Results of Mechanical Testing for Pyroceram™ Glass-Ceramic

Sung R. Choi
Ohio Aerospace Institute, Brook Park, Ohio

John P. Gyekenyesi
Glenn Research Center, Cleveland, Ohio

September 2003
Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA’s scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA’s institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA’s counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA’s mission.

Specialized services that complement the STI Program Office’s diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301–621–0134
- Telephone the NASA Access Help Desk at 301–621–0390
- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076
Results of Mechanical Testing for Pyroceram™ Glass-Ceramic

Sung R. Choi
Ohio Aerospace Institute, Brook Park, Ohio

John P. Gyekenyesi
Glenn Research Center, Cleveland, Ohio

National Aeronautics and Space Administration

Glenn Research Center

September 2003
Acknowledgments

The authors are grateful to Ralph Pawlik for the experimental work done during the course of this investigation. This work was conducted under Space Act Agreement No. SAA3–298 with Science and Applied Technology, Inc., Woodland Hills, California 91367.

This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

Trade names or manufacturers’ names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

The Propulsion and Power Program at NASA Glenn Research Center sponsored this work.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov
Results of Mechanical Testing for Pyroceram™ Glass-Ceramic

Sung R. Choi and John P. Gyekenyesi
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, OH 44135

Abstract
Mechanical testing for Pyroceram™ 9606 glass-ceramic fabricated by Corning was conducted to determine mechanical properties of the material including slow crack growth (or life prediction parameters), flexure strength, tensile strength, compressive strength, shear strength, fracture toughness, and elastic modulus. Significantly high Weibull modulus in flexure strength, ranging from $m=34$ to $52$, was observed for the ‘fortified’ test specimens; while relatively low Weibull modulus (but comparable to most ceramics) of $m=9-19$ were obtained from the ‘unfortified’ as-machined test specimens. The high Weibull modulus for the ‘fortified’ test specimens was attributed to the chemical etching process. The slow crack growth parameter $n$ were found to be $n = 21.5$ from constant stress-rate (“dynamic fatigue”) testing in flexure in room-temperature distilled water. Fracture toughness was determined as $K_{IC}=2.3-2.4$ MPa$\sqrt{m}$ (an average of 2.35 MPa$\sqrt{m}$) both by SEPB and SEVNB methods. Elastic modulus, ranging from $E=109$ to $122$ GPa, was almost independent of test temperature, material direction, and test method (strain gauging or impulse excitation technique) within the experimental scope, indicating that the material was homogeneous and isotropic. The existence of the 'fortified' layer played a crucial role in controlling and determining strength, strength distribution and slow crack growth behavior. It also acted as a protective layer. Valid testing was not achieved in tension, compression and shear testing due to inappropriate test specimen configurations (in compression and shear) provided and primarily due to the existence of ‘fortified’ layer (in tension).

I. OBJECTIVES AND TEST MATRIX
Mechanical testing for Pyroceram™ 9606 glass-ceramic fabricated by Corning was performed to determine mechanical properties of the material including slow crack growth (or life prediction parameters), tensile strength, compressive strength, shear strength, fracture toughness and elastic modulus. Test specimens with different geometries/treatments were provided by Science & Applied Technology, Incorporated, via Corning. The overall, original test matrix is shown in Table 1.

II. EXPERIMENTAL PROCEDURES
1. Material and Test Specimens
The material used in this work was Pyroceram™ 9606 glass ceramic, fabricated by Corning, Inc., (Corning, NY). The glass-ceramic material has been reported to be processed from a magnesium aluminosilicate glass containing titania as a nucleating agent, and cordierite ($2\text{MgO-2Al}_2\text{O}_3-5\text{SiO}_2$) is reported as the major crystalline phase in the material [1]. Test specimens were machined from billet(s) in accordance with the test matrix and were chemically etched to ‘fortify’ their surfaces. Both machining and etching of test specimens were made by the manufacturer, Corning. The apparent (not real) thickness of test specimens was all 2.5 mm (0.1”), with a fortified layer thickness of around 0.2 mm. In some cases, testing was performed with test specimens that were not chemically etched, termed ‘as-machined’ test specimens. These ‘unfortified,’ as–machined test specimens were used in part in constant stress testing, fracture toughness and elastic modulus testing.
2. Slow Crack Growth (Life Prediction) Testing: Constant Stress-Rate Testing

A). Basics

Constant stress-rate (also called "dynamic fatigue") testing has been utilized for several decades to quantify the slow crack growth behavior of glass and ceramic materials at both ambient and elevated temperatures. The merit of constant stress-rate testing over other methods lies in its simplicity: Strengths of test specimens are determined in a routine manner at four to five stress rates by applying constant crosshead speeds (displacement-control) or constant loading rates (load-control). The slow crack growth (SCG) parameters required for life prediction/reliability are simply calculated from a relationship between failure strength and stress rate. Because of its unique advantages, constant stress-rate flexural testing has been developed as ASTM test standards to determine SCG parameters of advanced ceramics at ambient temperature (Test Method C 1368 [2] and elevated temperatures (Test Method C 1465 [3]).

Slow crack growth of glass and ceramics under mode I loading above the fatigue limit is generally described by the following empirical power-law relation [4]:

\[ v = \frac{da}{dt} = A \left( \frac{K_I}{K_{IC}} \right)^n \]  

where \( v, a, t \) are crack velocity, crack size, and time, respectively. \( A \) and \( n \) are the material/environment-dependent SCG parameters. \( K_I \) is the mode I stress intensity factor (SIF), and \( K_{IC} \) is the critical stress intensity factor or fracture toughness of the material, subjected to mode I loading. Under constant stress-rate ("dynamic fatigue") loading using either constant displacement rate or constant loading rate, the corresponding failure strength (\( \sigma_f \)) can be derived as a function of stress rate (\( \dot{\sigma} \)) as follows [5,6]:

\[ \sigma_f = \left[ B(n+1)\sigma_i^{n-2} \right]^{\frac{1}{n+1}} \sigma_f^{\frac{1}{n+1}} \]  

where \( B = 2K_{IC}^{2}/AY^2(n-2) \) with \( Y \) being a crack geometry factor in the expression of \( K_I = Y\sigma\sqrt{a} \) with \( \sigma \) being a remote applied stress, and \( \sigma_i \) is the inert strength. By taking the logarithm both sides of Equation (2) yields [2]

\[ \log \sigma_f = \frac{1}{n+1} \log \dot{\sigma} + \log D \]  

where \( \log D = [1/(n+1)] \log[B(n+1)\sigma_i^{n-2}] \). The SCG parameters \( n \) and \( D \) can be obtained from the slope and the intercept, respectively, of Equation (3) by using a linear regression analysis of \( \log \sigma_f \) versus \( \log \dot{\sigma} \). The parameter \( A \) is determined from \( D \) together with appropriate constants. Equation (3) is the commonly utilized SCG solution, from which the SCG parameters required for life prediction of structural components are determined with experimental data of strength versus stress rate.

B). Testing

Constant stress-rate testing for ‘fortified’ test specimens was carried out in flexure at room temperature in distilled water (100% R.H.). A stainless steel, four-point flexure fixture with 20 mm-inner and 40 mm-outer spans was used with alumina roller pins. The apparent dimensions of flexure-beam test specimens were 2.5 mm by 5.1 mm by 46 mm, respectively, for thickness (depth), width and overall length. Six different (apparent) stress rates of 50, 5, 0.5, 0.05, 0.005 and 0.0005 MPa/s were employed under load control using an electromechanical test frame (Model 8562, Instron, Canton, MA). A total of 30 test specimens were used at each test rate, from 0.005 to 50 MPa/s, while a total 22 test specimens...
were tested at the lowest test rate of 0.0005 MPa/s. All testing was conducted in accordance with ASTM Test Method C 1368 [2]. Inert strength (strength without slow crack growth) was also evaluated in an inert environment (silicon oil, 704 Diffusion Pump Fluid, Dow Corning, Midland, MI) at a test rate of 50 MPa/s with a total of 30 test specimens. It was found from the fracture surface examinations of tested specimens that the average ‘fortified’ layer thickness was about 0.17 mm. Hence, the true stress or true strength (or true stress-rate) was calculated based on the actual specimen dimensions with the ‘fortified’ layer thickness being subtracted from the apparent dimensions. The ‘fortified’ layer will be discussed in more detail in the Results & Discussion section.

Additional constant stress-rate testing was performed for comparison in distilled water with ‘unfortified’ test specimens that were not chemically etched but as-machined. The apparent dimensions of as-machined test specimens were 2.5 mm by 5.1 mm by 46 mm in thickness (depth), width and overall length, respectively. Two test rates of 70 and 0.07 MPa/s were used with a total 20 test specimens at each test rate. Inert strength was also determined in silicon oil at 70 MPa/s using 20 test specimens. Test fixture and test frame used for the ‘unfortified’ test specimens were the same as those for the ‘fortified’ test specimens. A typical test fixture/specimen configuration used in slow-crack-growth flexure testing is shown in Figure 1.

