NATIONAL BUREAU OF STANDARDS REPORT

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FRACTURE MECHANICS STUDY OF SKYLAB WINDOWS

FINAL REPORT

Prepared for
NASA Manned Spacecraft Center
Structures and Mechanics Division
PR 1-168-022, T-5330A

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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ABSTRACT

The fracture properties of eight glass compositions intended for use in the Skylab module were studied. Critical stress intensity factors were determined in vacuum by the double cantilever technique and a technique which involved three point bending of edge cracked specimens. Both techniques gave identical stress intensity values for the glasses studied. Preannealing in vacuum at 300° C had no effect on the measured critical stress intensity factor. Measurements of crack velocities in water saturated air were also conducted. Measured crack velocities were exponentially dependent on the applied stress intensity factor for most glasses studied, however, exceptions to this behavior were noted. A discussion is presented of the use of these data for design purposes, and recommendations are given for an acceptance test for glass plates to be used as Skylab windows. Additional research is suggested to elucidate the fracture properties of glass intended for use in spacecraft modules.

1. SUMMARY

1.1 Critical stress intensity factors were determined in vacuum for eight of the glass compositions intended for use in the Skylab module. Values ranged from about 6.5 to 9.3 x 10^5 $N/m^{3/2}$ depending on the glass composition. Values obtained by the double cantilever cleavage technique were identical to those obtained by the edge cracked three point bending technique, and preannealing in vacuum at 300° C had no effect on the measured values.

1.2 Crack propagation studies in vacuum indicated that growth prior to catastrophic failure occurred in some of the glass compositions studied, but not in others. Crack growth was strongly dependent on temperature when it was observed.

1.3 Measurements of crack growth rates were made in air saturated with water for the eight glass compositions. The measured crack velocities were exponentially dependent on the applied stress intensity factor for most of the glasses studied, however, exceptions to this behavior were noted. Stress corrosion limits were not observed on any of the glasses studied, even at crack velocities as low as 10^{-11} m/s.

1.4 A critical crack size for failure in vacuum of 2.3 inches along the glass surface and 11/32 inches deep was estimated for glass disks 12 inches in diameter and 1/2 inch thick, exposed to a pressure of 5 psi. This large size indicates that astronauts on the spacecraft will have considerable warning before failure of the module windows.

1.5 Three methods of estimating survival time from crack velocity data were suggested. In the first method, statistical information on the distribution of flaws was needed to predict survival time under load. In

the second method,a proof test is used to limit the maximum size crack that could be present in the glass surface. Survival time was estimated from the maximum crack size. In the third method, survival time is estimated from experimental measurements of strength and time to failure of glass disks containing large size cracks. Once the growth characteristics of the large cracks are known, predictions for failure time of smaller cracks can be made, and visual inspection techniques can be used to eliminate specimens containing cracks that are too large.

1.6 An acceptance test is recommended for glass plates intended for use as spacecraft windows. The glass plates should first be examined optically at a pressure of 10 psi and then be loaded to 20 psi for a period of time not to exceed 10 seconds. This procedure guarantees a minimum lifetime of 2.6×10^3 days in moist environment for the least stress corrosion resistant glass studied and an infinite lifetime for all glasses exposed to vacuum conditions.

1.7 Four directions for additional research are suggested. They are:

1.7.1 A study of flaw structure introduced by grinding and polishing.

1.7.2 The development of non-destructive testing procedures for evaluating surface damage.

1.7.3 The development of a method to determine stress intensity factors along the boundary of large cracks in plates subjected to bending forces.

1.7.4 Evaluation of the effect of temperature on crack propagation in vacuum.

2. INTRODUCTION

This project was initiated to investigate the fracture properties of glass intended for use as windows in Skylab modules. This use represents one of the few cases in which glass must withstand tensile loads for extended periods of time. The conditions of use are stringent since blowout of the windows means immediate depressurization of the spacecraft. Therefore, the design of these components must be fail-safe. The data obtained in this report is intended to provide engineering information to accomplish this end.

The strength of glass is controlled by the distribution of cracks within the glass surface and the growth of these cracks under imposed load. Surface cracks are introduced accidentally when glass is handled, or during finishing procedures, and failure occurs when the crack tip stress exceeds the theoretical strength of the material. If a corrosive environment is present, crack growth and failure occur at a much lower stress as a consequence of reaction between the corrosive environment and the highly strained material at the roots of crack tips. This process leads to a time delay-to-failure, the time delay being equal to the time necessary for the cracks to grow from sub-critical to critical size. This process is called static fatigue and normally results from a reaction between glass and water in the environment.[1-6] Studies of static fatigue indicate that the time delay to failure is absent in the dry environments. Propagation of cracks in glass depends on the relative amount of water in the environment and upon the temperature to which the glass is exposed. Fracture mechanics techniques can provide information on the response of cracks to stress, temperature, and

environment.[6] These techniques are also useful for design purposes.

This report presents the results of a fracture mechanics study of glasses intended for use in the Skylab module. Eight glass compositions were studied and crack propagation data were obtained in 100% relative humidity and in vacuum. A discussion of how these data can be used for design purposes is given. In addition, data is presented on the failure of large glass plates subjected to the type of pressure loading expected on the Skylab vehicle.

3. EXPERIMENTAL PROCEDURE

3.1 Critical Stress Intensity Factor Data in Vacuum

The double cantilever cleavage technique and a technique involving three point bending of edge cracked specimens were used to obtain data on the fracture of the various glasses studied in this report, table 1. Double cantilever specimens consisted of glass microscope slides, 1" x 3" on each side and 2 mm thick, figure 1. The midplane of the specimen was notched to provide a guiding path for the crack. The unnotched thickness of the slide was approximately 1 mm. Cracks were initiated in the specimen by cutting away a portion of the notch near the loading points and applying the load to the specimen in a laboratory environment having a relative humidity of approximately 40%. Crack growth was monitored until the crack length was approximately two centimeters beyond the points of loading. Specimens were then removed from the laboratory environment, placed in vacuum of $<10^{-5}$ Torr and loaded until failure occurred. The critical stress intensity factor was calculated from the following formula,[7,8]

$$K_I = [PL/(wa)^{0.5}\ t^{1.5}]\ [3.47 + 2.32\ t/L] \qquad (1)$$

P is the load at failure; L is the crack length prior to failure; w is the thickness of the slides; "a" is the thickness remaining between the two notches; and t is half the height of the specimen. Tests were conducted both with and without a 30 min. preheat at 300° C to evaluate the effect of water on the measured value of the critical stress intensity factor.

Critical stress intensity factors were determined on glass remaining from the double cantilever cleavage experiments. A v-shaped notch was introduced into the specimen, figure 2, to initiate cracks into these specimens. Three-point loading was applied to the specimens in the laboratory environment and crack growth was monitored under a microscope until the predetermined crack length was reached. These specimens were then removed to a vacuum, $<10^{-5}$ Torr, and a load was applied until failure occurred. The critical stress intensity factor was calculated from the following formula:[9]

$$K_I = [(1.5\ SPa^{1/2})/(BW^2)][1.95-2.91(a/W) + 14.10(a/W)^2 - 24.55(a/W)^3 + 25.51(a/W)^4] \qquad (2)$$

Where P was the load applied for failure, S was the span between outer loading points, W was the height of the specimen, "a" was the crack length, and B was the thickness of the specimen. S/W was approximately 6.

