Finishing and proof testing of windows for manned space craft

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ABSTRACT

The development of the Space Shuttle Orbiter in the early 1970's marked the first time that a fracture mechanics approach was taken to the design of the window systems of a manned space craft. Earlier vehicles were never subjected to repeated launch and re-entry and therefore fatigue or slow crack growth were not a major concern.

The design and proof test methodology evolved at that time continues to be applied in the development of the window systems for the Space Station "Freedom". A combination of fixed abrasive grinding, lapping and chemical machining is employed on the fused silica window panes to insure that sub-surface damage is carefully controlled and minimized. All panes are proof tested under controlled atmospheric conditions which preclude crack growth during the test.

This paper also covers some of the history of space craft window design, the rationale for the material choices as well as a review of the finishing and test methods employed.

Material choices for space craft windows are dictated by the following conditions: pressure loading, temperature extremes, thermal shock, radiation darkening, visible, UV and IR transmittance as well as the commercial availability of materials meeting the functional requirements. The paper discusses how these factors differed for space craft ranging from the sub-orbital North American X-15 through Mercury, Gemini, Apollo, Sky Lab and the Shuttle Orbiter to the Space Station "Freedom".

1. INTRODUCTION

In spite of the fact that glass is inherently a very strong material, design of critical components - ones in which failure could be life threatening - is very difficult. The extreme sensitivity to surface flaws of this brittle family of materials dictates a high level of conservatism, but weight considerations, which cannot be ignored in space craft, demand that designs be optimized for weight and safety.

The use conditions encountered in all phases of space flight, launch, orbit and re-entry, dictate the required material properties. Launch conditions can involve shock and vibration and internal and external pressurization, but usually no extreme thermal conditions. In orbit the window system must withstand cabin pressure, shield the astronauts from damaging radiation without darkening, survive hypervelocity particle impact and yet provide a clear, undistorted view. In re-entry extreme heating is encountered which results in center to edge temperature gradients and corresponding hoop tensile stresses in the edges of the outer panes.

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2. TYPICAL SPACE CRAFT WINDOW DESIGNS

Over the years a typical space craft window system has evolved in which each window consists of three independent (unlaminated) panes (fig. 5). The outermost one, in vehicles subjected to re-entry, needs to be an inherently high temperature, thermal shock resistant material because of the intense heat generated when re-entering the atmosphere. Fortunately fused silica meets these criteria. It is also unique in that it doesn't darken under the influence of the harsh radiation environment of space. The design employed by the Space Shuttle features a redundant pane as the center one of the three pane configuration. It is intended to be able to perform the function of both the thermal (outer) pane as well as the pressure (inner) pane. The material of choice is again fused silica, only this pane is considerably thicker than the thermal pane in order to be able to safely withstand cabin pressure, should the primary pressure pane fail. The pressure pane typically is a strengthened (tempered) alumino silicate glass. Alumino silicate glasses are distinguished by moderately low thermal expansion, high strain point and a UV cut-off somewhat better (longer wavelength) than conventional soda lime glass.

3. SLOW CRACK GROWTH AND FATIGUE IN GLASS

Prior to the development of the Space Shuttle, fatigue and slow crack growth were a consideration in the design process only to the extent that conservative design criteria were employed which had their origins in the somewhat limited understanding that under long term loads glass exhibits substantially less strength than when rapidly loaded. No effort was made to define finishing or proof test requirements based on fracture mechanics criteria. Glass failure did occur during at least one of the early orbital flights, but luckily it was an instrument cover glass and not a window. Nevertheless, this mishap called attention to the fatigue phenomenon and in a small way paved the way for a much more scientific design approach on the Shuttle windows.

It is well known that the strength of glass decreases when it is subjected to tensile stress in the presence of moisture (see fig. 6). This phenomenon occurs even when the stress is well below the short term breaking strength of the material. It is known as static fatigue and is due to slow crack growth. Three conditions must be present in order for glass to fatigue. There must be one or more surface flaws which, because of the lack of any yield mechanism in glass, act to concentrate the stress at the crack tip. There must be some minimum level of tensile stress and there must also be moisture present. Water weakens the silicon-oxygen bonds at the crack tips and in the absence of moisture, no slow crack growth occurs. According to S.C. Keeton,[1] the most likely mechanism by which water effects the fatigue characteristics of glass is the formation of silanol sites on the glass surface which reduces the Si-O bond strength in the immediate neighborhood of the site.