3. Tensile Testing

Tensile strength testing of the material was conducted using ‘fortified,’ flat, shoulder-loaded tensile test specimens in accordance with ASTM Test Method C 1273 [7]. The apparent, overall dimensions of tensile test specimens were 2.5 mm by 3.2 mm by 89 mm, respectively, in thickness, width and overall length. The gage section had the apparent dimensions of 2.5 mm by 3.2 mm in cross section and about 50 mm in length. Each test specimen was loaded via four loading roller-pins (two for each end) that were in contact with the upper and lower shoulder regions of a specimen. Three different test temperature/environment conditions were used in tensile testing: room temperature in distilled water, 93 °C (200 °F) in distilled water, and 274 °C (525 °F) in ambient air. The number of test specimens used was 16, 15 and 15, respectively, at room temperature, 93 °C and at 274 °C. Test rates close to 70 MPa/s were used in load control using the electromechanical test frame (Model 8562, Instron).

Originally, alignment of each test specimen was intended by using strain gages attached to the specimen surfaces. However, a great difficulty was encountered in this approach after the finding of the existence of the ‘fortified’ layer on specimen surfaces, produced by a unique surface treatment by chemical etching that had left a ‘soft’ powdered layer on the specimen surface. This ‘fortified’ but soft layer was not appropriate to the application of strain gages. One might consider that the layer could be removed by careful scraping, sanding or polishing. However, this approach was vulnerable to generate new flaws by changing original flaw populations on brittle specimen surfaces. (The typical flaw size of ‘fortified’ test specimens was estimated to be about 50µm based on the inert strength (=303 MPa, Table 1) in flexure and fracture toughness (=2.35 MPa√m, Table 6) data.). Hence, because of this unique feature of test specimens, imposed through chemical etching, rigorous tensile strength testing with strain gages both to determine strength and elastic modulus was not feasible for the test specimens provided. Tensile testing was performed with the test specimens in as-provided condition. Figure 2 shows the tensile test set-up used in this work.

4. Compression Testing

Compression testing was conducted in room-temperature distilled water with ‘fortified,’ flat, rectangular cross-section test specimens in accordance with Test Method SACMA SRM-1 [8], derived from ASTM Test Method D 695 [9]. The apparent dimensions of test specimens were 2.5 mm by 12.5 mm by 81 mm, respectively, in thickness, width and overall length. Test specimens were supplied with three different material axes: Directions 1, 2 and 3. The use of a proper tapping material in strength testing, as recommended in Test Method SACMA SRM-1, was not feasible, again due to the existence of the soft, ‘fortified’ layer on the specimen surfaces. A copper or aluminum shim was placed between the
loading plate (of the upper push rod) and the top-end of a test specimen, to minimize localized stress. It was intended that compressive strength was to be determined at each material axis and that elastic modulus was to be evaluated for Direction 1. However, each individual specimen tested, due to its unique geometrical configuration, failed (‘crushed’) from the top end where a compression load was locally applied, resulting in localized failure leading to an invalid test. This will be discussed in the Results and Discussion section. Since strain gages could not be attachable (‘bonded’) to the soft ‘fortified’ layer, one specimen from each material axis was polished to remove the ‘fortified’ layer so that strain gages were applied to determine corresponding elastic modulus. All testing was conducted in displacement control with a test rate of 1.27 mm/min using the electromechanical test frame (Model 8562, Instron). The compression test set-up utilized is shown in Figure 3.

5. Shear Testing
Shear testing was carried out in room-temperature distilled water with ‘fortified,’ flat, V-notched test specimens in accordance with ASTM Test Method D 5379 [10], based on the asymmetric Iosipescu test. The apparent dimensions of test specimens were 2.5 mm by 20.3 mm by 76 mm, respectively, in thickness, depth and overall length. Again, due to the existence of the soft ‘fortified’ layer, strain gauging to determine shear modulus was not applicable to the test specimens. Testing was performed under displacement control with a test rate of 0.25 mm/min using the electromechanical test frame (Model 8562, Instron). Test set-up used in shear testing is shown in Figure 4.

6. Fracture Toughness Testing
Two different test methods were used in determining fracture toughness of the material. One was the single edge precracked beam (SEPB) method as specified in ASTM Test Method C 1421 [11]. The other was the single edge V-notched beam (SEVNB) method. The latter method has been recently practiced and appeared as a valid test technique through an international (VAMAS) round robin on fracture toughness [12]. The ‘fortified’ specimens with the apparent dimensions of 2.5 mm x 3.6 mm x 46 mm (width, depth and overall length) were used in SEPB method, while the ‘unfortified’ as-machined specimens with the dimensions of 2.5 mm x 5.1 mm x 46mm (width, depth and overall length) were used in SEVNB method. In SEPB method, a starting, indent crack was placed at the center of the 2.5 mm side of each test specimen (after removing the layer in a small area appropriate). The indented specimen was then placed onto a specially designed precracking fixture and then loaded via the fixture until the indent crack popped-in to form a sharp through-the-thickness crack [13], see Figure 5. In SEVNB method, a sharp razor blade with 1 µm diamond compound was placed into a precut straight saw notch to subsequently cut a very sharp V-notch with its root radius of typically less than 10 µm. A typical example of a SEVNB test specimen thus V-notch prepared is presented in Figure 6. A four-point flexure fixture with 20 mm-inner and 40 mm-outer spans was used to determine fracture load. A test rate of 0.5 mm/min was used via the electromechanical test frame (Model 8562, Instron) with a small load cell with a capacity of 1000 N. Silicon oil was used to minimize slow crack growth effect. Precrack sizes were optically determined from fracture surfaces of test specimens. A total of 10 and 9 test specimens were used, respectively, in SEPB and SEVNB methods.

7. Elastic Modulus Testing
Elastic modulus of the material was determined by methods including impulse excitation (ASTM C 1259 [14]) and strain gauging. It was found that the excitation impulse of vibration method was not applicable to the ‘fortified’ specimens due to their soft layer that acted as a damping medium by quickly diminishing vibration of test specimens. The determination of elastic modulus by the impulse excitation technique had to be made with test specimens without ‘fortified’ layer, that is, with as-machined test specimens. A total of 39 as-machined flexure beam test specimens, measured 2.5 mm by 5.1 mm by 46 mm, respectively, in depth, width and overall length, were used to determine elastic modulus at room temperature in ambient air by the impulse excitation method. A total of 10 specimens (out of the 39 as-
machined flexure test specimens) were used to determine elastic modulus at three different temperatures of room temperature, 93 °C (200 °F) and 274 °C (525 °F) in ambient air by a high-temperature excitation rig. This testing was a substitute to the originally planned tensile testing in which elastic modulus (together with strength) was intended to be determined by strain gauging at the three temperatures, but which later appeared inappropriate due to the soft, ‘fortified’ layer on the tensile test specimens provided.

As stated in the Compression Testing section, elastic modulus by strain gauging could not be obtained in compression testing with the test specimens provided, again due to the ‘fortified’ layer. One compression test specimen from each material axis -a total of three specimens in all three material directions- was polished to remove the ‘fortified’ layer from its major sides to be able to attach strain gage. With these strain-gauged specimens, elastic modulus was determined in compression in accordance with Test Method SACMA SRM-1 [8] as well as in four-point flexure (both in tension and in compression by reversing test specimens upside down) with 20/40 mm spans. Hence, three values of elastic modulus were obtainable by this approach with one test specimen.

III. RESULTS AND DISCUSSION

1. Slow Crack Growth Testing: Constant Stress-Rate Testing

A summary of the results of constant stress-rate testing for both ‘fortified’ and ‘unfortified’ test specimens is presented in Table 2, where test conditions, mean (arithmetic average) strength and Weibull parameters are included. Also included are inert strength data determined in silicon oil. The Weibull parameters \(m\) and \(m \ln \sigma_o\) were evaluated using strength data obtained at each test condition, based on the following two-parameter Weibull formula

\[
\ln \ln \frac{1}{1-F} = m \ln \sigma_f - m \ln \sigma_o
\]

where \(F\) is failure probability, \(m\) is Weibull modulus, \(\sigma_o\) is the characteristic strength. The Weibull mean strength in Table 2 corresponds to the strength when \(F = 0.5\) or 50 %. It is also noteworthy to mention that an excellent relationship between Weibull modulus and coefficient of variation (C.V) for a given test condition holds

\[
m \approx 1.2 \frac{1.2}{CV} \sigma_f = 1.2 \frac{s}{\sigma_f}
\]

where \(s\) is the (±1.0) standard deviation and \(\sigma_f\) is the arithmetic mean strength. The above relation can be checked using the data given in Table 2.