3.2 Crack Velocity Measurements

Crack velocity studies were conducted in an environment of 100% relative humidity and in vacuum. A dead weight loading system was

used to apply the load to the double cantilever specimens in environments of 100% relative humidity. The equipment consisted of a pan balance and a semi-enclosed environmental chamber that was maintained at 100% relative humidity by water in the bottom of the chamber. The double cantilever specimen was attached to one arm of the pan balance and the load was placed on the other arm. Crack motion was monitored using a 20X microscope to which a filar eyepiece was attached. Velocity measurements ranged from 10^{-3} to 10^{-11}m/s. Specimens were introduced cautiously into the environmental chamber to avoid water condensation at the crack tip before studies could be conducted. Condensation always occurred if the slides were slightly cooler than the water used to control the environment. To avoid condensation, an initial water temperature of approximately 10 degrees less than room temperature was used in the specimen chamber. The specimen chamber was then enclosed and measurements were made after the water had reached room temperature. In this way, condensation was avoided at the crack tip during the initial stages of the experiment. Despite these precautions, crack tip condensation was almost unavoidable for crack velocity measurements of the order of 10^{-10} m/s, as these required runs of the order of a week to accomplish.

Crack velocity studies were conducted in vacuum as a function of temperature. Double cantilever specimens were used and load was applied by a universal testing machine. Crack velocity measurments were made with a 20X microscope containing a filar eyepiece. Crack velocities ranged from 10^{-5} to 10^{-8} m/s. Glasses studied in vacuum included the low-alkali aluminosilicate glass and the borosilicate crown glass, table 1. The high-silica glasses and the borosilicate glass all failed

without prior warning, and thus the crack velocities could not be measured. Crack velocity measurements were not attempted on the 61 percent leaded glass.

3.3 Pressure Tests on Large Plate Glass Specimens

Disks of soda-lime silicate glass 12" in diameter and 1/2" thick were selected to study the effect of environment on the fracture of specimens comparable in size to spacecraft windows. Soda-lime silicate glass was selected because fracture mechanics data for this glass were already available and because plates of this size were easily obtained and were inexpensive. Eleven disks were broken in the as-received condition. Three of the eleven were loaded rapidly to failure, while the others were held at preset pressures and the time measured to failure. Five disks were scratched with a diamond scribe to introduce more serious damage into the glass surface than was present in the as-received condition. These were then loaded to a preset level and times to failure measured. Fianlly, large planar surface cracks were introduced into the center of three disks and a preset load was applied to cause crack propagation. These three disks were mechanically shocked once every second during crack propagation to provide surface marks that could be used to measure the crack velocity after the disks had failed. Cracks were approximately 1 to 2 inches along the crack surface and 1/4 inch deep. Cracks were introduced by scratching the plates in their center, heating them to 175° C and then thermally shocking them with a drop of water. These cracks were easily visible and the commencement of crack growth could be easily established.

The crack surfaces of all of the disks were examined after

fracture to locate the fracture origin and to determine the size of the flaw that caused the fracture. The failure stress of the as-polished or scratched specimens was determined from the following equation:[10]

$$\sigma_r = 3(3 + \nu)\ a^2\ zq/32\ c^3 \qquad (3)$$

where ν is Poisson's ratio, "a" is the location of the failure origin, c is half the thickness of the glass plate, and q is the pressure applied to cause failure. All tests on the glass plates were conducted in an environment of 100% relative humidity. Water was used as a pressure transmitting fluid because of its easy availability and relative incompressibility. The glass plates were entirely supported against a loading annulus and thus were simply supported pressure plates. No additional edge effects are believed to have occurred.

4. PRESENTATION OF RESULTS

4.1 Critical Stress Intensity Factor Measurements

The results of the critical stress intensity factor measurements in vacuum are given in tables 2 thru 4. Table 2 gives values obtained in vacuum using the double cantilever specimen geometry without prior heat treatment. Table 3 gives the data obtained on double cantilever specimens with a prior heat treatment of 300° C for 30 mins. and table 4 presents data obtained using the edge-cracked, three-point bend specimens. In addition, table 5 presents data obtained on borosilicate glass tested in nitrogen gas relative humidity <0.02%. In all cases, at least three measurements were made for each test condition. The average and standard deviation of the measurements are presented in the tables.

The critical stress intensity factors ranged from approximately 6.5 to 9.3×10^5 N/m$^{3/2}$. Thus the critical stress intensity factors were not strongly dependent on the composition of the glass. Prior heat treatment did not affect the measured stress intensity factor of the glasses studied, with the exception of the borosilicate crown glass which exhibited a small increase in average value. Within statistical scatter, identical values were obtained using the double cantilever and the edge-cracked, three-point bend specimens. This point is of interest because differences in values have been reported for these two techniques by other authors studying other ceramic materials. Finally, identical values for the critical stress intensity factor are obtained in vacuum and dry nitrogen.

4.2 Crack Velocity Studies

Crack velocity data are presented in figures 3 through 10. Data is plotted as the logarithm of the crack velocity versus the applied stress intensity factor. Data plotted in this manner appears as straight lines over the entire range of velocities studied for five of the eight glasses investigated. For two of the other glasses, some curvature occurs at the lower stress intensity factor portion of the curve, and for the remaining glass, the borosilicate crown glass II, a slight curvature occurs over the entire range of variables. The data shown in figures 3 through 10 were fitted by the method of least squares, minimizing the error along the stress intensity factor axis. The average slope and intercept are presented in table 6. Lines drawn through the data represent this least squares fit. Stress corrosion limits were not observed on any of the glasses studied even at velocities as low as

10^{-11} m/s.

Condensate usually formed at crack tips after exposure to water-saturated air for a few weeks. Crack velocity data taken from such crack tips agreed within experimental error with data obtained from specimens that appeared to have dry crack tips. Thus, the presence of condensate at crack tips had little influence on the positions or slopes of crack propagation curves obtained in water-saturated air.

Data for crack propagation in vacuum are presented in figures 11 and 12 for the borosilicate crown glass I and the aluminosilicate glass, respectively. The data also appears as straight lines over the range of variables studied. However, the slopes of these curves are considerably steeper than those obtained in the water environments. The position of the curves depends on the temperature of the study. The curve shifts to lower stress intensity factors as the temperature is increased. In addition, the slopes of the curves decrease with increasing temperature. This observation suggests that crack propagation in vacuum is an activated process. The magnitude of the stress intensity factor decrease for the borosilicate crown glass was approximately 20% at a velocity of 10^{-6} m/s for a temperature rise of 200° C. This suggests a similar decrease in strength for glass. Attempts at crack propagation were unsuccessful for the other glasses used in this investigation. Failure was always very sudden and controlled crack propagation could not be obtained.

4.3 Strength Measurements on Soda-Lime Silicate Glass Plates

The strength data for the soda-lime silicate glass plates tested in either as-received or scratched condition is presented in

table 7. The appearance of the plates after fracture is shown in figure 13. The fracture source in the as-received plates ranged from the center of the plate to 3.4 inches from the center. Specimens that were loaded rapidly ranged in strength from approximately 5,000 to 7,000 psi and sustained pressures ranging from 30 to 50 psi prior to fracture. Plates exposed to static pressure ranged in strength from approximately 3300 psi to nearly 4,000 psi, and sustained pressures before fracture ranging from 20 to 33 psi. The strength of the glass disks could not be correlated with the location of the fracture origin. The scratched disks had strengths ranging from approximately 2700 psi to as high as 4500 psi. Although the strengths of the scratched disks were generally lower than those of the as-received ones, the strength reduction was not as great as might have been expected. In fact, one of the scratched specimens had a strength higher than most of the unscratched specimens subjected to static loading. Pressures for failure of the scratched specimens ranged from 16 to 26 psi. The lower pressure values were due to the central location of the fracture initiating flaw. Flaw origins in the as-received plates ranged from 50 to 100μm deep and extended along the surface for distances > 1000μm. These flaws were probably introduced by the grinding and polishing process used to finish the glass surface.

An attempt was made to determine the largest surface flaw that the glass plates could contain and still support a pressure difference of 5 psi. To accomplish this, large elliptical surface cracks were introduced into the center of the glass, figure 14. Disks containing these cracks were pressure loaded commencing at a pressure of 5 psi.