Common design practice is to use 1000 psi as the maximum allowable tensile stress in annealed glass. This represents about a 2:1 safety factory when one considers that a lower limit for stress which can cause slow crack growth in an abraded glass body is about 2000 psi. This standard was unacceptable for the space shuttle windows because it would have led to excessively heavy windows. But, in order to deviate from the conventional, conservative design practice, a whole new methodology for design, analysis, fabrication and testing had to be developed. The new approach was based on the several premises. The first is that in tempered glass fatigue is of no concern because tempering induces residual compressive stress in the surface of the glass and unless that compressive stress is completely relieved by applying very large external loads, no slow crack growth occurs (see fig. 7). There is therefore no concern regarding static fatigue with the tempered alumino silicate pressure panes. Unfortunately, because of its low expansion coefficient, thermal tempering is not possible with fused silica. But, on the other hand, fused silica was known to be less severely effected by conditions leading to fatigue in glass and, also, one can control the threshold stress at which slow crack growth is initiated by controlling the flaw population in the surface of the glass.

It was determined, by means of finite element analysis, that a maximum stress of just over 2800 psi in the thermal pane would lead to an acceptable thickness. The problem then became one of specifying the finishing operations such that the residual flaws left by grinding would not grow when subjected to repeated loading to that stress level. Also, a proof test at 8500 psi had to be devised which would assure safe performance at the 2800+ psi stress level and yet not weaken at the glass as a result of the test.

Inglis[2] found that for an elliptical shaped crack in purely elastic solids the ratio of the maximum stress developed at a crack tip to the applied stress can be approximated by the following relationship:

$$\frac{s\,\text{max.}}{s\,\text{appl.}} = 2\sqrt{\frac{l}{r}}$$

where l is the crack depth and r the radius of curvature at the crack tip. If one assumes a theoretical strength of 2 million psi, a crack tip radius of 40 Angstroms (0.15 millionth of an inch) and an applied stress of 8700 psi, the calculated crack depth is 0.002".

4. SUB-SURFACE DAMAGE FROM GRINDING

It was well known that grinding of glass involves not only visible and measurable surface damage but also sub-surface flaws which can only be detected after a special chemical etching process. Stoll, Forman and Edelman of Perkin Elmer[3] published the results of a study relating the strength of fused silica to the details of the grinding sequence used. They found that for fixed abrasive grinding the depth of sub-surface damage was approximately three times the size of the grinding media used. Additionally it turned out that the depth of measurable damage in the actual surface was of about the same magnitude as the size of the abrasive particle. Based on these findings, one can make the assumption, which is actually quite conservative, that a visible flaw in the surface of a polished window may have associated within it an invisible flaw as much as three times as deep. A consequence of this assumption is that any window with a visible surface flaw deeper than 0.0006" is rejected. (0.0006" is roughly one third of the 0.002" calculated crack depth, above).

A finishing sequence was designed in which each step subsequent to the first always removes at least an amount equal to three times the grit size of the previous step. While the actual sequence is proprietary, it can be said that on the surfaces two fixed abrasive diamond grinding steps are followed by an acid polishing operation which, while it is intended primarily to insure high strength edges, also provides an essentially flawless starting point for the final mechanical finishing operations. One additional fine diamond grinding step on each surface is then followed by three loose abrasive lapping steps and finally polishing with cerium oxide. The edges are finished with four progressively finer fixed abrasive grinding operations followed by the acid polishing step.

5. MAPPING AND PROOF TESTING

Edge lighting is probably the most effective way to inspect both the interior and the surfaces of polished windows for inclusions and surface flaws. The window edge is positioned over a fluorescent light source and viewed against a black background. A mylar map is prepared which shows the location and size and type of all defects. This map is furnished to the customer after the finished window has passed a proof test so that any new damage incurred in use can be differentiated from that which was in the glass at the time of shipment.