The results of constant stress-rate testing are also summarized in Figure 7, where each individual fracture strength was plotted as a function of the corresponding applied stress rate in a form of log (fracture stress) vs. log (stress rate) based on Equation 3. Also presented are the inert strength data for comparison as well as the best-fit regression line. As can be seen from the figure, strength decreases with decreasing stress rate, which represents the susceptibility to slow crack growth, a unique feature typical of glasses and advanced ceramics. Based on Equation (3), a linear regression analysis of log (individual fracture stress in MPa) versus log (true stress rate in MPa/s), as specified in ASTM C 1368 [2], for a total of 172 data points determined from true stress rates ranging from 71 MPa/s to 0.00071 MPa/s, yields the following result

\[
\log \sigma_f = 0.04455 \log \sigma + 2.27207; \quad r^2_{cof} = 0.9743
\]
where \( r_{\text{coef}}^2 \) is the square of the coefficient of correlation in regression. Using Equations (5) and (3), the slow crack growth (SCG) parameters \( n \) and \( D \) can be determined as follows:

\[
n = 21.45 \quad \text{and} \quad D = 187.1
\]  

(6)

The units of \( D \), rather complicated, can be evaluated from Equations (3) and (5). It is noted that the value \((n = 21)\) of SCG parameter determined from this material is close to the value of soda-lime glass that has been known as one of materials highly susceptible to stress corrosion in a moisture environment. Because of this high SCG susceptibility to the environment, the inert strength (with no slow crack growth) degrades significantly when the specimen is loaded in distilled water. For example, the inert strength \((=303\ \text{MPa})\) degraded by 25% at the fastest test rate of 71 MPa/s, whereas it degraded by 55% at the lowest test rate of 0.00071 MPa/s (see Table 2). This slow crack growth behavior of the material controls the life of structural components so that component design should be performed in conjunction with an appropriate reliability/life-prediction methodology.

Also as can be seen in Figure 7, the strength scatter was very small and almost consistent regardless of test rate or type of test environment. As seen from Table 2, except for the strength determined at the lowest stress rate of 0.00071 MPa/s (but note that the number of test specimens was only 22 at this test rate), the corresponding Weibull modulus ranged from \(m=41\) to \(m=52\), which is significantly greater than those \((m=10-20)\) of typical advanced ceramics such as silicon nitrides, silicon carbides and aluminas. This significantly high Weibull modulus exhibited by the test material compares well with Weibull modulus \((m=50-100)\) of polymer-coated optical fused-silica glass fibers. A summary of all the Weibull strength distributions based on Equation (4), including inert strength, is shown in Figure 8. Evident from the figure are consistent Weibull modulus (slope) and systematic strength degradation with respect to decreasing test rate. Individual Weibull strength plots as well as the raw test data are included in the Appendix.

The reason for the significantly high Weibull modulus can be explored from fractographic analysis. A typical example of the fracture surface of a ‘fortified’ specimen tested is shown in Figure 9. A red dye-penetrant, customarily utilized in our lab to reveal cracks in ceramics (e.g., a SEPB crack such as in Figure 5), was placed around the specimen close to the fracture surface. Due to the existence of the surrounding soft ‘fortified’ layer, the dye quickly penetrated into the soft layer, thus revealing a clear demarcation between the base material and the soft layer. In fact, this was the way we determined the thickness of ‘fortified’ layers for different test specimens. Figure 9 clearly shows that fracture originated from the boundary between the base material and the layer. In other word, fracture was initiated from the surface of the base material. Further in-depth examinations of fracture surfaces for many tested specimens drew the same conclusion. The chemical etching process applied to the test specimens generated entirely new surface-flaw populations at the base material with a very tight distribution in flaw sizes by removing loosely distributed machining flaws.

The generation of new flaw populations by chemical etching can be further verified by comparing with the Weibull strength data obtained from the as-machined (‘unfortified’) test specimens. The strength and Weibull-parameter data for the as-machined specimens tested at 70 MPa/s, 0.07 MPa/s and in silicon oil (inert) are shown in Table 2, as well as in Figure 10. It should be noted that the Weibull modulus ranged from \(m=9\) to 19, appreciably lower compared to \(m=40\) to 50 for the ‘fortified’ test specimens. A comparison in strength between the ‘fortified’ and the as-machined test specimens is also illustrated in Figure 11: The strength scatter for the as-machined test specimens was greater than that of the ‘fortified’ counterparts. Also note that strength was lower for the as-machined test specimens than for the ‘fortified’ counterparts. A typical fracture surface of an as-machined specimen tested is presented in Figure 12, showing that fracture originated from a predominant machining flaw, typical of many ceramic materials. The machining damage was a primary failure source for the as-machined test specimens, resulting in both lower Weibull modulus due to loosely distributed flaw sizes. This compares well with the behavior of many as-machined advanced ceramic specimens that typically exhibit Weibull modulus of \(m = 10\) to 20.
Therefore, based on the above observations and results, it can be concluded that the outcome of the significantly high Weibull modulus for the ‘fortified’ test specimens was attributed to extremely tightly distributed flaw sizes, formed as a result of the chemical etching process.

Finally, it should be noted that the soft ‘fortified’ layer cannot sustain any external loading so that when calculating accurate stress or strength, the layer thickness must be subtracted from the apparent specimen dimensions. In four-point flexure testing, strength ($\sigma_f$) can be calculated from the following equation

$$\sigma_f = \frac{3P_f (L_o - L_i)}{2bh^2}$$  \hspace{1cm} (7)

where $P_f$ is the fracture load, $L_o$ and $L_i$ are outer and inner spans, respectively, $b$ is the specimen width, and $h$ is the specimen depth. The values of $b$ and $h$ in order to obtain true strength (or true stress rate) should be determined as follows:

$$b = b_n - 2t \text{ and } h = h_n - 2t$$  \hspace{1cm} (8)

where $b_n$ and $h_n$ are apparent width and depth of a test specimen (measured, for example, with a micrometer), respectively, and $t$ is the average ‘fortified’ layer thickness determined from fractography or any other appropriate methods. The value of the average ‘fortified’ layer thickness was found to be $t=0.17$ mm, estimated from about 10 flexure test specimens.

2. Tensile Strength

As mentioned in the Experimental Procedures section, rigorous alignment of test specimens in tensile testing was not feasible due to the existence of the soft ‘fortified’ layer that made the use of strain gages infeasible. Tensile strength testing was conducted under this imperfect condition. A summary of test results determined at three different temperature/environment conditions is presented in Table 3. Corresponding Weibull strength distributions are presented in Figure 13. Contrary to the case for the ‘fortified’ flexure test specimens, no consistent, high Weibull modulus was observed in tensile testing. Instead, Weibull modulus changed considerably from $m=45$ at room temperature to $m=6-8$ at 93 and 274 °C, indicative of some inconsistent factors associated with tensile testing. Figure 14 depicts strength as a function of temperature. The average strength was highest in 274 °C air, intermediate in room temperature distilled water and lowest in 93 °C-distilled water. The highest strength at 274 °C could be understood by the fact that the high temperature would have reduced the moisture content of the ambient air surrounding inside the test furnace. It is well known that strength of a brittle material susceptible to slow crack growth depends on relative humidity: The higher strength yields at the lower relative humidity, and vice versa. The lower strength in 93 °C-distilled water, as compared with the room temperature strength, may be attributed to the effect of temperature. For the given environment (distilled water here), strength is known to decrease with increasing temperature, due to increased crack velocity by the relation of $v = \alpha [K_i]^{n} e^{Q/RT}$ with $v$, $\alpha$, $Q$, $R$ and $T$ being crack velocity, parameter, activation energy, gas constant, and temperature, respectively.

Figure 15 shows two typical fracture patterns associated with tensile failure: gage-section failure and transition-region failure. Transition (or ‘neck’) region failure might have occurred due to geometrical discontinuity of test specimens between the end of shoulder region and the end of gage section. This type of failure has been observed frequently in many dog-boned tensile ceramic specimens, primarily due to improper specimen machining. Because of its possible severe machining damage, discontinuity and/or subsequent higher stress concentration, this transition region acts as a failure origin, resulting in inaccurate strength measurements. About 46% of all the tensile specimens tested failed from this
transition region. Nevertheless, the strength data of those transition-region-failed specimens were not excluded from the data pool for a description purpose.

As aforementioned, the existence of the soft ‘fortified’ layer hindered the use of strain gages for specimen alignment in tensile testing. It also worsened the alignment of specimens because of its thinning effect of specimen thickness. It was found that the average ‘fortified’ layer thickness for the tensile test specimens was about 0.21 mm. This gives an actual specimen thickness of 2.1 mm (=2.5 mm –0.42 mm) from 2.5 mm. This thickness would not be sufficient for supporting tensile loading under shoulder-loading configuration. Small deviation in parallelism between loading pins can result in significant misalignment, occurring undesirable failure such as loading-pin region failure that in turn would give under- or overestimated strength values. In fact, about 26 % of all the tensile specimens tested failed from the loading-pin contact region, giving rise to lower strength values (e.g, the three lower data points at 274 °C in Figure 14). Moreover, the non-uniform ‘fortified’ layer thickness around a test specimen would result in an additional source toward misalignment. Because of these limiting factors associated with tensile testing, it is recommended that the tensile strength data should not be used as design data (but for information purpose only).

Figure 16 represents a typical example of fracture surface showing fracture originating from a surface flaw. Despite several limiting factors, surface flaws were dominant strength-limiting flaws in tensile specimens. When a material highly susceptible to slow crack growth is exposed to an (SCG) environment, the material surface is most susceptible to failure because of slow crack growth. By contrast, flaws inside the bulk material –i.e, volume flaws- would remain in inert condition, giving much less chance to failure. Even in terms of size, surface flaws formed by chemical etching seemed to be greater than inherent volume flaws in view of all the flexure and tension testing results in this work.

