot{\sigma}$ denotes the stress rate for measuring σ_f, and m denotes Weibull slope of strength distribution[5]. The most critical manufacturing step in terms of stress/time history for 8m ULE blanks is the sagging step with a duration of nearly two weeks[2], i.e. $\tau_s = 1.2 \times 10^6$ sec; see Figs. 1 and 5. Substituting mean MOR and stress rate values from Table 1 and using the minimum value of n from Table 2 for a conservative estimate of design stress into eqn. 5, we obtain for ULE mirrors:

$$\sigma_d = 0.57\,\sigma_f\,(A_d / A_m)^{1/m} \tag{6}$$

Table 1. MOR Data for ULE Glass with 220-240 Grit Surface Finish

Mirror Material	N	MOR (psi)	Stress Rate (psi/sec)	S.D. (psi)	m	c_f meas. (10^{-3} in)	c_f eqn. 2 (10^{-3} in)
ULE	8	7740	220	1125	6.1	4.7	4.7

Table 2. Fracture and Fatigue Properties of ULE Glass

Mirror Material	Fracture Toughness K_{Ic} (MPa$\sqrt{\text{m}}$)*	Stress Corrosion Constant n N	Stress Corrosion Constant n Mean	Stress Corrosion Constant n 95%C.I.
ULE	0.70	31	41.3	24.1-135.1
*1 MPa$\sqrt{\text{m}}$ = 910 psi$\sqrt{\text{in}}$				

5. SAFE ALLOWABLE STRESS AND ITS VERIFICATION

To estimate the safe allowable stress, it is first necessary to know the stressed area A_m and stress duration τ_s of the mirror blank during its various manufacturing steps. Only two of these steps are considered critical for the ULE 8m blank due to either the high stress or long stress duration or both. These are summarized in Table 3. The safe allowable stress for the mirror blank is synonymous with design stress, namely:

$$\sigma_s = \sigma_d = \sigma_f \left(\frac{A_d}{A_m}\right)^{1/m} \left[\frac{(\sigma_f/\dot{\sigma})/(n+1)}{\tau_s}\right]^{1/n} \tag{7}$$

Table 3. Stressed Area, Maximum Stress and Stress Duration During Critical Manufacturing and Shipping Steps for ULE Mirror Blanks with Two Different Surfaces Finishes

Manufacturing Step	Stressed Area A_m (in^2)	Max. Stress Duration τ_s (sec.)	Max. Operating Stress (psi)	Surface Finish
Sagging of blank on sagform	6470	1.2×10^6	750	270/325 grit + etching
Transportation of sagged blank	960	7.9×10^6	435	120 grit

Tables 4 and 5 provide the total disc area subjected to stress σ_f, corresponding to a failure probability of 1 x 10^{-6}, for an equivalent static duration of $[(\sigma_f/\dot{\sigma}) / (n + 1)]$, together with the pertinent Weibull slopes and fatigue constants representing the surface finish relevant to the two critical manufacturing steps. The 270/325 grit finish followed by acid etching was deemed appropriate for the sagging step due to high stress and relatively long stress duration. Similarly, the 120 grit finish was selected for those areas of mirror blank subjected to lower stress over an extended period of time during its transportation to the polisher.

Using the data in Tables 3, 4 and 5, both the area reduction factor and fatigue factor in eqn. 5 can be computed. The safe allowable stress σ_s is then estimated by using eqn.7 and σ_f values from Table 4.

Table 4. Strength of ULE Discs Corresponding to Failure Probability of 1x10^{-6}

Surface Finish	σ_d (P_f = 1x10^{-6}) (psi)	No. of Discs Tested N	Total Area Ad Subjected to Max. Stress σ_d (in^2)
120 grit	3430	20	54
120 grit + etching	3050	19	51
270/325 grit	4720	25	67
270/325 grit + etching	3175	22	59

Table 5. Stressed Area, Stress Duration, Weibull Slope and Fatigue Constant for ULE Discs with Two Different Surface Finishes

Manufacturing Step	Max. Disc Area A_d (psi)	Equivalent Static Duration for Strength Measurement (sec.)	Weibull Slope m	Fatigue Constant n	Surface Finish
Sagging of blank on sagform	59	1.65	13.2	24.1	270/325 grit + etching
Transportation of sagged blank	54	1.20	24	24.1	120 grit

The results of these computations are summarized in Table 6 which also shows the maximum operating stress on mirror blank during sagging and shipping. Let us note that the allowable stress is nearly 2 to 4 times larger than the operating stress providing an additional safety margin for high reliability during manufacturing. These safety margins are a direct consequence of high m and n values, i.e. low variability in strength distribution due to consistent finishing process and high fatigue resistance of ULE glass.

Table 6. Estimate of Safe Allowable Stress for ULE Mirror Blank during its Critical Manufacturing and Shipping Steps for Failure Probability of 1x10^{-6}

Manufacturing Step	Disc Strength at P_f = 1x10^{-6} (psi)	Area Reduction Factor	Fatigue Factor	Safe Allowable Stress σ_s (psi)	Max. Operating Stress (psi)
Sagging of blank on sagform	3175	0.70	0.65	1450	750
Transportation of sagged blank	3430	0.89	0.60	1820	435

To verify the ultimate reliability of a mirror blank, eight discs with 270/325 grit surface finish plus acid etching were subjected to a static biaxial stress of 800 psi in 100% RH for 14 days. Their strengths were re-measured after 14 days and found to be identical to the initial distribution as shown in Figure 6. This confirmed that the sagform stress of 750 psi was below the threshold value for acid-etched 270/325 grit surface finish and would not lead to slow crack growth. Needless to say, all of the 8-m class mirror blanks, manufactured at Corning to date, have survived the sagging stresses with no evidence of flaw growth. Similarly, to evaluate the reliability of a generated mirror blank, ten ULE discs with 120 grit surface finish were subjected to a static biaxial stress of 435 psi in 100% RH for 90 days. Their strength was re-measured after 90 days and found to be identical to the initial distribution as shown in Figure 7.

