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# PROOF TEST DIAGRAMS FOR ZERODUR GLASS-CERAMIC

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**16. Abstract**

Proof test diagrams for Zerodur glass-ceramic are calculated from available fracture mechanics data. It is shown that the environment has a large effect on minimum time-to-failure as predicted by proof test diagrams.

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## INTRODUCTION

Brittle materials such as glass and glass-ceramics which exhibit slow crack growth and subsequent fast fracture to failure exhibit a time dependence in strength.[1] The decrease in strength for a constant applied load for a given period of time is known as static fatigue. In many cases, environment plays a major role in the material lifetime. It has been shown for silicate glasses that crack velocity will increase as the amount of water vapor in the environment increases.[2,3] Other variables which affect glass strength, and subsequently lifetime, are surface finish and rate of applied load. A rough surface finish leads to a lower tensile strength than for a highly polished, flaw-free finish. The strength of glass is observed in general to increase with increasing load rate. This phenomenon is known as dynamic fatigue. All of the above-named factors need to be considered when glass is to be used in load bearing applications.

One method which can be used to predict glass lifetime for a given application is proof testing. In this test, the glass article which will be placed in service is tested. Survival of the proof test guarantees the preselected lifetime for the service article.

In this report, proof test diagrams for Zerodur glass-ceramic are presented.

## THEORY

In most applications using glass (e.g., pressure panes), low loads are applied over long periods of time. Thus, crack velocities are low and termed subcritical. Subcritical flaw growth can be written in terms of a power law function[4]

$$V = AK_I^N \tag{1}$$

where

$V$ = crack velocity

$A$ = constant

$N$ = constant

$K_I$ = stress intensity factor.

The time $t$, required for a crack to propagate from subcritical to critical size, where failure occurs, can be derived from the definition of crack velocity[4]

$$da/dt = V \qquad (2)$$

where $a$ = crack length. Also, the stress intensity is related to the applied load by[4]

$$K_I = \sigma_a Y a^{1/2} \qquad (3)$$

where:

$\sigma_a$ = applied load

$Y$ = geometric flaw factor.

Combining equations (2) and (3) gives

$$t = 2/\sigma_a^2 Y^2 \int_{K_{Ii}}^{K_{If}} (K_I/V)dK_I , \qquad (4)$$

where:

$K_{Ii}$ = initial value of stress intensity

$K_{If}$ = final value of stress intensity.

Using equations (1) and (4) one can write

$$t = 2(K_{Ii}^{2-N} - K_{If}^{2-N})/[(N-2)A\sigma_a^2 Y^2] . \qquad (5)$$

Since failure is essentially instantaneous when $K_{If} = K_{Ic}$, the time-to-failure is

$$t = 2(K_{Ii}^{2-N} - K_{Ic}^{2-N})/[(N-2)A\sigma_a^2 Y^2] . \qquad (6)$$

where $K_{Ic}$ = fracture toughness or critical stress intensity factor. Also, since $15 < N < 50$ for glass, $K_{Ic}^{2-N} << K_{Ii}^{2-N}$ and $K_{Ii} << 0.9K_{Ic}$, then

$$t \approx 2K_{Ic}^{2-N}/[(N-2)A\sigma_a^2 Y^2] . \qquad (7)$$

Thus, the time-to-failure can be determined provided that $K_{Ii}$, the stress intensity factor at the largest initial flaw, and the $K_I - V$ curve are known, for a particular glass.

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It has been demonstrated by several authors[5,6] that an upper limit to $K_{Ii}$ and thus a lower limit to the time-to-failure can be obtained by proof testing. Survival of the proof test guarantees that the stress intensity at the crack tip does not exceed $K_{Ic}$, otherwise, failure would have occurred.[1] Therefore, one can say

$$K_{Ii}/\sigma_a = (K_I)_{\text{proof}}/\sigma_p < K_{Ic}/\sigma_p \ . \tag{8}$$

Substituting $K_{Ii} < \sigma_a K_{Ic}/\sigma_p$ into equation (7) gives the minimum time-to-failure expression

$$t_{\min} = 2(\sigma_p/\sigma_a)^{N-2}/[(N-2)A\sigma_a^2 Y^2 K_{Ic}^{N-2}] \ . \tag{9}$$

By taking logarithms of $t_{\min}$ and $\sigma_a$, one can represent the minimum time-to-failure in graphical form. Different values of $\sigma_p/\sigma_a$ will appear as parallel lines in the diagram.

## ZERODUR PROOF TEST DIAGRAMS

Fracture mechanics data used to produce proof test diagrams for Zerodur were obtained from references 7 and 8. The data are tabulated in table 1. The data were substituted into equation (9) for various proof stress ratios ($\sigma_p/\sigma_a$). The value of the geometrical flaw constant, $Y$, was taken as $\pi^{1/2}$ which is valid for surface flaws.

The calculated proof test diagrams are shown in figures 1, 2, and 3. Figures 1 and 2 correspond to the data in reference 7, while figure 3 was calculated using the data in reference 8. The difference in figures 1 and 2 is quite evident. This is due to the difference in environment. Crack growth is enhanced by increasing the water vapor present in the environment, which manifests itself as a lower time-to-failure at a given applied stress and proof-stress ratio.