3. Compression Testing

A typical example of a specimen tested in compression testing is shown in Figure 17. The specimen failed from the top end where compression load was applied and where localized stress(es) occurred. All the test specimens tested (a total of 11 test specimens) showed the same failure mode leading to load-point failure. A few of them exhibited the pulverization of top end. As a result, all compression testing conducted was of invalid testing. It is recommended that short, dumbbell-type, cylindrical compression test specimens, as recommended in ASTM Test Method C 1424 [15], be used to determine compression strength of the material. The test results, although invalid, are shown in Table 4 and Figure 18. The average ‘fortified’ layer thickness of compression test specimens was estimated as t=0.22 mm.

4. Shear Testing

A typical failure pattern of a test specimen subjected to asymmetric Iosipescu shear testing is presented in Figure 19. It is apparent that a desirable shear fracture did not occur. Instead, fracture originated from the notch roots at approximately 45 degree (to the shear force direction) where a maximum, principal tensile stress existed, resulting in tensile failure. Failure of brittle ceramics and glasses, in general, is governed by the maximum-principal-tensile-stress criterion even under multiaxial state of stresses. A total of 6 test specimens were tested and their failure patterns were all the same as that shown in the figure. Occurrence of pure-shear failure is rarely expected to this brittle test material under the current test fixture/specimen configuration. Shear test results, although not valid, are shown in Table 5 and Figure 20. The average ‘fortified’ layer thickness of shear test specimens was estimated to be t=0.21 mm.

5. Fracture Toughness

A summary of the results of fracture toughness testing using SEPB and SEVNB methods is shown in Table 6 and Figure 21. The values of fracture toughness were $K_{IC} = 2.3\pm0.05$ MPa√m and $2.4\pm0.08$ MPa√m, respectively, by SEPB and SEVNB methods. The two methods yield excellent
agreement in fracture toughness, thereby confirming the accuracy of the values of fracture toughness determined in this work. The average value of fracture toughness is $K_{IC} = 2.35 \text{ MPa}\sqrt{\text{m}}$

6. Elastic Modulus

A summary of elastic modulus determinations is presented in Table 7. Elastic modulus determined using a room-temperature test rig was $E=122\pm2 \text{ GPa}$ with a total of 39 as-machined flexure test specimens. Using a high-temperature test rig by impulse excitation, elastic modulus was found as $E=118\pm2 \text{ GPa}$, $115\pm2 \text{ GPa}$, and $122\pm2 \text{ GPa}$, respectively, at room temperature, $93 \degree\text{C}$ and $274 \degree\text{C}$. Figure 22 shows a summary of elastic modulus determined by these two different test rigs. The variation of elastic modulus with temperature was insignificant.

Effect of material direction (axis) on elastic modulus is shown in Figure 23 (also in Table 7), where compression test specimens, with ‘fortified’ layer removed and strain gages attached, were subjected to pure compression (by Test Method SACMA SRM-1), four-point flexure tension and four-point flexure compression. No appreciable effect of material axis on elastic modulus was observed, indicative of material’s homogeneity and/or isotropy. The compression specimen of ‘Direction 1’ was additionally subjected to impulse excitation. The value was found as $E = 116 \text{ GPa}$, consistent with the values determined by strain gauging. An overall comparison of elastic modulus at room temperature determined using the three different techniques (impulse, resonance and strain gauging) is shown in Figure 24, from which a conclusion -a homogeneous and isotropic nature of the material- would be drawn.

IV. SIMPLIFIED LIFE PREDICTION

In this section, a simplified life prediction is made based on the slow crack growth data determined in this work. Time to failure (or life) of brittle ceramic, glass, or glass-ceramic components under a constant stress is expressed [6]

\[ t_f = B \sigma_i^{-n} \sigma^{-n} \]  \hspace{1cm} (9)

where $t_f$ is time to failure, $\sigma$ is the inert strength, and $\sigma$ is the applied stress. The parameter $B$ and $n$ are already defined in Equations (1) and (2). The two-parameter Weibull formula for the inert strength can be rewritten from Equation (4)

\[ \ln \ln \frac{1}{1-F} = m \ln \sigma_i - m \ln \sigma_{io} \]  \hspace{1cm} (10)

where $\sigma_{io}$ is the characteristic inert strength. Solving for $\sigma_i$ from Equation (10) and substituting it into Equation (9) yield

\[ t_f = B \left\{ \exp \left[ \frac{1}{m} \left( \ln \ln \frac{1}{1-F} + m \ln \sigma_{io} \right) \right] \right\}^{-n} \sigma^{-n} \]  \hspace{1cm} (11)

From Equations (2) and (3), $B$ can be solved as follows:

\[ B = \frac{D^{n+1}}{(n+1)\sigma_i^{n-2}} \]  \hspace{1cm} (12)
From the slow crack growth data in Table 2, $n=21.45$, $D=187.1$ (both from (6)) and $\sigma_i=303$ MPa (mean inert strength, from Table 2), giving $B=24.3897$. Substitute $B (=24.3897)$, $m=50$ (inert Weibull modulus from Table 2) and $m \ln \bar{\sigma}_i = 285.4$ (inert Weibull intercept from Table 2) into Equation (11):

$$t_f = 24.3897 \left\{ \exp \left[ 0.02 \ln \ln \frac{1}{1-F} + 5.7082 \right] \right\}^{19.45} \sigma^{-21.45} \tag{13}$$

where units are second in $t_f$ and MPa in $\sigma$. The use of Equation (13) allows one to estimate a component life (with the component having the same geometry as the test coupons) for a given applied stress and failure probability. An example of a life prediction diagram based on Equation (13) is shown in Figure 25, where lifetime (time to failure) is plotted as a function of applied stress for five different levels of failure probabilities of $F = 0.5, 0.1, 1 \times 10^{-2}, 1 \times 10^{-6}$ and $1 \times 10^{-8}$. For example, for an applied stress of 100 MPa with a failure probability of $1 \times 10^{-6}$, a component life would be about 23,000 s, which is about 6.5 h. Of course, different level of failure probability yields different lifetime.

The above approach to life prediction is based on a simple loading condition in which a constant stress is applied. Since static loading (constant stress) gives the shortest component life as compared to the case of cyclic loading or any time-varying loading as long as a peak value of time-varying load is the same as the static load, the above approach can be considered as a conservative estimate (Cyclic fatigue, a dominant crack propagation in most metals or polymers, is rarely operative in many ceramics). Although simplified, this approach has been used in life prediction for optical glass fibers (typically yielding very high Weibull modulus ranging from $m = 50$ to 100), glasses and other advanced ceramics both at room and elevated temperatures. Since the slow crack growth data in this work were obtained in the worst environment (i.e., distilled water) with 100% relative humidity, they also can be utilized as conservative data since ambient air contains much less humidity than distilled water. In general, slow crack growth parameter $n$ remains unchanged but $D$ (through increase in strength) increases with decreasing humidity, thus increasing life, as reflected in Equations (11) and (12) ($B$ increases with increasing $D$, and vice versa). Decreasing temperature exhibits the similar effect (due to the relation of $v \sim \alpha [K_i]^n e^{-Q/RT}$, as reasoned in Section III-2).

If a component is complicated in its shape giving rise to complex stress distributions, which is typical of most structural components, an appropriate life prediction tool such as the CARES/Life design code (developed by NASA Glenn Research Center, Cleveland, OH) in conjunction with finite element modeling should be used to predict accurate reliability/life-prediction of the components concerned.

V. CONCLUSIONS AND SUGGESTIONS

1. Six different testing for Pyroceram™, including slow crack growth flexure testing, tensile strength, compression, shear, fracture toughness, and elastic modulus testing, was conducted in various test conditions. Valid testing was not achieved in tension, compression and shear testing due to inappropriate test specimen configurations (in compression and shear) and primarily due to the existence of ‘fortified’ layer (in tension).

2. In slow crack growth testing, considerably high Weibull modulus ranging from $m=34$ to 52 was observed for the ‘fortified’ test specimens; while relatively low Weibull modulus (but comparable to most ceramics) of $m=9-19$ were obtained from the ‘unfortified’ as-machined test specimens. Fractography and strength data on the ‘unfortified’ as-machined test specimens verified that the high Weibull modulus for the ‘fortified’ test specimens was attributed to the chemical etching process that had generated new surface-flaw populations with extremely tightly distributed sizes of flaws.

3. The slow crack growth parameters $n$ and $D$, required in component design, were found to be $n = 21.45$ and $D = 187.1$ from a total of 172 ‘fortified’ test specimens. Six different stress rates of 71, 7.1, 0.71, 0.071, 0.0071, and 0.00071 MPa/s were used.
4. Fracture toughness was determined as $K_{IC}=2.3-2.4 \text{ MPa}^\sqrt{\text{m}}$ (an average of 2.35 MPa$^\sqrt{\text{m}}$) both by SEPB and SEVNB methods.