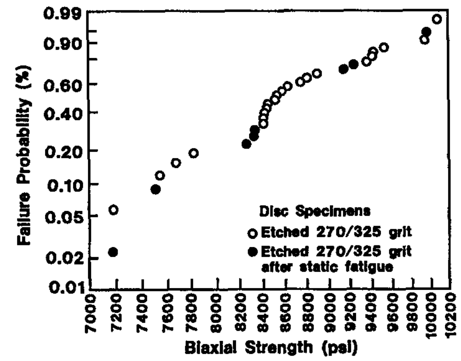

Figure 6. Effect of Static Stress on Strength Distribution of ULE Discs with 270/325 Grit Surface: σ_s = 800 psi, τ = 14 days, T = 25°C, RH = 100%

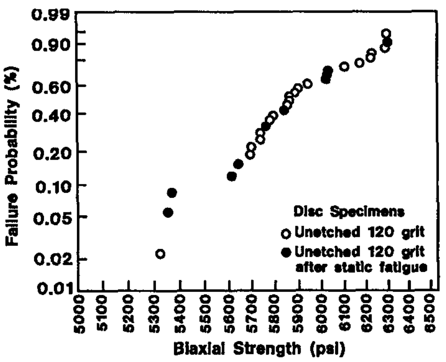

Figure 7. Effect of Static Stress on Strength Distribution of ULE Discs with 120 Grit Surface: σ_s = 435 psi, τ = 90 days, T = 25°C, RH = 100%

Thus, no slow crack growth is expected on the 120 grit surface due to a long-term static stress of 435 psi. It is worth pointing out that the additional safety factor of two to four in the above computations not only promotes mechanical reliability of mirror blanks, it does so at an ultra low failure probability $< 1 \times 10^{-6}$ as may be verified from Weibull distribution function[5] given by eqn. 8.

$$P_f = 1\text{-}\exp\left[-(\sigma/\sigma_0)^m\right] \tag{8}$$

In eqn. 8, P_f denotes failure probability corresponding to stress σ, and σ_0 and m are Weibull parameters.

6. SUMMARY

Thus, the mechanical reliability of very large monolithic mirror blanks during their fabrication requires thorough understanding of stress/time history at each of the manufacturing steps. Such knowledge helps select an appropriate surface finish with strength and fatigue characteristics capable of sustaining manufacturing stresses without measurable crack growth in corrosive environment. The latter is ascertained by comparing strength distributions before and after subjecting a large sample of glass discs to static stress in corrosive environment over a finite period of time, representative of the process, and making sure that the two distributions are indistinguishable. Thus, a 270/325 grit surface finish is deemed appropriate for the sagging step which induces a static stress of 650 psi over the two-week period, and a 120 grit surface finish is appropriate for transporting the mirror blank which induces a static stress of 435 psi over the three-month period.

The use of biaxial strength and fatigue data, obtained by testing a large sample of 15 cm discs, together with Weibull distribution helps estimate a safe allowable stress for the mirror blank during its manufacture and transportation taking full account of stress/time history, test environment and ultra low failure probability.

7. ACKNOWLEDGEMENT

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8. REFERENCES

[1]Gulati, S.T. and Edwards, M.J.; "ULE™-Ultralow Expansion, Low Density and Dimensionally Stable Material for Lightweight Optical Systems," *SPIE Conference*; San Diego, CA; July 26-28, 1997.

[2]Gulati, S.T. and Powell, W.R., "Mechanical Reliability of 8m Class ULE™ Glass Telescope Blanks during Manufacturing, "SPIE Proc.; 2546 (1995).

[3]Gulati, S.T., "Optimization of Surface Finish of 8m Class ULE'Glass Telescope Mirror Blanks for Lifetime Mechanical Reliability, "SPIE Proc., 2774 (1996).

[4]Gulati, S.T.; "Dynamic and Static Fatigue of Silicate Glasses under Biaxial Loading: Application to Space Windows, CRTs and Telescope Mirrors," *5th International Otto Schott Colloqium*, Jena Germany; July 10-14, 1994.

[5]Weibull, W.; "A Statistical Distribution Function of Wide Applicability; "J. App. Mech., Vol. 18; 1951.

[6]Kerper, M.J.; Lathey, C. and Robinson, E.R.; "Properties of Glasses at Elevated Temperatures," WADC Tech. Report-56-645, Part I, National Bureau of Standards, Washington, D. C.; 1956.

[7]Kerper, M.J. and Scuderi, T.G.; "Modulus of Rupture in Relation to Fracture Pattern;" Ceramic Bulletin, Vol. 43, No. 9; 1964.

[8]Micahlske, T.A. and Bunker, B.C.; "The Fracturing of Glass;" *Scientific American*, Vol. 257, No. 6; Dec. 1997.

[9]Wiederhorn, S.M. and Bolz, L.H.; "Stress Corrosion and Static Fatigue of Silicate Glass," J. Am. Ceram. Soc., 53, 10 (1970).

[101]Wiederhorn, S.M.; "Subcritical Crack Growth in Ceramics, "Fracture Mech. of Ceramics, Plenum Press, New York; 1974.

[11]Ritter, J.E. and Sherburne, C.L.; "Dynamic and Static Fatigue of Silicate Glasses;" J.Am. Ceram. Soc., 54, 12 (1971).

[12]Gulati, S.T. and Glaesemann, G.S.; "Design Methodology for the Mechanical Reliability of Optical Fiber;" Optical Engineering Journal; 1991.