The differences between figures 1 and 3 are less noticeable. This is to be expected since the fracture mechanics values used to calculate these two diagrams are in good agreement. The differences that are seen are most likely due to experimental methods used in obtaining the fracture values. The authors in reference 8 used a notched beam specimen technique, while the author in reference 7 used Vicker's indentation in combination with static and dynamic methods.

These diagrams could now be used to determine minimum time-to-failure of an article of Zerodur. There are, however, some limitations of proof testing.[9] The proof test itself should nearly identically simulate the stress state and boundary conditions that the article will see in service. The test itself should be run in an environment which precludes subcritical flaw growth, i.e., in dry air, dry gas, or vacuum. The rate of loading and unloading should be extremely rapid such that there is no flaw growth prior and subsequent to the peak load. This is especially important during the unloading of the article. If the rate is too slow, there could be subcritical flaw growth which was not detected by the proof test. Also, the surfaces and edges of the article must be protected after proof testing to prevent accidental introduction of flaws which would nullify the proof test.

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Table 1. Fracture mechanics data from references 7 and 8.

| Reference | $K_{Ic}$ (MPa·m 1/2) | $N$ | $A$ |
|---|---|---|---|
| 7[1] | 0.91 | 59.3 | $80\times10^6$ |
| 7[2] | 0.91 | 30.7 | 1012 |
| 8[3] | 0.84 | 51.7 | $5.8\times10^6$ |

1. 50-percent relative humidity and 25 °C.
2. 100-percent relative humidity and 25 °C.
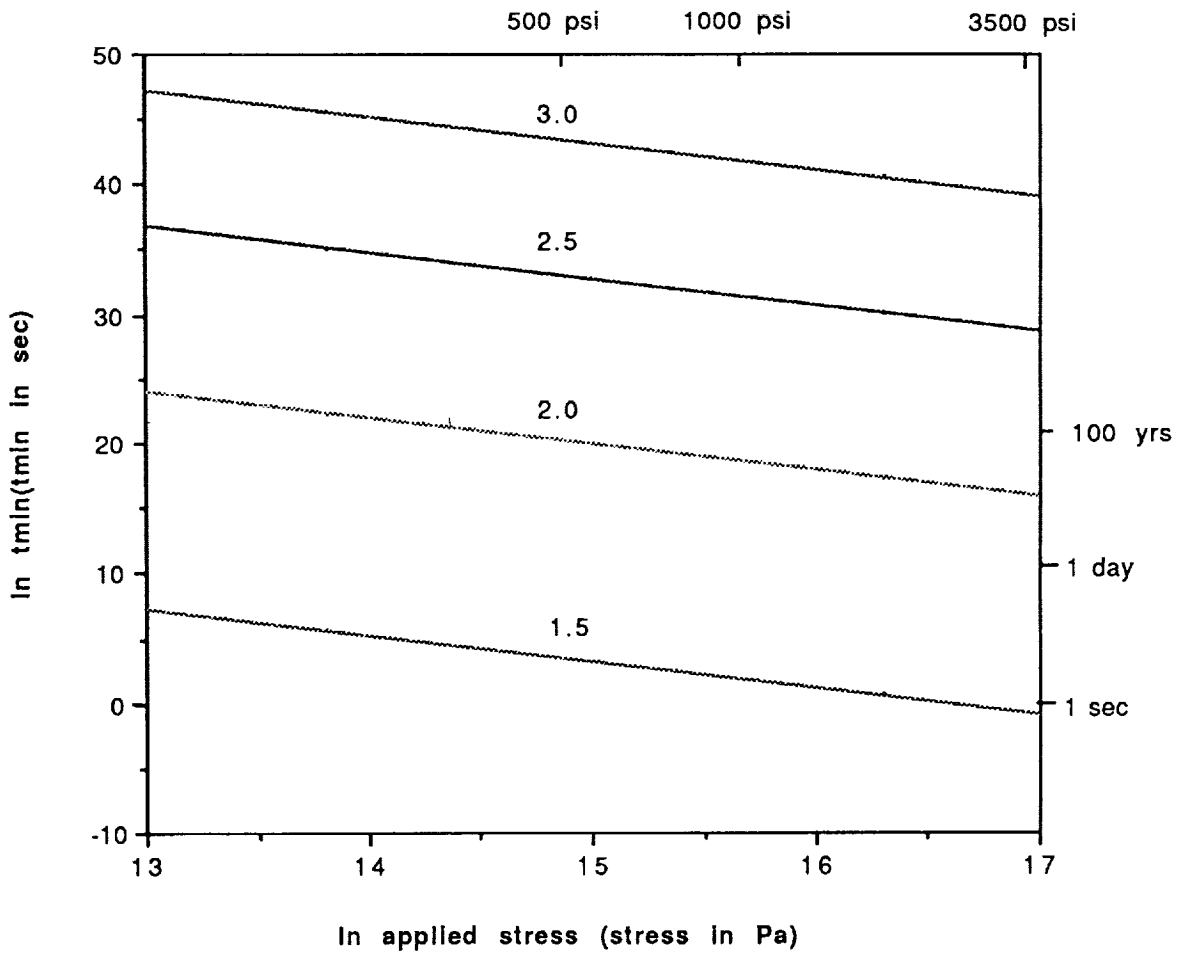3. 50-percent relative humidity and 25 °C.