5. Elastic modulus, ranging from $E=109$ to 122 GPa, was almost independent of test temperature, material direction, and test method (strain gauging or excitation technique) within the experimental scope, indicating that the material was homogeneous and isotropic.

6. The existence of the 'fortified' layer plays a crucial role in controlling and determining strength, strength distribution and slow crack growth behavior. It also acts as a protective layer. Therefore, it is very important to keep this layer intact from any deteriorative scratching, rubbing with hard surface or mishandling. Furthermore, consistent etching from batch to batch or from lot to lot is a prerequisite for the reproducibility of strength and slow crack growth behavior.

7. Use of an appropriate life prediction tool such as the NASA Glenn CARES/Life code in conjunction with finite element modeling is recommended for accurate reliability/life-prediction of the components related.
REFERENCES

Table 1.—Test Matrix for Pyroceram™ Testing

<table>
<thead>
<tr>
<th>Type of Tests</th>
<th>Parameters Determined</th>
<th>Specimen Dimensions, mm (inch)</th>
<th>Test Method</th>
<th>Test Conditions</th>
<th>No. of Test Specimens</th>
<th>Remarks/Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Tension</td>
<td>σ, E</td>
<td>89x3.2x2.5 (3.5x0.125x0.1)</td>
<td>ASTM C1273</td>
<td>RT, -65°F, 200°F, 525°F</td>
<td>30</td>
<td>Strain-gauging; fractography</td>
</tr>
<tr>
<td></td>
<td>σ, E</td>
<td></td>
<td></td>
<td>R/H100% (300N/s) (300N/s) (300N/s) (300N/s)</td>
<td>15</td>
<td>Strain-gauging; fractography</td>
</tr>
<tr>
<td></td>
<td>σ, E</td>
<td></td>
<td></td>
<td>Strain gauging; fractography</td>
<td>15</td>
<td>Strain-gauging; fractography</td>
</tr>
<tr>
<td></td>
<td>σ, E</td>
<td></td>
<td></td>
<td>Strain gauging; fractography</td>
<td>15</td>
<td>Strain-gauging; fractography</td>
</tr>
<tr>
<td>Pure Compression</td>
<td>σ</td>
<td>81x12.5x2.5 (3.2x0.5x0.1)</td>
<td>SACMA SRM-1</td>
<td>RT, R/H100, R/H100, R/H100</td>
<td>30</td>
<td>Direction 1; No strain gauging; fractography</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td></td>
<td></td>
<td>(1.27mm/min) (1.27mm/min) (1.27mm/min) (1.27mm/min)</td>
<td>10</td>
<td>Direction 2; No strain gauging; fractography</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td></td>
<td></td>
<td>Direction 3; No strain gauging; fractography</td>
<td>20</td>
<td>Direction 1; strain gauging</td>
</tr>
<tr>
<td>Shear</td>
<td>τ, G</td>
<td>76x20.3x2.5 (3.0x0.8x0.1)</td>
<td>ASTM D5379</td>
<td>RT, R/H100</td>
<td>20</td>
<td>Strain gauging; fractography</td>
</tr>
<tr>
<td>Slow Crack Growth (SCG)</td>
<td>σ</td>
<td>46x5.1x2.5 (1.8x0.2x0.1)</td>
<td>ASTM C1368</td>
<td>RT, R/H100</td>
<td>(50 MPa/s)</td>
<td>Fractography; (strain gauging)</td>
</tr>
<tr>
<td>(“Dynamic Fatigue”)</td>
<td>σ</td>
<td></td>
<td></td>
<td>(5 MPa/s)</td>
<td>30</td>
<td>Fractography; (strain gauging)</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td></td>
<td></td>
<td>(0.5 MPa/s)</td>
<td>30</td>
<td>Fractography; (strain gauging)</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td></td>
<td></td>
<td>(0.05 MPa/s)</td>
<td>30</td>
<td>Fractography; (strain gauging)</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td></td>
<td></td>
<td>(0.005 MPa/s)</td>
<td>30</td>
<td>Fractography; (strain gauging)</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td>KIC (SEPB)</td>
<td>46x3.6x2.5 (1.8x0.14x0.1)</td>
<td>ASTM C1421</td>
<td>RT, Inert</td>
<td>10-15</td>
<td>Fractography</td>
</tr>
<tr>
<td></td>
<td>KIC (SEVNB)</td>
<td></td>
<td></td>
<td>(0.5 mm/min)</td>
<td>10-15</td>
<td>Fractography</td>
</tr>
</tbody>
</table>

Notes:
1. The exact test rate(s) for a given type of testing will be determined after slow crack growth (“dynamic fatigue”) testing, based on the degree of slow crack growth of the material.
2. The type of inert environment to be used will also be determined based on the results of slow crack growth testing.
3. Elastic modulus (“E”) and/or shear modulus (“G”) of the material will also be determined by the impulse excitation method (ASTM C1259 [14]) using the compression and slow-crack-growth test specimens (in rectangular flexure-beam configuration). In this case, the use of strain gages in the slow-crack-growth test specimens will be minimized.
4. Fracture toughness will be determined by the two methods of SEPB and SEVNB. The use of two test rates, originally planned in SEPB testing, is to be changed to the use of only one test rate, since no test-rate effect is expected for ceramics in inert environment.
5. Concern about the specimen machining employed – discussion needed.
6. Concern about some surface treatment of test specimens (after machining), observable from their fracture surfaces.
8. Test matrix may be changeable and/or adjustable depending on the individual test results as testing proceeds.
# Table 2: Summary of Constant Stress-Rate ("Dynamic Fatigue") Testing Results

<table>
<thead>
<tr>
<th>Specimen Configurations</th>
<th>Test Method</th>
<th>Test Conditions</th>
<th>Mean Strength (MPa)</th>
<th>Weibull Parameters</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Test Method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specimen Configurations</td>
<td>Test Conditions</td>
<td>No. of Test Specimens</td>
<td>Weibull Modulus, m</td>
</tr>
<tr>
<td>Nominal 5.1x2.5x46 (mm³); Fortified</td>
<td>ASTM C1368 [2]</td>
<td>RT</td>
<td>100% RH</td>
<td>7.1x10⁴</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RT</td>
<td>100% RH</td>
<td>7.1x10⁴</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RT</td>
<td>100% RH</td>
<td>7.1x10⁶</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RT</td>
<td>100% RH</td>
<td>7.1x10³</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RT</td>
<td>Oil (inert)</td>
<td>7.1x10⁴</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RT</td>
<td>Oil (inert)</td>
<td>7.1x10³</td>
<td>30</td>
</tr>
</tbody>
</table>

| Nominal 5.1x2.5x45 (mm³); Not-Fortified | ASTM C1368 [2] | RT | 100% RH | 7.1x10⁴ | 20 | 216.6(23.6) | 10.66 | 57.81 | 218.9 |
|                                        |             | RT | 100% RH | 7.1x10⁴ | 5 | 180.1(6.3) | - | - | - |
|                                        |             | RT | 100% RH | 0.07 | 20 | 153.3(9.3) | 18.80 | 95.13 | 154.6 |
|                                        |             | RT | Oil (inert) | 7.1x10⁴ | 20 | 235.7(30.9) | 8.57 | 47.32 | 239.6 |

**Notes:**
1. Four-point flexure with 20 mm-inner and 40 mm-outer spans used.
2. Test mode under load control.
3. Test environments: 100% relative humidity (distilled water) in fatigue testing, and silicon oil in inert testing.
4. Average fortified layer estimated to be 0.17 mm.
5. Specimen-edge polishing for the unfortified, as-machined specimens were made prior to testing, except for the testing with five specimens.
6. The parentheses in the mean-strength column indicate ±1.0 standard deviations.
7. Two-parameter Weibull statistics was used: Ln ln [1/(1-F)] = m ln σf – m ln σo, where F is failure probability, σf fracture stress, σo characteristic strength, and m ln σo is the intercept in the Weibull plot. The Weibull mean strength corresponds to the strength when F = 0.5 or 50%.
<table>
<thead>
<tr>
<th>Specimen Configurations</th>
<th>Test Method</th>
<th>Test Conditions</th>
<th>Mean Strength (MPa)</th>
<th>Weibull Parameters</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal 3.2x2.5x89 (in mm); Fortified</td>
<td>ASTM C1273 [7]</td>
<td>RT 93 (200F) 100% RH</td>
<td>70 16</td>
<td>172.3(4.6)* 45.23 233.78 174.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100% RH 274(525F) Air</td>
<td>82 15</td>
<td>133.1(20.4) 7.50 37.17 135.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>212.6(37.5) 5.82 31.66 216.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
1. Specimens in shoulder-loading configuration.
2. Test mode under load control.
3. Test environments: 100% relative humidity (distilled water) at RT (25 °C) and 93 °C (200F), and ambient air at 274 °C (525F).
4. Average fortified layer estimated to be 0.21 mm.
5. The parentheses in the mean-strength column indicate ±1.0 standard deviations.
6. Two-parameter Weibull statistics was used: Lnln [1/(1-F)] = m ln σ_f – m ln σ_o, where F is failure probability, σ_f fracture stress, σ_o characteristic strength, and m ln σ_o is the intercept in the Weibull plot. The Weibull mean strength corresponds to the strength when F = 0.5 or 50%.
### Table 4.—Summary of Compression Testing Results