Increments of 1 psi were added every five minutes until crack growth was observed. Crack growth was permitted to occur at a final preset pressure until the plate failed. Cracks ranged in size from 1 to 2 inches on the surface and were 1/4 inch deep prior to catastrophic failure. Fracture occurred at pressures of 5, 8 and 10 psi. The plate that broke at 5 psi took 5 days to fail. Had the plates been tested in vacuum, none of the plates tested would have failed at 5 psi. The fact that the plates could support a pressure difference of 5 psi in saturated air with cracks of this magnitude suggests that plates for the space lab will be safe at a pressure difference of 5 psi provided no large flaws are visible. Failure is not expected short of collision with some external body.

4.4 Effect of Condensation on the Strength of Glass

Some experiments were conducted to elucidate the characteristics of glass after condensate had formed at the crack tip. Fused silica specimens with condensate at the crack tip were transferred to an environmental chamber in which the percent relative humidity could be controlled. The crack tip was observed as the environment was changed from 100% relative humidity to less than 0.02%. Condensate at the crack tip required approximately an hour to evaporate. Furthermore, a residue was left after the condensate had evaporated. This residue left the portion of the crack surface near the crack tip non-reflecting, suggesting that the residue consisted of a silicate gel. Condensate reappeared after introducing water-saturated nitrogen gas into the chamber. The disappearance of the reflecting quality of the glass surface was attributed to an increase in index of reflection of the gel as water

evaporated.

5. DISCUSSION OF RESULTS

Crack velocity data presented in this report can be used to obtain estimates of survival time for glass under load. Three methods of estimation will be discussed. The first assumes that flaw size distributions have been obtained for the glass prior to loading. The second uses a proof test to determine the maximum flaw size that could have been present in the glass surface. The third method uses visual inspection to determine if cracks present in the surface are smaller than easily visible ones whose growth characteristics are known to be insufficient to cause failure. In each of the three methods, the time to failure can be calculated from the initial flaw size and the crack velocity data.

The total time to failure can be determined from the definition of crack velocity, $dL/dt = v$, and the assumption that the stress intensity factor, K_I, is related to the applied load, σ, by the following equation,

$$K_I = \sigma\sqrt{\pi L}, \tag{4}$$

where L represents the depth of the surface crack. This equation is approximately correct for cracks that are small with respect to the plate thickness and for which the length of the crack on the surface is much greater than its depth. Assuming a constant load, the following equation for total failure time, t, is obtained by substituting equation (4) into the definition of crack velocity.[11]

$$t = (2/\sigma^2\pi) \int_{K_1}^{K_{IC}} (K/v)\, dK \tag{5}$$

v is the crack velocity and K_1 is the stress intensity factor calculated from the initial crack length and applied load.

Equation (5) can be integrated either numerically or analytically provided v is known as a function of K. For much of the data obtained for this report, the crack velocity was found to be exponentially dependent on the applied stress intensity factor,

$$v = v_o \exp \beta K_I. \tag{6}$$

For purposes of discussion, it will be assumed that all of the crack velocity data can be satisfactorily described by this analytical representation.

Substituting equation (6) into (5), the following integrated expression for failure time is obtained provided small terms are neglected,[12]

$$t = 2L_1/\beta K_1 v_1 = (2\sqrt{L_1})/(\beta\sigma v_o \sqrt{\pi} \exp \beta\sigma\sqrt{\pi L_1}). \tag{7}$$

v_1 is the initial crack velocity corresponding to the initial stress intensity factor K_1. This equation has been checked with numerically integrated times to failure using the actual crack velocity curves and agreement was excellent over the entire practical range of crack growth.[12]

The time to failure depends only on the applied load σ and the initial crack length L_1. The other therms of equation are constants obtained from crack velocity data. If the initial flaw size is known, equation (7) provides a unique relationship between applied load and time to failure, and is of course the equation needed for design purposes. For safe design, the initial flaw length, L_1, selected for equation should be larger than flaws actually occurring in the glass surface. This procedure will guarantee a greater time to failure

than calculated from equation (7).

Statistical information on flaws contained in a glass surface can be obtained from strength measurements under very dry conditions such as liquid nitrogen where stress corrosion does not occur.[13] The statistical information can be used to select a safe initial flaw size for substitution into equation (7). The probability of the glass containing flaws larger than that selected gives the probability of failure in a time less than that calculated from equation (7)[1]. The statistical estimation of flaw severity should be typical of those expected for plates in service for this method to be of value. The method also cannot guarantee that the flaw distribution has not been altered by accidental mishandling of the glass.

Proof testing can be used to eliminate weak glass plates and to estimate the largest possible flaw in the plates at the time of testing. Survival of a proof test guarantees that the stress intensity factor of the most serious flaw in the glass plate has not exceeded K_{IC} since fracture is almost instantaneous when $K_I = K_{IC}$. The maximum flaw length contained in the glass surface is given by $L_1 = (K_{IC}/\sigma_P)^2/\pi$, where σ_P is the proof test stress. The minimum time to failure can be calculated from equation (7). Greater safety at operating stresses is obtained by proof testing at high loads for short periods of time. Although proof testing guarantees a minimum lifetime at the time of the

[1]Equation (7) applies to a glass body under uniform surface tension. For pressure loaded plates, the variation of surface stress across the plate surface would have to be taken into account.

test, it loses value if subsequent surface damage is incurred.

Ideally, non-destructive test methods are desirable to monitor the surface structure of glass at any time during service. Visual inspection techniques can be used provided the surface cracks exceed 1 mm. Glass windows intended for use in the Skylab module will be expected to support a pressure of 5 psi for indefinite periods of time. At this pressure, a maximum surface stress of 800 psi ($\sim 4.2 \times 10^6$ N/m^2) would be expected in the 0.5 x 12 inch glass disks used to simulate spacecraft windows. An estimate of maximum crack size prior to failure can be calculated from equation (4) provided it is assumed that this surface stress is constant through the glass thickness. The estimated length, $L = (K_{IC}/\sigma)^2/\pi = (8.2 \times 10^5/4.2 \times 10^6)^2/\pi = 1.21 \times 10^{-2}$ m, is approximately equal to the thickness of the glass disks. Since the actual tensile stress in a pressure loaded disk decreases with distance from the glass surface, the above estimate is not correct. Much larger cracks would be expected. These should grow preferentially along the glass surface and assume a pseudo-elliptical shape prior to fracture as has been observed in this study and has been reported earlier.[14]

From the present report, it can be concluded that crack sizes of the order of two inches in length and more than 1/4 inch in depth represent the critical size for failure at an operational load of 5 psi. Cracks smaller than this size will require considerable growth time for failure and will be easily observable by astronauts aboard the spacecraft. The plate broken at 5 psi, for example, contained a crack, 1.25 inches long, which required five days to grow to critical size, 2.3

inches long and 11/32 inches deep, before failure. In vacuum the failure time for this plate would have greatly exceeded five days and, in fact, failure probably would not have occurred. For design purposes, the fact that the critical crack size for catastrophic fracture is so large, 2.3 inches x 11/32 inches[1], leads to the conclusion that fracture of the spacecraft windows will not occur as long as visible cracks are not present in the glass surface. Thus, spacecraft windows can be inspected visually during service and safety can be assured by the absence of visible cracks.

In principle, accurate estimates of failure time for large cracks can be obtained from crack velocity data and equation (5). Unfortunately, the method is not viable at the present time because a relationship similar to equation (4) is not available for large cracks in plates subjected to bending forces. It is possible however to obtain an estimate of failure time for large cracks at a reduced load if the crack velocity and failure time are known at a higher load. The crack velocity, v_1, of the plate broken at 10 psi was 1.4×10^{-4} m/s 5 seconds prior to failure. From previously published crack velocity data,[6] the stress intensity factor, K_1, at this time is estimated to have been 7×10^5 N/m$^{3/2}$. Reduction of load to 5 psi 5 seconds prior to failure would have imposed a stress intensity factor, K_1^*, of 3.5×10^5 N/m$^{3/2}$ on the crack tip. From equation (7) the failure time t^* relative to

[1] From crack velocity studies it is observed that the onset of rapid crack motion occurs when $K_I \approx K_{IC}$. Consequently, this dimension is close to the critical size for crack propagation in vacuum.

that actually observed, t, is given by

$$t^*/t = v_1 K_1 / v_1^* K_1^*,$$

where v_1^* is the crack velocity at a stress intensity factor K_1^*. From previously published crack velocity data,[6] v_1^* is estimated to be 2×10^{-9} m/s and the calculated failure time is 7×10^5 seconds or 8.3 days which is in good agreement with the 5 day duration of the plate containing a 1.25 inch crack.