Figure 1. Proof test diagram from reference 7, 50-percent relative humidity and 25 °C.
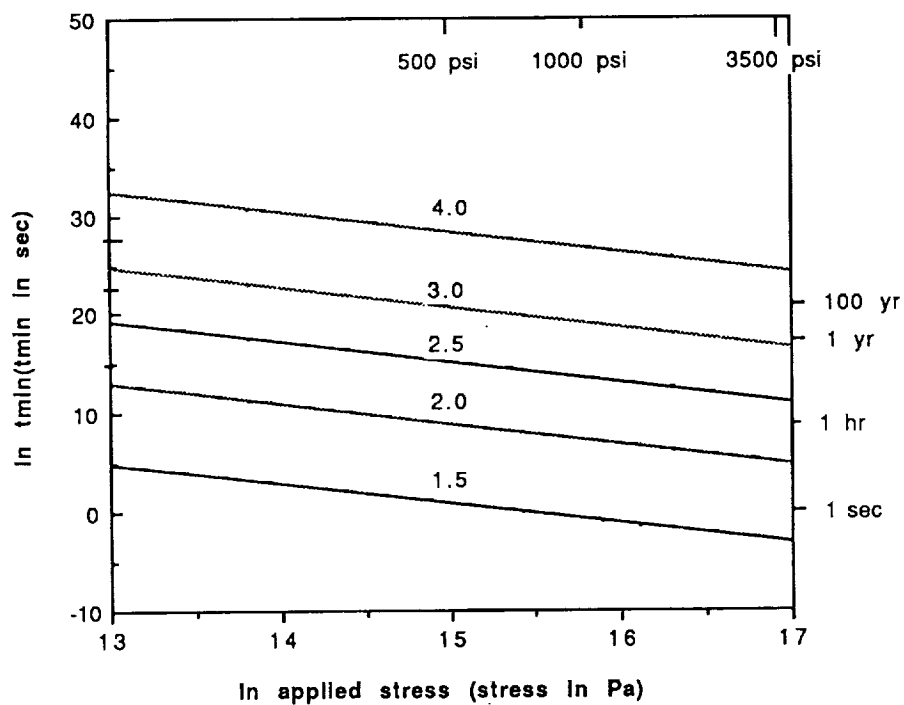
Figure 2. Proof test diagram from reference 7, 100-percent relative humidity and 25 °C.
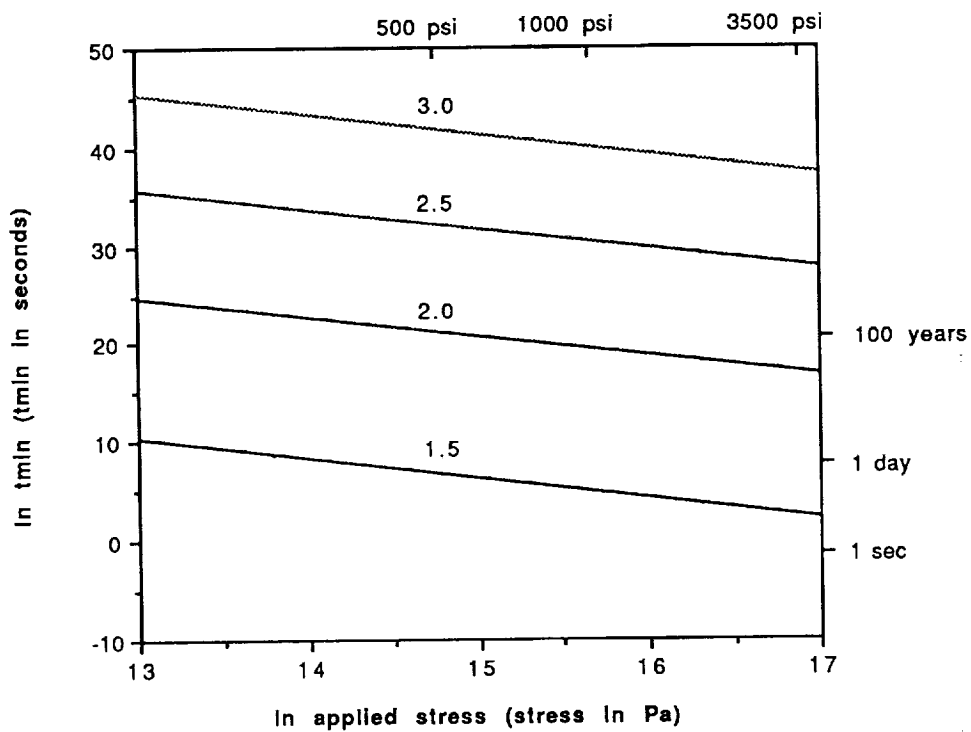


Figure 3. Proof test diagram from reference 8, 50-percent relative humidity and 25 °C.

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# APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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