<table>
<thead>
<tr>
<th>Specimen Configurations</th>
<th>Test Method</th>
<th>Test Conditions</th>
<th>Mean Strength (MPa)</th>
<th>Weibull Parameters</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Temp (°C)</td>
<td>Environmen t</td>
<td>Test Rate (mm/min)</td>
<td>No. of Test Specimens</td>
</tr>
<tr>
<td>Nominal 12.5x2.5x81 (in mm); Fortified</td>
<td>SACMA SRM-1 [8]</td>
<td>RT</td>
<td>100% RH</td>
<td>1.27</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RT</td>
<td>100% RH</td>
<td>1.27</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RT</td>
<td>100% RH</td>
<td>1.27</td>
<td>3</td>
</tr>
</tbody>
</table>

**Notes:**

1. Test mode under displacement control.
2. Test environments: 100% relative humidity (distilled water).
3. Average fortified layer estimated to be 0.22 mm.
4. All the specimens tested failed from the top portion of specimens where compression load was applied via an aluminum shim. Crushing from the top portion of test specimens was a typical exclusive failure mode. Invalid testing, hence unable to determine the valid compressive strength of the material.

### Table 5.—Summary of Shear Testing Results

<table>
<thead>
<tr>
<th>Specimen Configurations</th>
<th>Test Method</th>
<th>Test Conditions</th>
<th>Mean Strength (MPa)</th>
<th>Weibull Parameters</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Temp (°C)</td>
<td>Environmen t</td>
<td>Test Rate (mm/min)</td>
<td>No. of Test Specimen s</td>
</tr>
<tr>
<td>Nominal 20.3x2.5x76 (in mm) with Double Notches; Fortified</td>
<td>ASTM D 5379 [10]</td>
<td>RT</td>
<td>100% RH</td>
<td>0.25</td>
<td>6</td>
</tr>
</tbody>
</table>

**Notes:**

1. Test mode under displacement control.
2. Test environments: 100% relative humidity (distilled water).
3. Average fortified layer estimated to be 0.21 mm.
4. All the specimens tested failed in a mode of the principal-stress-failure criterion in which a crack propagated from the maximum-tensile stress direction at the root of each notch. Hence, no valid shear testing was obtained, and unable to determine the valid shear strength of the material.
Table 6.—Summary of Fracture Toughness Testing Results

<table>
<thead>
<tr>
<th>Specimen Configurations</th>
<th>Test Method</th>
<th>Test Conditions</th>
<th>Mean Fracture Toughness, $K_{IC}$ (MPa√m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6x2.5x46 (in mm); Fortified</td>
<td>SEVNB</td>
<td>RT Oil (inert) 0.5 9</td>
<td>2.4 (0.08)</td>
<td></td>
</tr>
<tr>
<td>5.1x2.5x46 (in mm); Not-Fortified</td>
<td>SEPB (ASTM C 1421 [11])</td>
<td>RT Oil (inert) 0.5 10</td>
<td>2.3 (0.05)</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Four-point flexure with 20 mm-inner and 40 mm-outer spans used for both SEVNB (single edge v-notched beam) and SEPB (single edge precracked beam) methods.
2. Test mode under displacement control.
3. Test environment: silicon oil (inert).
4. The fortified test specimens were used for the SEPB method, while the not-fortified, as-machined test specimens used for the SEVNB method.
Table 7.—Summary of Elastic Modulus Determinations

<table>
<thead>
<tr>
<th>Specimen Configurations</th>
<th>Method</th>
<th>Test Conditions</th>
<th>E (GPa)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1x2.5x46 (in mm); As-machined, not-fortified</td>
<td>Impulse excitation (by RT rig); ASTM C 1259 [14]</td>
<td>RT</td>
<td>Air</td>
<td>122.3 (2.1)</td>
</tr>
<tr>
<td></td>
<td>Impulse excitation (by high-temp rig); ASTM C 1259 [14]</td>
<td>RT</td>
<td>Air</td>
<td>118.1 (2.4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>93 (200F)</td>
<td>Air</td>
<td>114.6 (2.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>274 (525F)</td>
<td>Air</td>
<td>121.7 (2.4)</td>
</tr>
<tr>
<td>12.5x2.5x81 (in mm); Compression Specimens; Fortified-layer removed</td>
<td>Direction 1</td>
<td>Pure compression/strain gauging</td>
<td>RT</td>
<td>Air</td>
</tr>
<tr>
<td></td>
<td>Flexure compression/strain gauging</td>
<td>RT</td>
<td>Air</td>
<td>116.9</td>
</tr>
<tr>
<td></td>
<td>Flexure tension/strain gauging</td>
<td>RT</td>
<td>Air</td>
<td>114.1</td>
</tr>
<tr>
<td></td>
<td>Direction 2</td>
<td>Pure compression/strain gauging</td>
<td>RT</td>
<td>Air</td>
</tr>
<tr>
<td></td>
<td>Flexure compression/strain gauging</td>
<td>RT</td>
<td>Air</td>
<td>109.0</td>
</tr>
<tr>
<td></td>
<td>Flexure tension/strain gauging</td>
<td>RT</td>
<td>Air</td>
<td>109.1</td>
</tr>
<tr>
<td></td>
<td>Direction 3</td>
<td>Pure compression/strain gauging</td>
<td>RT</td>
<td>Air</td>
</tr>
<tr>
<td></td>
<td>Flexure compression/strain gauging</td>
<td>RT</td>
<td>Air</td>
<td>115.4</td>
</tr>
<tr>
<td></td>
<td>Flexure tension/strain gauging</td>
<td>RT</td>
<td>Air</td>
<td>114.3</td>
</tr>
<tr>
<td></td>
<td>Direction 1</td>
<td>Impulse/ASTM C 1259</td>
<td>RT</td>
<td>Air</td>
</tr>
<tr>
<td></td>
<td>Impulse/ASTM C 1259 (For shear modulus)</td>
<td>RT</td>
<td>Air</td>
<td>G = 45.0</td>
</tr>
</tbody>
</table>

Notes:
1. The fortified layers of the compression specimens were removed by polishing the specimens. Strain gages were attached to the as-removed surface of the specimens to determine elastic modulus as a function of direction. Elastic modulus for each direction was determined in three different loading configurations such as pure compression, four-point (20/40 mm spans) flexural tension, and four-point (20/40 mm spans) flexural compression.
Figure 1.—Four-point flexure test fixture with a test specimen placed, used in flexure strength and slow crack growth (“dynamic fatigue”) testing for Pyroceram at ambient temperature.

Figure 2.—Shoulder-loaded tensile test fixture with a test specimen placed, used in tension testing for Pyroceram: (a) overall view; (b) closed-up view.
Figure 3.—Compression test fixture with a test specimen placed, used in compression testing for Pyroceram at ambient temperature.

Figure 4.—Shear test fixture with a test specimen placed, used in shear testing for Pyroceram at ambient temperature.
Figure 5.—A typical example of a precracked SEPB fracture toughness specimen. A precrack is shown as a (red) line revealed through dye penetrant.

Figure 6.—A typical example of a sharp notch produced in a SEVNB fracture toughness specimen: (a) overall view; (b) enlarged view of notch
Figure 7.—Results of constant stress-rate (“dynamic fatigue”) testing for ‘fortified’ Pyroceram test specimens in room-temperature distilled water in flexure. The best-fit regression line was included with a slow crack parameter of \( n = 21.4 \). Inert strength determined in oil was included for comparison.

Figure 8.—Summary of Weibull strength distributions in constant stress-rate (“dynamic fatigue”) testing in flexure in room-temperature distilled water for ‘fortified’ Pyroceram test specimens. Inert strength determined in oil was included for comparison.
Figure 9.—Typical fracture surface of a ‘fortified’ Pyroceram specimen tested in slow crack growth testing in flexure in room-temperature distilled water. ‘Fortified’ layer is seen outside of the specimen as a red band revealed through dye penetrant.

Figure 10.—Summary of Weibull strength distributions for ‘unfortified’, as-machined Pyroceram test specimens in flexure at ambient temperature.
Figure 11.—Results of constant stress-rate (“dynamic fatigue”) testing in flexure for as-machined Pyroceram test specimens in room-temperature distilled water. The data (“triangle” marks with $n=21.4$) on the “fortified” Pyroceram test specimens are included for comparison.

Figure 12.—A typical fracture surface of an as-machined Pyroceram flexure specimen tested in room temperature distilled water.
Figure 13.—Summary of Weibull strength distributions for ‘fortified’ Pyroceram test specimens in tension at three different test temperature-environment conditions of 25 °C (RT) in distilled water, 93 °C in distilled water, and 274 °C in ambient air.