6. RECOMMENDATIONS

6.1 Acceptance Test for Spacecraft Windows

Proof testing in combination with visual examination of the windows is recommended. The windows should be first loaded to a pressure of 10 psi and examined for cracks. Any windows exhibiting cracks should not be used in the spacecraft. The windows should then be loaded to 20 psi, which is four times the operating pressure, and held at pressure for a period of time not to exceed 10 seconds. This procedure will guarantee a minimum lifetime of 2.6×10^3 days in saturated air for the SF1 glass windows, which exhibit the poorest static fatigue behavior. All other glass compositions intended for use on the spacecraft will greatly exceed this life expectancy. Since the tensile surface of the spacecraft windows will normally be exposed to vacuum, all windows passing this test should have an infinite life expectancy in vacuum.

6.2 Suggestions for Additional Research

6.2.1 Examination of Flaw Structure Introduced by Grinding and Polishing

Since the strength of glass is controlled by the severity of damage introduced by grinding and polishing, a research

project is recommended to determine a relationship between the finishing procedures and the severities of flaws introduced by grinding and polishing. Information of this sort can be obtained by varying the finishing procedure, measuring the strength, and studying the flaws that initiate fracture, either by optical or scanning electron microscopy.

6.2.2 Development of a Non-Destructive Test Procedure to Evaluate Surface Damage

While proof testing does provide information on surface damage, the method does increase the severity of flaws contained in the surface as a result of crack growth. Non-destructive testing would not have this drawback. Work at the National Bureau of Standards and the Naval Research Laboratory has suggested the use of ultrasonic surface waves as a means of detecting small size flaws in glass surfaces. It is recommended that this technique be applied to evaluate surface flaws in spacecraft windows.

6.2.3 Evaluation of Stress Intensity Factors at the Boundary of Large Cracks

A surprising observation of the present study was the ability of the glass disks to support a 5 psi pressure differential in the presence of large cracks. For large size cracks, techniques for predicting failure time from crack size cannot be used because of the lack of a relationship between crack size, load and stress intensity factor. It is recommended that a relationship of this type be developed to better understand the motion of large cracks in plate glass. By using a sonic pulse technique, it should be possible to mark successive positions of the crack front, and so obtain the crack front velocity as

a function of position along the crack front. Relative stress intensity factors can then be obtained as a function of position from known crack velocity--stress intensity factor data.

6.2.4 Effect of Temperature on Crack Velocity in Vacuum

The observed dependence of crack velocity data in vacuum on temperature implies a reduction of glass strength with increase in temperature. Information on this reduction in strength may be important to the design of the reusable space shuttles, since the windows of the shuttle will be exposed to a thermal cycle each time the shuttle re-enters the atmosphere. It is therefore recommended that crack growth data be obtained in vacuum as a function of temperature for glasses that are intended for use in the space shuttle.

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Figure Captions

1. Double Cantilever Beam Configuration

   $K_I = [PL/(wa)^{0.5}\ t^{1.5}]\ [3.47 + 2.32\ t/L]$

2. Edge Cracked, Three Point Bend Specimens

   $K_I = [(1.5\ SPa^{1/2})/(BW^2)][1.95-2.91(a/W) + 14.10(a/W)^2 - 24.55(a/W)^3 + 25.51(a/W)^4]$

   B is the specimen thickness, not shown in the figure.

3. Fused Silica, C7940, air, 100% RH.

4. High Silica I, C7900, air, 100% RH.

5. High Silica II, C7913, air, 100% RH.

6. Aluminosilicate, C1723, air, 100% RH.

7. Borosilicate, C7740, air, 100% RH.

8. Borosilicate Crown I, BK7, air, 100% RH.

9. Borosilicate Crown II, UBK7, air, 100% RH.

10. 61% Lead Glass, SF1, Air, 100% RH.

11. Borosilicate Crown I, BK7, Vacuum, 10^{-5} Torr.

12. Aluminosilicate, C1723, Vacuum, 10^{-5} Torr.

13. Fracture Appearance of Disks

    a. Specimen 8, Fracture Pressure 16 psi.

    b. Specimen 9, Fracture Pressure 18 psi.

    c. Specimen 15, Fracture Pressure 24 psi.

    d. Specimen 16, Fracture Pressure 33 psi.

14. Specimen 19, Crack Growth at 5 psi. Original crack size indicated by two crayon marks on the side of the crack away from the ruler.

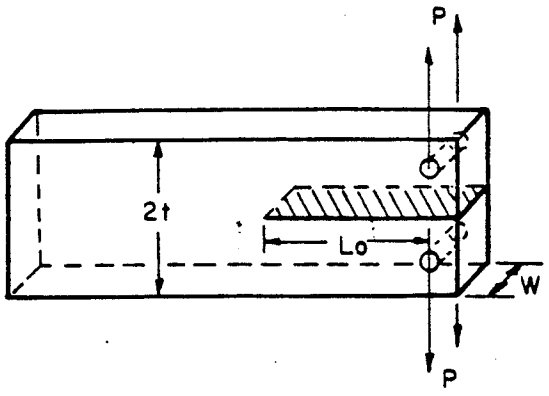

Fig. 1. Double Cantilever Beam Configuration

$$K_I = [PL/(wa)^{0.5}\ t^{1.5}]\ [3.47 + 2.32\ t/L]$$

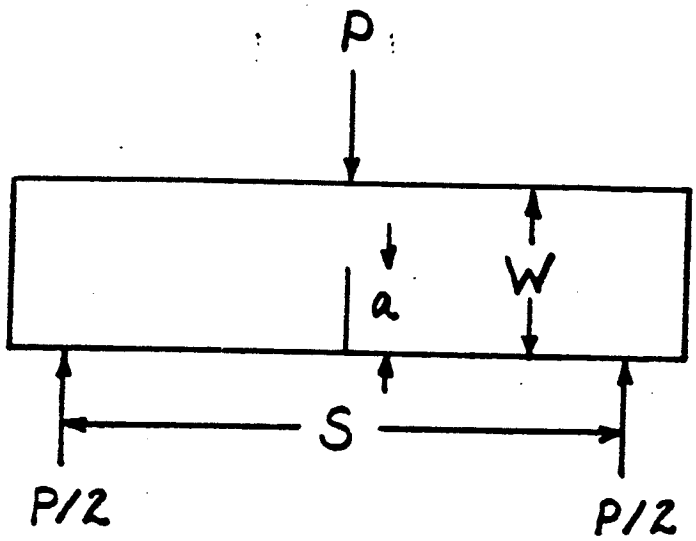

Fig. 2. Edge Cracked, Three Point Bend Specimens

$$K_I = [(1.5\ SPa^{1/2})/(BW^2)][1.95-2.91(a/W) + 14.10(a/W)^2 - 24.55(a/W)^3 + 25.51(a/W)^4]$$