Prior to shipment all space craft windows are proof tested at a pressure which results in three times the maximum stress expected to be encountered in use. In order to insure that the test does not result in any slow crack growth and thereby degrades the window, an atmosphere of dry nitrogen is introduced into the test chamber. Prior to pressurization the window is also heated to drive any residual moisture from the surface and any flaws which may still be present on the surface. Since the actual maximum operating stress is about 2800 psi, the stress specified for the proof test is 8500 psi. The fact that the failure rate at this stress level is very low attests to the excellence of the finish achieved when the "prescription" approach described above is employed. When ordinary finishing techniques are employed, the modulus of rupture of fused silica is typically between 7 and 8000 psi. The technique employed on the space craft windows results in 12-14,000 psi as determined by the use of witness pieces which are finished alongside the actual windows.

In the event of a proof test failure, every effort is made to locate the origin and identify the nature of the break source. The mylar map is always consulted, but very seldom do the flaws which are identified on the map correspond to a break source. More often than not the break source turns out to be a handling flaw which was polished over and invisible because the fracture surfaces were in optical contact.

6. FLIGHT EXPERIENCE

In the over 30 years experience with manned space craft, there has never been a window failure. Based on fracture analysis of salvaged fragments, it is safe to say that even the Challenger windows were intact until they impacted the water. Nevertheless, each space shuttle outer window is carefully inspected for in-flight damage after the mission is complete. Micrometeoroid and other particle impact damage is often found and the outer (thermal) windows require frequent replacement. The criteria for replacement are based on visible damage, the assumption that there may be hidden damage up to three times as deep as actually measured and location relative to the known stress distribution. No redundant or pressure panes have ever had to be replaced.

At high impact velocity, the kinetic energy of the particle is largely changed into thermal energy which results in local melting and evaporation of the glass. The low coefficient of thermal expansion of the fused silica is therefore an advantage because it limits the thermal stress resulting from this kind of local heating.

7. FUTURE DEVELOPMENTS

Fused silica continues to be the material of choice for the windows on the space station "Freedom". Even though there is no re-entry, most of the features that this material brings with it, are still beneficial. The thermal stresses generated when a window is partially shaded are too high when an ordinary, high expansion glass, such as soda-lime is used. The superior fatigue characteristics of fused silica are even more valuable in an application such as this because of the requirement for a 30 year life. The unmatched resistance to radiation darkening of this material is also an obvious benefit.

The main threat facing the windows of the space station is micrometeoroid impact. Experience on the shuttle oribiter has shown that high velocity impacts by even microscopic particles can damage the nearly flaw free surface that is supplied by the manufacturer. Special micrometeoroid shields are therefore planned which will prevent particle impact from damaging the pressure panes. The shields are designed to be replaceable in orbit. In a sense this harks back to one of the most demanding applications ever, the Lunar Landing Module of the Apollo missions. In the interest of extreme light weight, only a single structural pane was employed in the main, triangular windows which served as the substrate for the reticle used to align the vehicle for landing. This pane was chemically strengthened lithium alumino-silicate glass with a modulus of rupture of over 80,000 psi. It too needed the protection of a micrometeoroid shield since chemically strengthened glass is actually quite sensitive to particle impact.

8. SUMMARY

The design and specification of window systems for manned space craft is an exercise which brings together an interesting balance of theory and practice. The extreme conservatism which often guides design with brittle materials such as glass is not acceptable because of the weight limitations imposed on space craft. As additional theoretical and experimental work is being done in the area of strength of glass, and its fracture mechanical behavior, it turns out that some of the assumptions which went into the design of the space shuttle windows were very close to optimum.

9. ACKNOWLEDGMENTS

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[1]S. C. Keeton, "Delayed failure in glass," *Sandia Laboratories Report No. SCL - RR 710010,* April 1971.
[2]C. E. Inglis, "*Trans. Inst. Naval Arch.*" 55, 219, 1913.
[3]R. Stoll, P. F. Forman, J. Edelman, "*The effect of different grinding procedures on the strength of scratched and unscratched fused silica.*" Perkin Elmer Corp., 1961.