Figure 14.—Tensile strength as a function of temperature for ‘fortified’ Pyroceram test specimens. Test temperature-environments were 25 and 93 °C in distilled water, and 274 °C in ambient air.
Figure 15.—Typical Pyroceram tensile specimens showing two different failure locations: gage-section failure (top) and transition-region failure (bottom).

Figure 16.—A typical fracture surface of a ‘fortified’ test specimen in tension, showing fracture origin and ‘fortified’ layer. The ‘fortified’ layer is seen outside of the specimen as a red band revealed through dye penetrant.
Figure 17.—A typical fracture pattern of a Pyroceram compression specimen tested in pure compression testing at ambient temperature.

Figure 18.—Compressive strength as a function of material direction (axis) for ‘fortified’ Pyroceram test specimens, determined in room-temperature distilled water.
Figure 19.—A typical fracture pattern of a Pyroceram shear specimen tested in shear testing at ambient temperature.

Figure 20.—Results of shear strength testing for ‘fortified’ Pyroceram shear test specimens, tested in room-temperature distilled water.
Figure 21.—A summary of fracture toughness determined for Pyroceram by SEPB and SEVNB methods.

Figure 22.—Elastic modulus (E) as a function of temperature (T), determined for as-machined Pyroceram flexure test specimens. Two different test rigs (room-temperature(RT) rig and high-temperature rig) by impulse excitation method [14] were used.
Figure 23.—Results of elastic modulus by strain gauging as a function of material axis for Pyroceram, determined at room temperature by three different loading configurations in compression, flexure tension, and flexure compression.
Figure 24.—Comparison of elastic modulus of Pyroceram, determined at room temperature by various methods of strain gauging and impulse excitation. “s.g.” represents strain gauging.
Figure 25. Simplified life prediction diagram for ‘fortified’ Pyroceram flexure test specimens, based on the slow crack growth data determined in flexure in room-temperature distilled water. The solid horizontal line, as an example, represents a case for an applied stress of 100 MPa. F: probability of failure.
APPENDIX

1. Individual Weibull plots and raw strength data in slow crack growth testing in flexure: ‘Fortified’ Pyroceram test specimens
2. Individual Weibull plots and raw strength data in slow crack growth testing in flexure: ‘Unfortified’ Pyroceram test specimens
3. Individual Weibull plots and raw strength data in tension: ‘Fortified’ Pyroceram test specimens
4. Raw strength data in compression testing
5. Raw strength data in shear testing
6. Raw fracture toughness data
7. Raw elastic modulus data
1. Individual Weibull Plots and Raw Strength Data in Slow Crack Growth Testing in flexure: ‘Fortified’ Test Specimens

**Material:** Pyroceram

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>288.55</td>
<td>0.02</td>
<td>5.665</td>
<td>-4.086</td>
</tr>
<tr>
<td>2</td>
<td>290.31</td>
<td>0.05</td>
<td>5.671</td>
<td>-2.970</td>
</tr>
<tr>
<td>3</td>
<td>291.01</td>
<td>0.08</td>
<td>5.673</td>
<td>-2.442</td>
</tr>
<tr>
<td>4</td>
<td>293.81</td>
<td>0.12</td>
<td>5.683</td>
<td>-2.087</td>
</tr>
<tr>
<td>5</td>
<td>294.57</td>
<td>0.15</td>
<td>5.686</td>
<td>-1.817</td>
</tr>
<tr>
<td>6</td>
<td>295.69</td>
<td>0.18</td>
<td>5.689</td>
<td>-1.597</td>
</tr>
<tr>
<td>7</td>
<td>295.69</td>
<td>0.22</td>
<td>5.689</td>
<td>-1.410</td>
</tr>
<tr>
<td>8</td>
<td>295.76</td>
<td>0.25</td>
<td>5.690</td>
<td>-1.246</td>
</tr>
<tr>
<td>9</td>
<td>299.82</td>
<td>0.28</td>
<td>5.703</td>
<td>-1.099</td>
</tr>
<tr>
<td>10</td>
<td>299.94</td>
<td>0.32</td>
<td>5.704</td>
<td>-0.966</td>
</tr>
<tr>
<td>11</td>
<td>301.26</td>
<td>0.35</td>
<td>5.708</td>
<td>-0.842</td>
</tr>
<tr>
<td>12</td>
<td>301.29</td>
<td>0.38</td>
<td>5.708</td>
<td>-0.727</td>
</tr>
<tr>
<td>13</td>
<td>301.57</td>
<td>0.42</td>
<td>5.709</td>
<td>-0.618</td>
</tr>
<tr>
<td>14</td>
<td>302.39</td>
<td>0.45</td>
<td>5.712</td>
<td>-0.514</td>
</tr>
<tr>
<td>15</td>
<td>303.31</td>
<td>0.48</td>
<td>5.715</td>
<td>-0.415</td>
</tr>
<tr>
<td>16</td>
<td>305.16</td>
<td>0.52</td>
<td>5.721</td>
<td>-0.319</td>
</tr>
<tr>
<td>17</td>
<td>306.53</td>
<td>0.55</td>
<td>5.725</td>
<td>-0.225</td>
</tr>
<tr>
<td>18</td>
<td>306.62</td>
<td>0.58</td>
<td>5.726</td>
<td>-0.133</td>
</tr>
<tr>
<td>19</td>
<td>306.91</td>
<td>0.62</td>
<td>5.727</td>
<td>-0.042</td>
</tr>
<tr>
<td>20</td>
<td>307.53</td>
<td>0.65</td>
<td>5.729</td>
<td>0.049</td>
</tr>
<tr>
<td>21</td>
<td>307.64</td>
<td>0.68</td>
<td>5.728</td>
<td>0.140</td>
</tr>
<tr>
<td>22</td>
<td>307.79</td>
<td>0.72</td>
<td>5.729</td>
<td>0.232</td>
</tr>
<tr>
<td>23</td>
<td>308.22</td>
<td>0.75</td>
<td>5.731</td>
<td>0.327</td>
</tr>
<tr>
<td>24</td>
<td>309.16</td>
<td>0.78</td>
<td>5.734</td>
<td>0.425</td>
</tr>
<tr>
<td>25</td>
<td>310.08</td>
<td>0.82</td>
<td>5.737</td>
<td>0.529</td>
</tr>
<tr>
<td>26</td>
<td>311.19</td>
<td>0.85</td>
<td>5.740</td>
<td>0.640</td>
</tr>
<tr>
<td>27</td>
<td>311.39</td>
<td>0.88</td>
<td>5.741</td>
<td>0.765</td>
</tr>
<tr>
<td>28</td>
<td>313.30</td>
<td>0.92</td>
<td>5.747</td>
<td>0.910</td>
</tr>
<tr>
<td>29</td>
<td>313.46</td>
<td>0.95</td>
<td>5.748</td>
<td>1.097</td>
</tr>
<tr>
<td>30</td>
<td>315.81</td>
<td>0.98</td>
<td>5.755</td>
<td>1.410</td>
</tr>
</tbody>
</table>

**Weibull Analysis**

Pyroceram Flexure in Silicon Oil
Without .17mm Fortification Layer Dimension
Stress Rate (MPa/s): 50.0

\[ y = 49.85x - 285.41 \]
\[ R^2 = 0.9558 \]
Material: Pyroceram

n = 30 Specimens
Average Failure Stress: 228.12 (MPa)
Std. Dev. +/-: 5.29 (MPa)