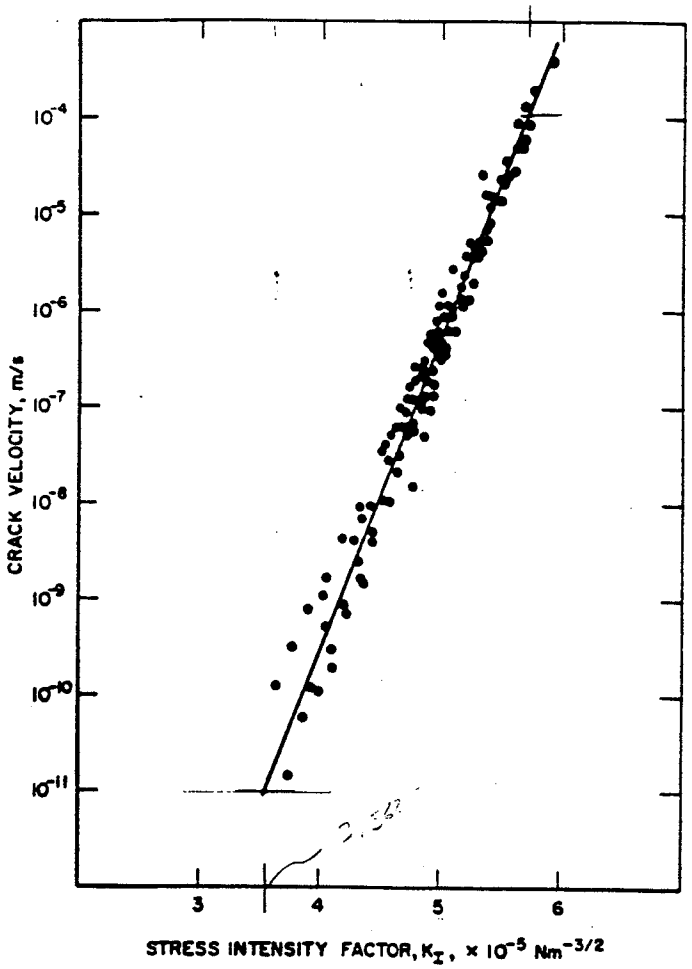

Fig. 3. Fused Silica, C7940, air, 100% RH.

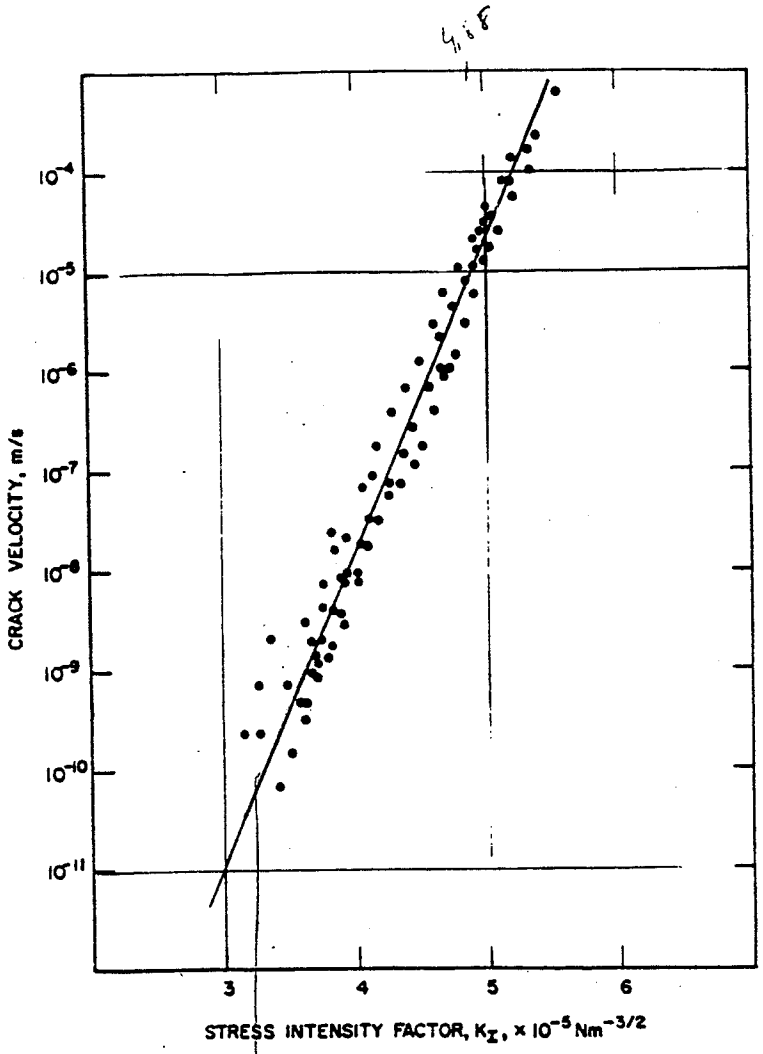

Fig. 4. High Silica I, C7900, air, 100% RH.

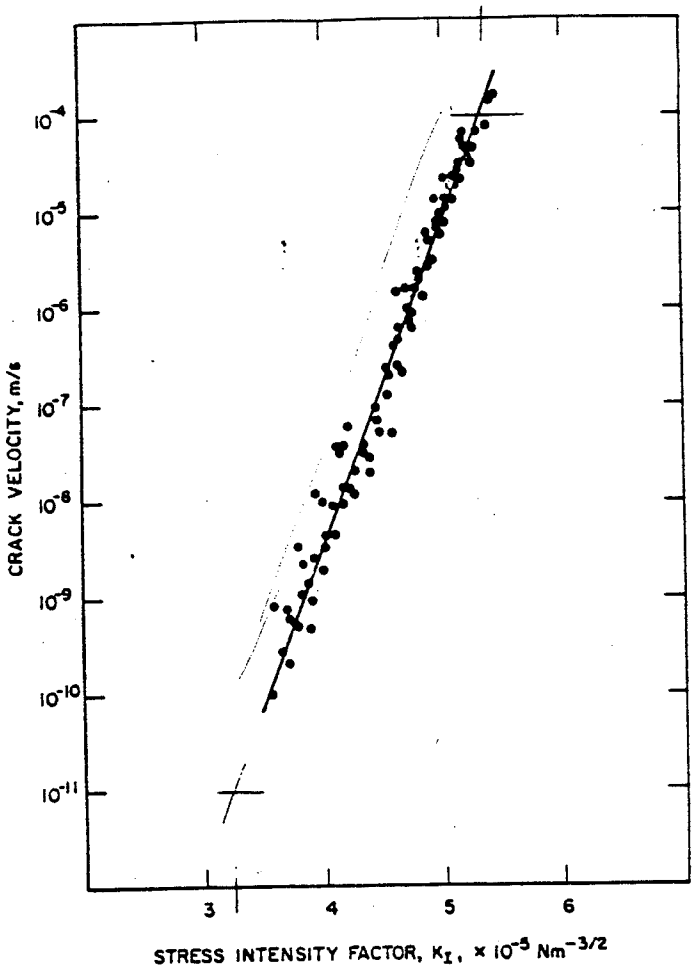

Fig. 5. High Silica II, C7913, air, 100% RH.

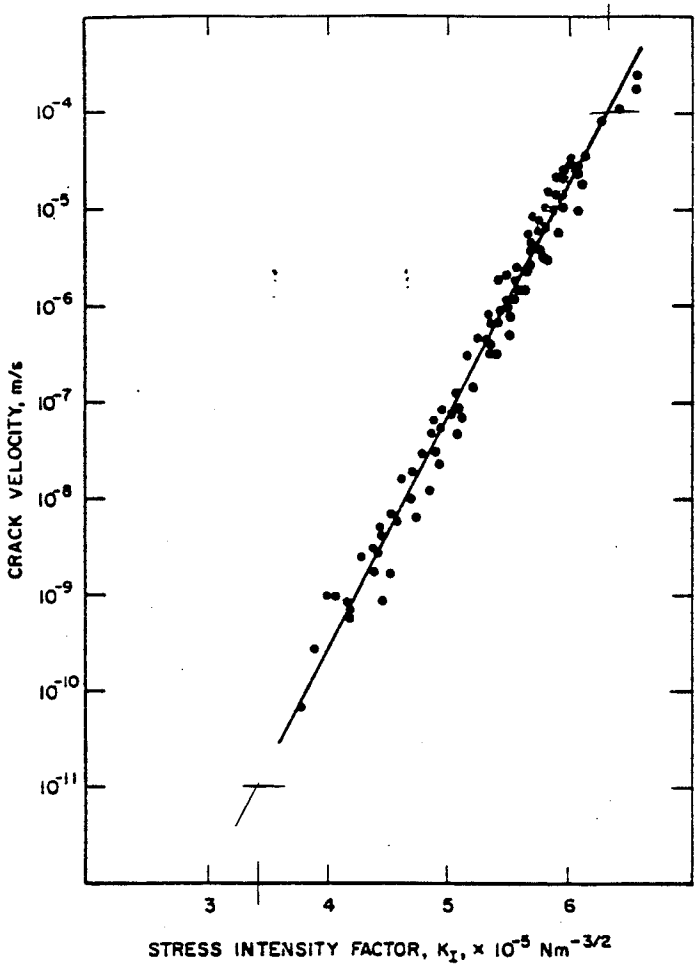

Fig. 6. Aluminosilicate, C1723, air, 100% RH.