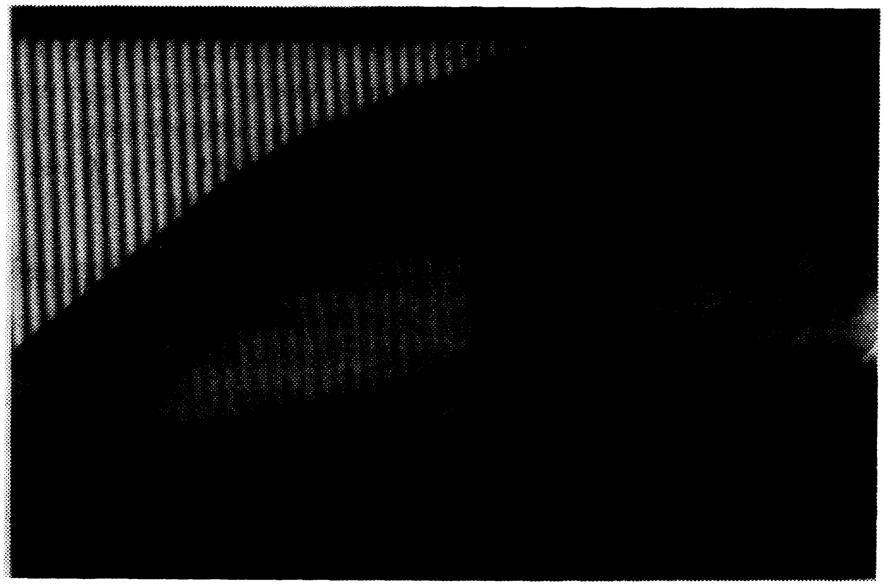

FIG. 1: North American "X-15"
Oval Window

FIG. 2: North American X-15
Later Design

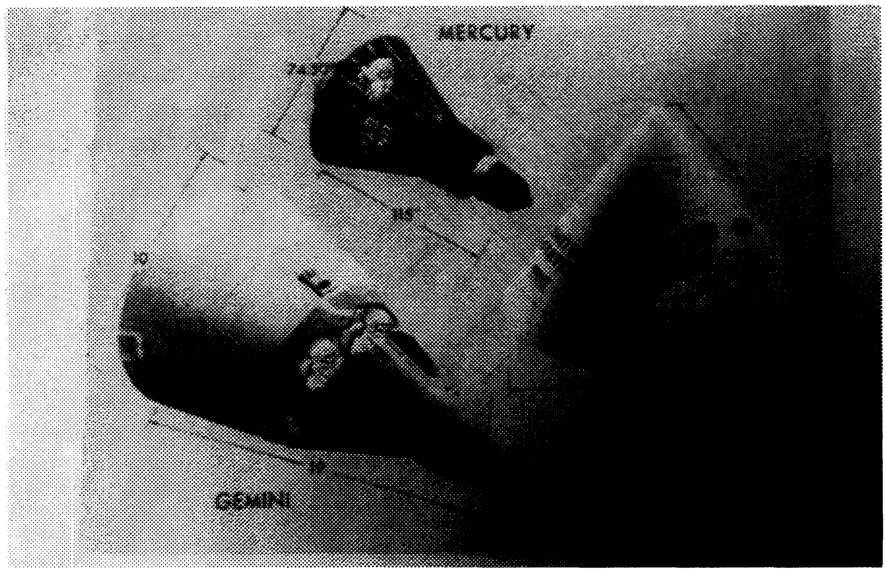

FIG. 3: Mercury, Gemini and Apollo Space Craft