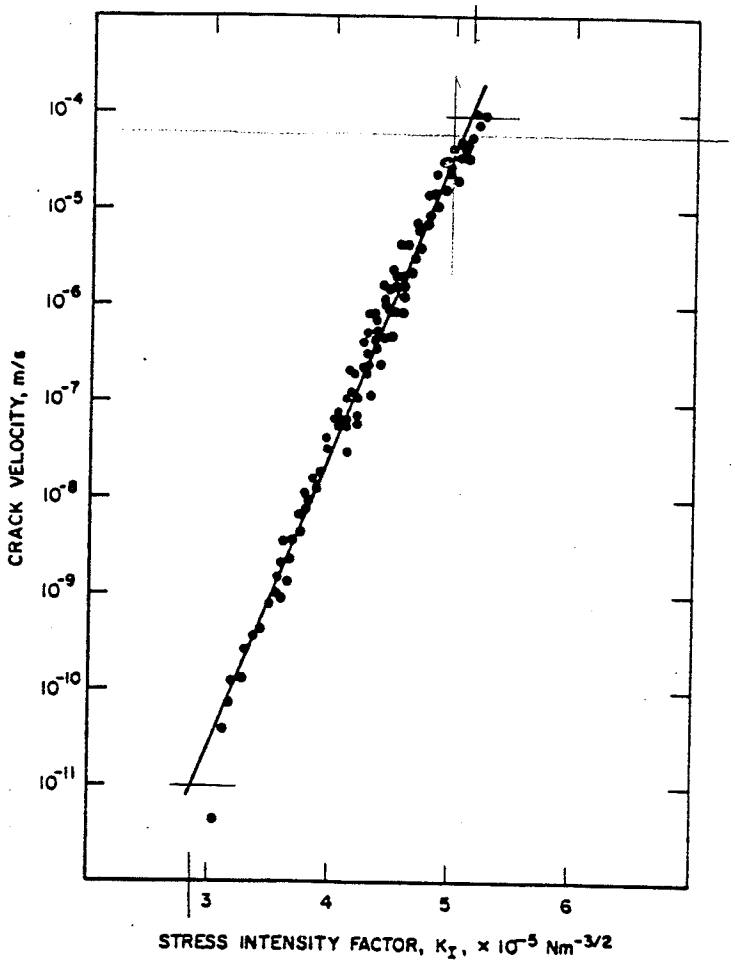

Fig. 7. Borosilicate, C7740, air, 100% RH.

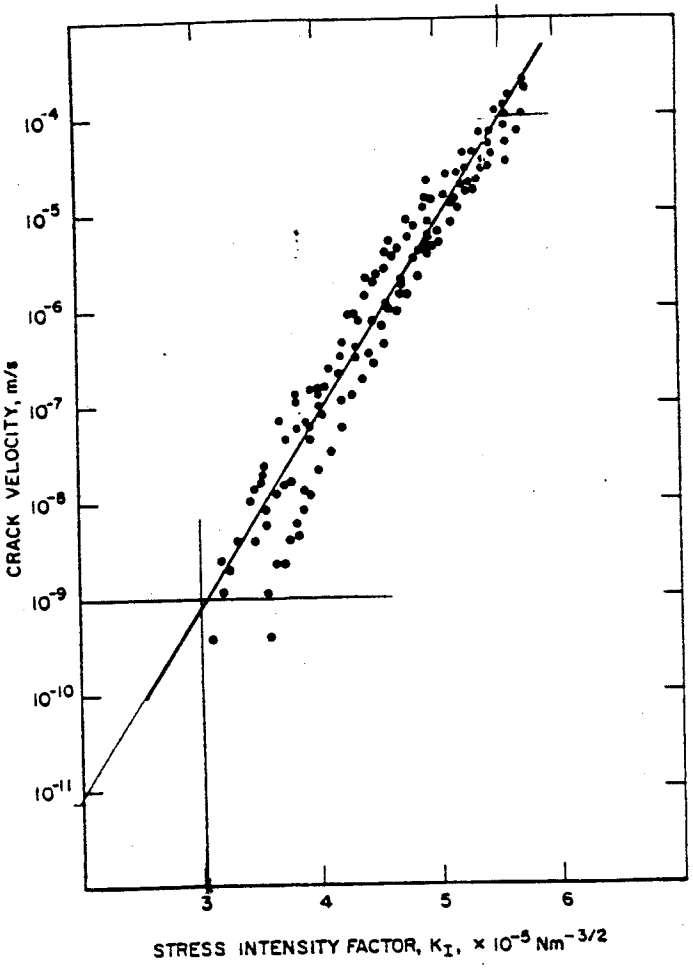

Fig. 8. Borosilicate Crown I, BK7, air, 100% RH.

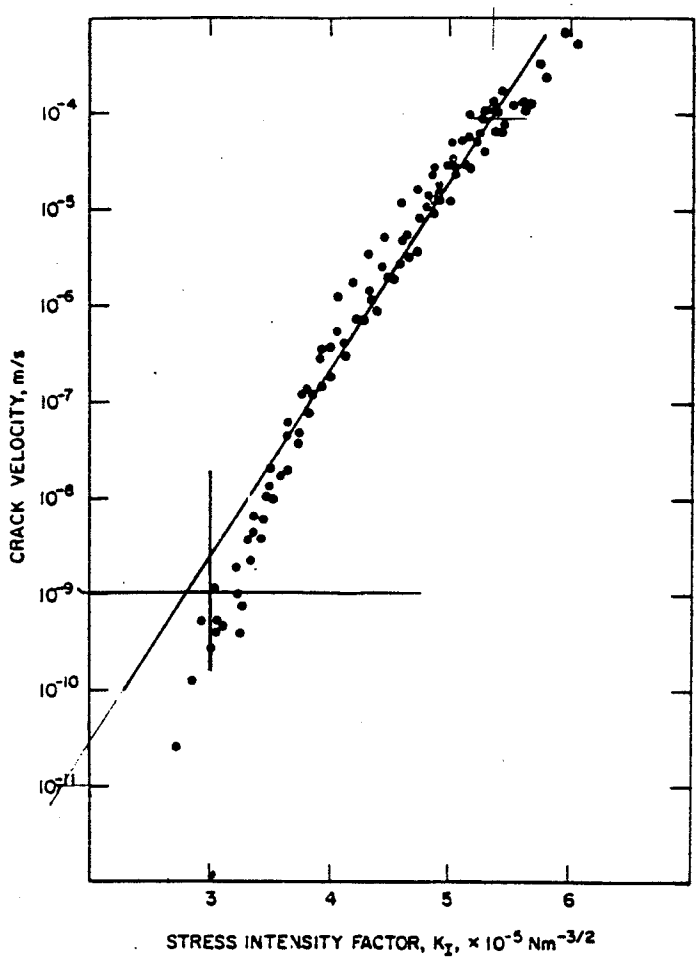

Fig. 9. Borosilicate Crown II, UBK7, air, 100% RH.