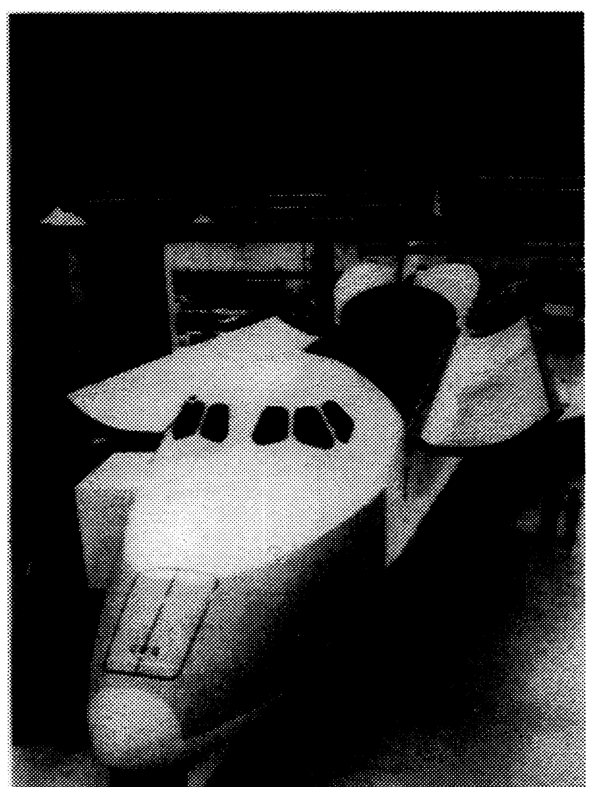

FIG. 4: Space Shuttle Orbiter

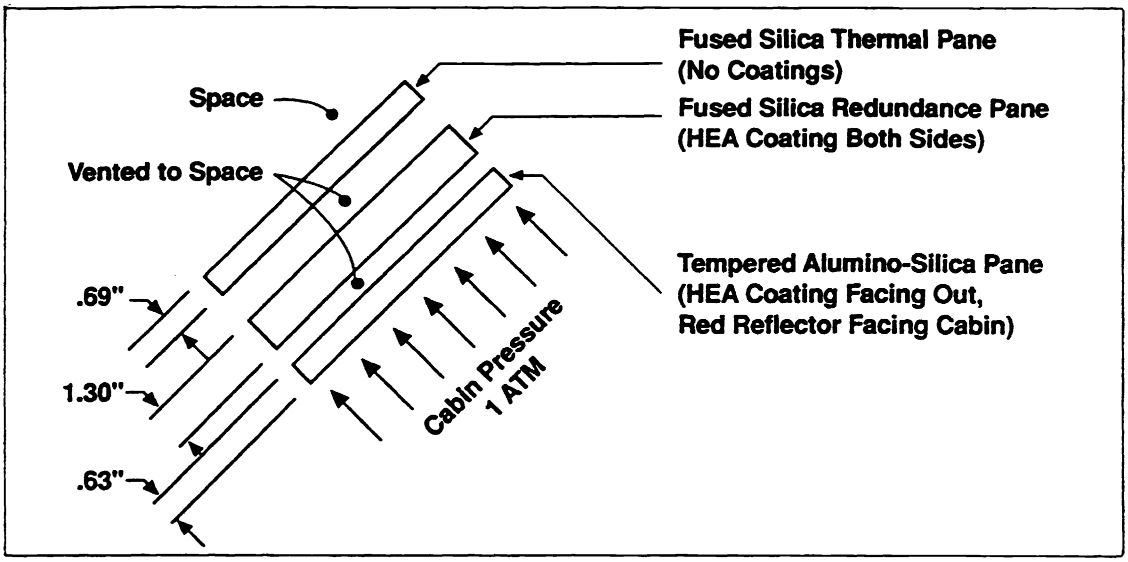

FIG. 5: Typical Design Shuttle Oribeter Forward Windshield