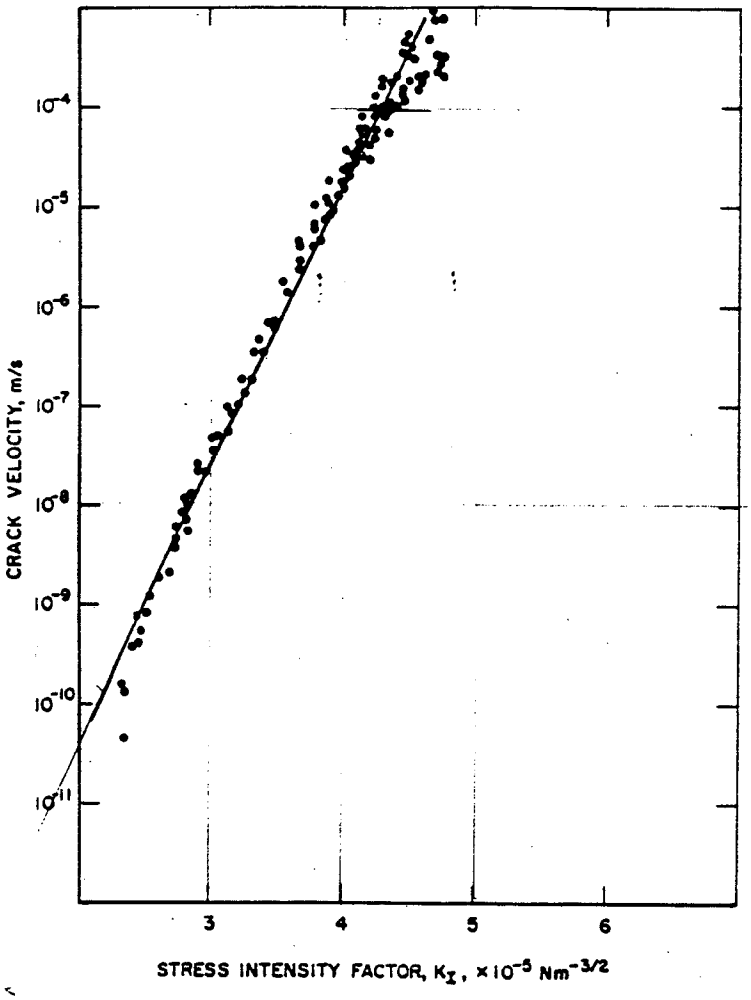

Fig. 10. 61% Lead Glass, SF1, air, 100% RH.

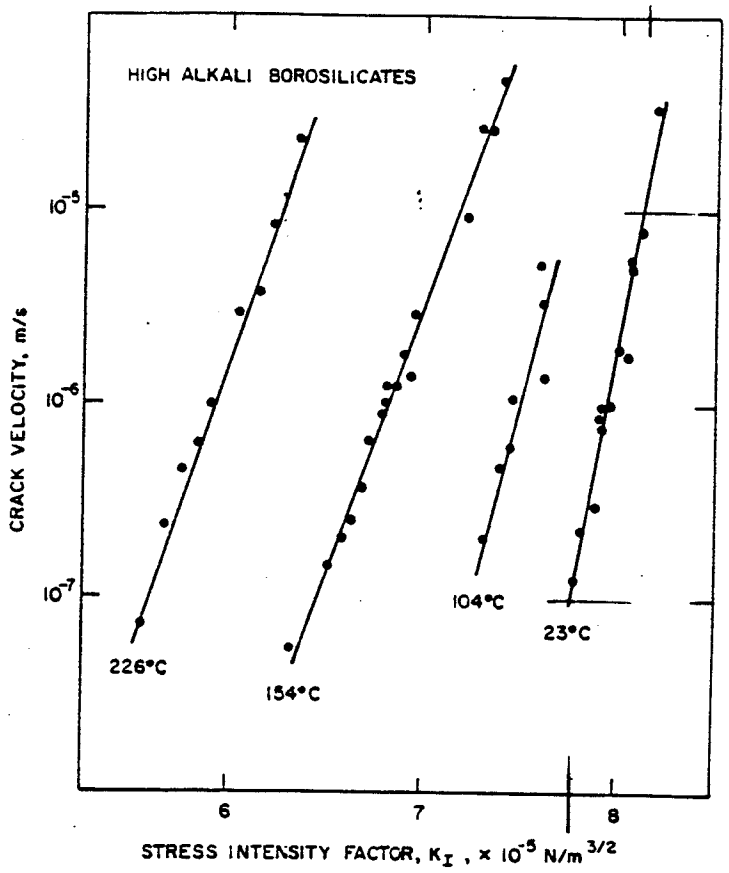

Fig. 11. Borosilicate Crown I, BK7, Vacuum, 10^{-5} Torr.

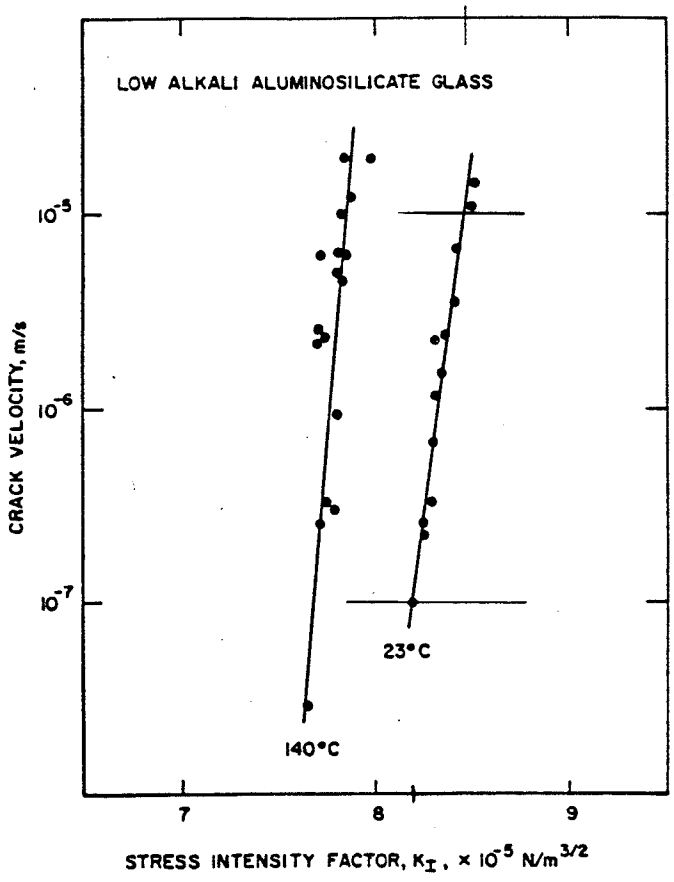

Fig. 12. Aluminosilicate, C1723, Vacuum, 10^{-5} Torr.