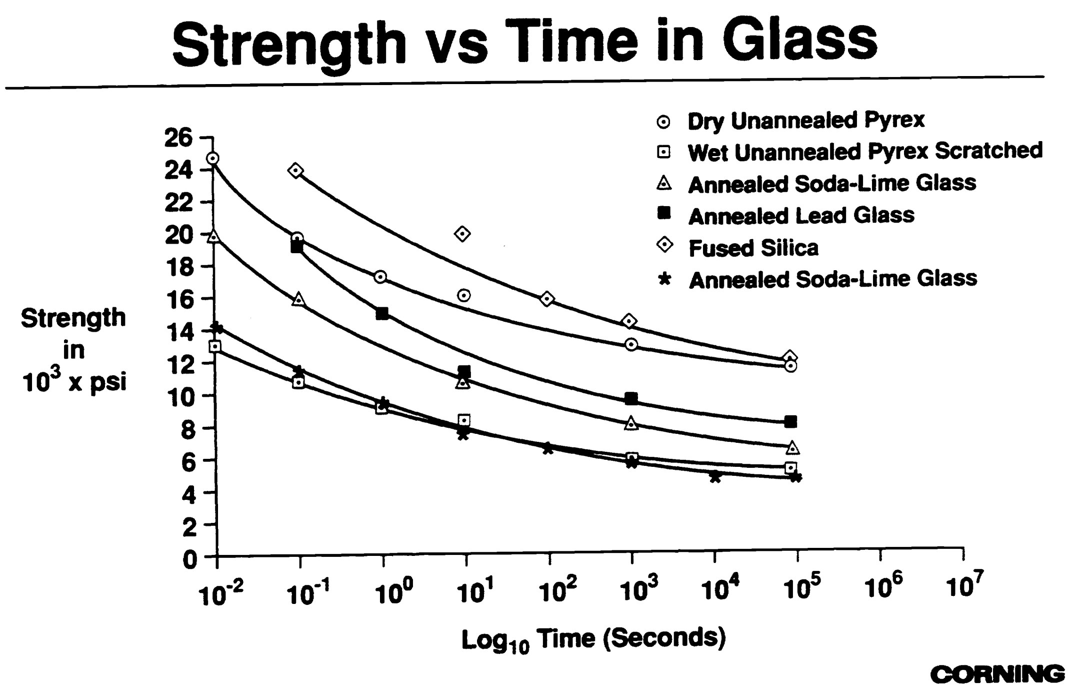

FIG. 6: Strength vs. Time Under Load in Glass

Tempering as Protection Against Fatigue

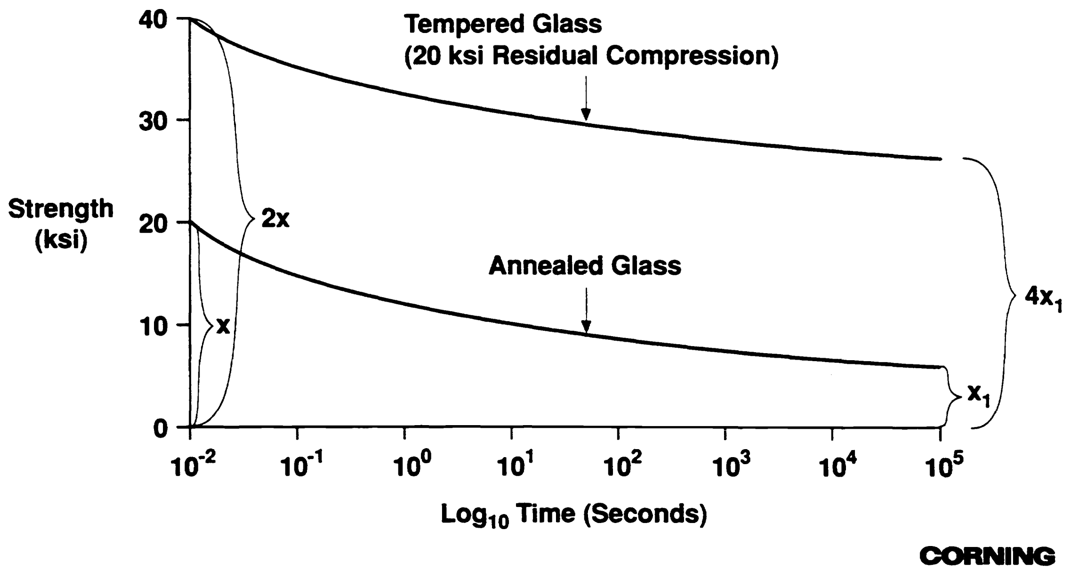

FIG. 7: Tempering as Protection Against Fatigue