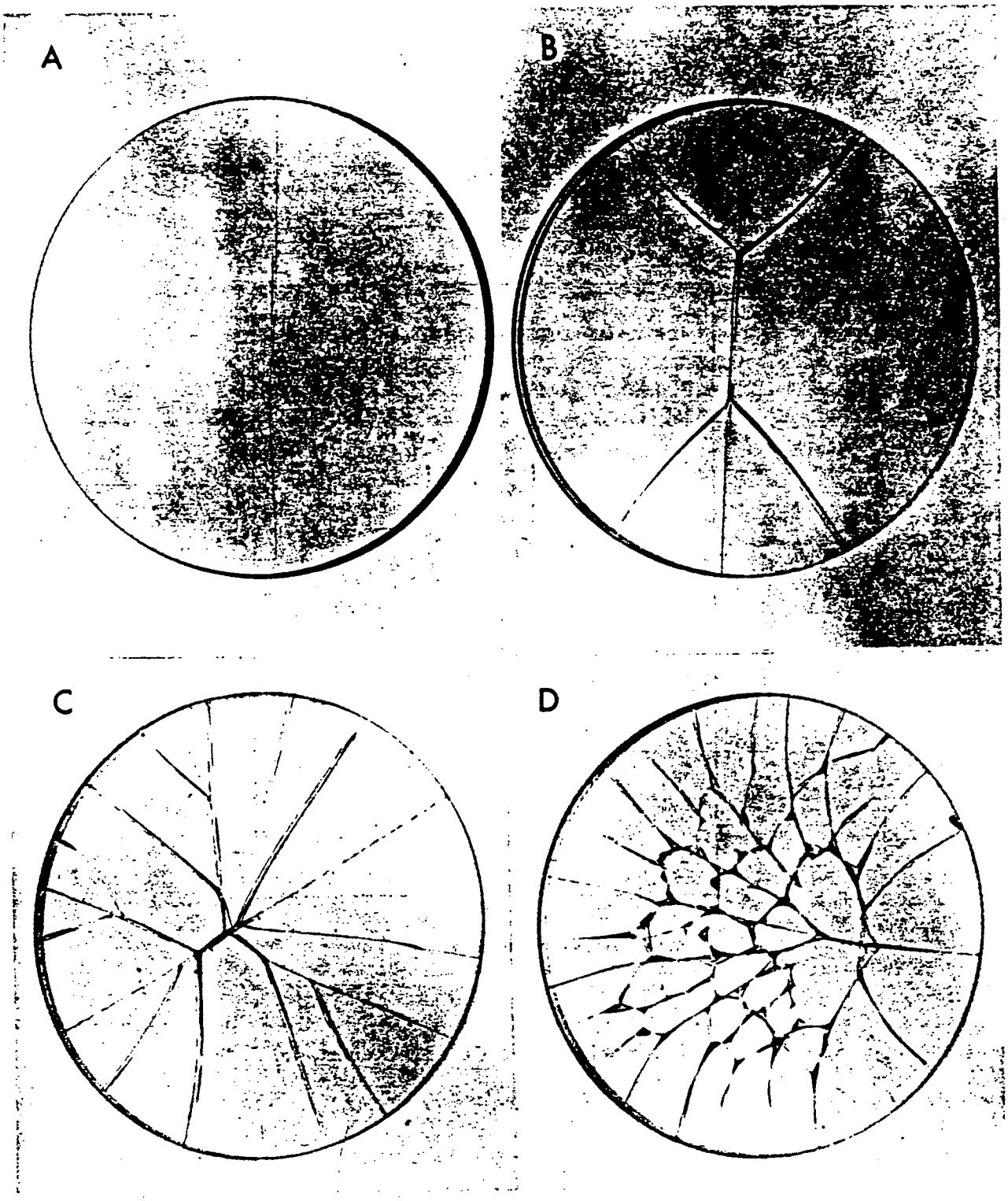

Fig. 13. Fracture Appearance of Disks

a. Specimen 8, Fracture Pressure 16 psi.

b. Specimen 9, Fracture Pressure 18 psi.

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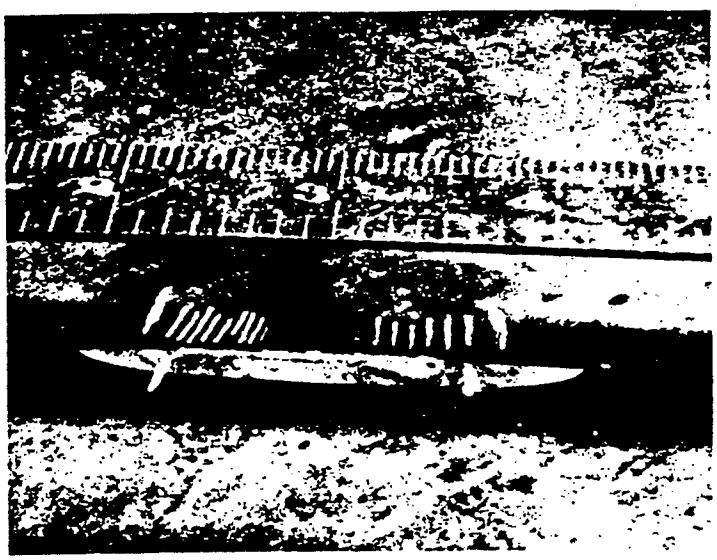

Fig. 14. Specimen 19, Crack Growth at 5 psi. Original crack size indicated by two crayon marks on the side of the crack away from the ruler.

TABLE 1. Glass Compositions, % by wght.

Glass	SiO_2	Al_2O_3	B_2O_3	Na_2O	K_2O	MgO	CaO	Others
C7940, Fused Silica	99.9							
C7900, High Silica I	96	0.3	3					
C7913, High Silica II	96.5	0.5	3					
C1723, Aluminosilicate	57	15	5			7	10	6% BaO
C7740, Borosilicate	81	2	13	4				
BK7, Borosilicate Crown I	69		11	10	7		0.2	2% BaO, 1% CeO
UBK7, Borosilicate Crown II	70		11	10	7		0.2	2% BaO
SF1, 61% Lead Glass	35			4				61% PbO

TABLE 2. Critical Stress Intensity Factors, K_I, X 10^{-5} $N/m^{3/2}$
Double Cantilever Beam Specimens
Vacuum, 10^{-5} Torr, no preheat

Glass	K_I	Standard Deviation	Number of Specimens
C7940	7.41	0.25	6
C7900	7.00	0.24	4
C7913	7.15	0.07	3
C1723	8.46	0.23	3
C7740	7.60	0.07	6
BK7	8.62	0.32	4
UBK7	8.86	0.01	3
SF1	6.24	0.09	3

TABLE 3. Critical Stress Intensity Factors, K_I, X 10^{-5} $N/m^{3/2}$
Double Cantilever Beam Specimens
Vacuum, 10^{-5} Torr, Preheat 300° C for 30 minutes

Glass	K_I	Standard Deviation	Number of Specimens
C7940	7.29	0.23	3
C7900	7.11	0.09	3
C7913	6.99	0.12	4
C1723	8.74	0.11	4
C7740	7.70	0.12	3
BK7	9.27	0.10	4
UBK7	8.79	0.34	3
SF1	6.25	0.08	3

TABLE 4. Critical Stress Intensity Factors, K_I, X 10^{-5} $N/m^{3/2}$

Edge Cracked, 3 Point Bend Specimens

Vacuum, 10^{-5} Torr, no preheat

Glass	K_I	Standard Deviation	Number of Specimens
C7940	7.53	0.30	4
C7900	7.09	0.40	3
C7913	7.46	0.09	4
C1723	8.36	0.32	5
C7740	7.77	0.32	5
BK7	8.42	0.07	4
UBK7	9.04	0.14	3
SF1	6.43	0.09	3

TABLE 5. Critical Stress Intensity Factors, K_I, X 10^{-5} $N/m^{3/2}$
Double Cantilever Beam Specimens
In Nitrogen Gas, <0.02% RH

Glass	K_I	Standard Deviation	Number of Specimens
C7740	7.64	0.08	5
C7940	7.58	-	1

TABLE 6. Least Squares Fit of Crack Velocity Data to $K_I = a + b \ln v$

Glass	a X 10^{-5}	σ_a $N/m^{3/2}$	b X 10^{-4}	σ_b $N/m^{3/2}$
C7940	6.931	0.034	1.342	0.022
C7900	6.490	0.048	1.388	0.029
C7913	6.507	0.034	1.298	0.022
C1723	7.950	0.041	1.797	0.027
C7740	6.431	0.028	1.414	0.018
BK7[1]	7.530	0.071	2.165	0.052
UBK7[1]	7.406	0.063	2.226	0.049
SF1	5.717	0.023	1.557	0.017

[1]Data exhibited curvature. Least square fit on data for $v > 10^{-8}$ m/s.