Environment: Distilled Water
Temperature: rt
Stress Rate (MPa/s): 50.0

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>216.79</td>
<td>0.02</td>
<td>5.379</td>
<td>-4.086</td>
</tr>
<tr>
<td>2</td>
<td>221.04</td>
<td>0.05</td>
<td>5.398</td>
<td>-2.970</td>
</tr>
<tr>
<td>3</td>
<td>221.29</td>
<td>0.08</td>
<td>5.399</td>
<td>-2.442</td>
</tr>
<tr>
<td>4</td>
<td>221.67</td>
<td>0.12</td>
<td>5.401</td>
<td>-2.087</td>
</tr>
<tr>
<td>5</td>
<td>222.25</td>
<td>0.15</td>
<td>5.404</td>
<td>-1.817</td>
</tr>
<tr>
<td>6</td>
<td>222.66</td>
<td>0.18</td>
<td>5.406</td>
<td>-1.597</td>
</tr>
<tr>
<td>7</td>
<td>223.04</td>
<td>0.22</td>
<td>5.407</td>
<td>-1.410</td>
</tr>
<tr>
<td>8</td>
<td>223.31</td>
<td>0.25</td>
<td>5.409</td>
<td>-1.246</td>
</tr>
<tr>
<td>9</td>
<td>224.16</td>
<td>0.28</td>
<td>5.412</td>
<td>-1.099</td>
</tr>
<tr>
<td>10</td>
<td>224.86</td>
<td>0.32</td>
<td>5.415</td>
<td>-0.966</td>
</tr>
<tr>
<td>11</td>
<td>225.08</td>
<td>0.35</td>
<td>5.416</td>
<td>-0.842</td>
</tr>
<tr>
<td>12</td>
<td>226.64</td>
<td>0.38</td>
<td>5.423</td>
<td>-0.727</td>
</tr>
<tr>
<td>13</td>
<td>226.88</td>
<td>0.42</td>
<td>5.424</td>
<td>-0.618</td>
</tr>
<tr>
<td>14</td>
<td>227.79</td>
<td>0.45</td>
<td>5.428</td>
<td>-0.514</td>
</tr>
<tr>
<td>15</td>
<td>228.49</td>
<td>0.48</td>
<td>5.432</td>
<td>-0.415</td>
</tr>
<tr>
<td>16</td>
<td>229.08</td>
<td>0.52</td>
<td>5.434</td>
<td>-0.319</td>
</tr>
<tr>
<td>17</td>
<td>229.69</td>
<td>0.55</td>
<td>5.437</td>
<td>-0.225</td>
</tr>
<tr>
<td>18</td>
<td>229.72</td>
<td>0.58</td>
<td>5.437</td>
<td>-0.133</td>
</tr>
<tr>
<td>19</td>
<td>230.11</td>
<td>0.62</td>
<td>5.439</td>
<td>-0.042</td>
</tr>
<tr>
<td>20</td>
<td>230.57</td>
<td>0.65</td>
<td>5.441</td>
<td>0.049</td>
</tr>
<tr>
<td>21</td>
<td>230.85</td>
<td>0.68</td>
<td>5.441</td>
<td>0.140</td>
</tr>
<tr>
<td>22</td>
<td>231.08</td>
<td>0.72</td>
<td>5.443</td>
<td>0.232</td>
</tr>
<tr>
<td>23</td>
<td>232.87</td>
<td>0.75</td>
<td>5.450</td>
<td>0.327</td>
</tr>
<tr>
<td>24</td>
<td>233.05</td>
<td>0.78</td>
<td>5.451</td>
<td>0.425</td>
</tr>
<tr>
<td>25</td>
<td>233.22</td>
<td>0.82</td>
<td>5.452</td>
<td>0.529</td>
</tr>
<tr>
<td>26</td>
<td>233.37</td>
<td>0.85</td>
<td>5.453</td>
<td>0.640</td>
</tr>
<tr>
<td>27</td>
<td>234.87</td>
<td>0.88</td>
<td>5.459</td>
<td>0.765</td>
</tr>
<tr>
<td>28</td>
<td>235.13</td>
<td>0.92</td>
<td>5.460</td>
<td>0.910</td>
</tr>
<tr>
<td>29</td>
<td>237.08</td>
<td>0.95</td>
<td>5.468</td>
<td>1.097</td>
</tr>
<tr>
<td>30</td>
<td>237.37</td>
<td>0.98</td>
<td>5.470</td>
<td>1.410</td>
</tr>
</tbody>
</table>

Weibull Plot

Weibull Analysis
Pyroceram Flexure in Distilled Water Without .17mm Fortification Layer Dimension
Stress Rate (MPa/s): 50.0

y = 52.421x - 285.19
R² = 0.9432
Weibull Plot

Weibull Analysis

Pyroceram Flexure in Distilled Water

Without .17mm Fortification Layer Dimension

Stress Rate (MPa/s): 5.0

Material: Pyroceram

n: 30 Specimens

Average Failure Stress: 202.67 (MPa)

Std. Dev. +/-: 5.04 (MPa)

Temperature: rt

Environment: Distilled Water

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>190.81</td>
<td>0.02</td>
<td>5.251</td>
<td>-4.086</td>
</tr>
<tr>
<td>2</td>
<td>193.25</td>
<td>0.05</td>
<td>5.264</td>
<td>-2.970</td>
</tr>
<tr>
<td>3</td>
<td>193.67</td>
<td>0.08</td>
<td>5.266</td>
<td>-2.442</td>
</tr>
<tr>
<td>4</td>
<td>197.67</td>
<td>0.12</td>
<td>5.287</td>
<td>-2.087</td>
</tr>
<tr>
<td>5</td>
<td>197.71</td>
<td>0.15</td>
<td>5.287</td>
<td>-1.817</td>
</tr>
<tr>
<td>6</td>
<td>198.20</td>
<td>0.18</td>
<td>5.287</td>
<td>-1.597</td>
</tr>
<tr>
<td>7</td>
<td>199.20</td>
<td>0.22</td>
<td>5.299</td>
<td>-1.410</td>
</tr>
<tr>
<td>8</td>
<td>199.23</td>
<td>0.25</td>
<td>5.294</td>
<td>-1.246</td>
</tr>
<tr>
<td>9</td>
<td>200.66</td>
<td>0.28</td>
<td>5.302</td>
<td>-1.099</td>
</tr>
<tr>
<td>10</td>
<td>200.85</td>
<td>0.32</td>
<td>5.303</td>
<td>-0.966</td>
</tr>
<tr>
<td>11</td>
<td>201.21</td>
<td>0.35</td>
<td>5.304</td>
<td>-0.842</td>
</tr>
<tr>
<td>12</td>
<td>201.33</td>
<td>0.38</td>
<td>5.305</td>
<td>-0.727</td>
</tr>
<tr>
<td>13</td>
<td>201.37</td>
<td>0.42</td>
<td>5.305</td>
<td>-0.618</td>
</tr>
<tr>
<td>14</td>
<td>202.23</td>
<td>0.45</td>
<td>5.314</td>
<td>-0.514</td>
</tr>
<tr>
<td>15</td>
<td>202.37</td>
<td>0.48</td>
<td>5.315</td>
<td>-0.415</td>
</tr>
<tr>
<td>16</td>
<td>203.42</td>
<td>0.52</td>
<td>5.315</td>
<td>-0.319</td>
</tr>
<tr>
<td>17</td>
<td>203.90</td>
<td>0.55</td>
<td>5.318</td>
<td>-0.229</td>
</tr>
<tr>
<td>18</td>
<td>204.21</td>
<td>0.58</td>
<td>5.319</td>
<td>-0.133</td>
</tr>
<tr>
<td>19</td>
<td>204.43</td>
<td>0.62</td>
<td>5.320</td>
<td>-0.042</td>
</tr>
<tr>
<td>20</td>
<td>204.93</td>
<td>0.65</td>
<td>5.323</td>
<td>0.049</td>
</tr>
<tr>
<td>21</td>
<td>205.17</td>
<td>0.68</td>
<td>5.324</td>
<td>0.140</td>
</tr>
<tr>
<td>22</td>
<td>205.79</td>
<td>0.72</td>
<td>5.332</td>
<td>0.232</td>
</tr>
<tr>
<td>23</td>
<td>206.98</td>
<td>0.75</td>
<td>5.333</td>
<td>0.327</td>
</tr>
<tr>
<td>24</td>
<td>207.16</td>
<td>0.78</td>
<td>5.333</td>
<td>0.425</td>
</tr>
<tr>
<td>25</td>
<td>207.44</td>
<td>0.82</td>
<td>5.335</td>
<td>0.529</td>
</tr>
<tr>
<td>26</td>
<td>207.51</td>
<td>0.85</td>
<td>5.335</td>
<td>0.640</td>
</tr>
<tr>
<td>27</td>
<td>208.21</td>
<td>0.88</td>
<td>5.339</td>
<td>0.765</td>
</tr>
<tr>
<td>28</td>
<td>209.33</td>
<td>0.92</td>
<td>5.344</td>
<td>0.910</td>
</tr>
<tr>
<td>29</td>
<td>209.70</td>
<td>0.96</td>
<td>5.346</td>
<td>1.097</td>
</tr>
<tr>
<td>30</td>
<td>210.55</td>
<td>0.98</td>
<td>5.350</td>
<td>1.410</td>
</tr>
</tbody>
</table>

y = 49.598x - 264
R² = 0.9808
Material: Pyroceram
n: 30 Specimens
Average Failure Stress: 183.47 (MPa)
Std. Dev. +/-: 5.41 (MPa)
Environment: Distilled Water

Weibull Analysis
Pyroceram Flexure in Distilled Water
Without .17mm Fortification Layer Dimension
Stress Rate (MPa/s): 0.5

Weibull Plot

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>170.94</td>
<td>0.02</td>
<td>5.141</td>
<td>-4.066</td>
</tr>
<tr>
<td>2</td>
<td>172.97</td>
<td>0.05</td>
<td>5.153</td>
<td>-2.970</td>
</tr>
<tr>
<td>3</td>
<td>177.03</td>
<td>0.08</td>
<td>5.176</td>
<td>-2.442</td>
</tr>
<tr>
<td>4</td>
<td>177.34</td>
<td>0.12</td>
<td>5.178</td>
<td>-2.087</td>
</tr>
<tr>
<td>5</td>
<td>178.02</td>
<td>0.15</td>
<td>5.182</td>
<td>-1.817</td>
</tr>
<tr>
<td>6</td>
<td>179.07</td>
<td>0.18</td>
<td>5.188</td>
<td>-1.597</td>
</tr>
<tr>
<td>7</td>
<td>179.46</td>
<td>0.22</td>
<td>5.190</td>
<td>-1.410</td>
</tr>
<tr>
<td>8</td>
<td>179.79</td>
<td>0.25</td>
<td>5.192</td>
<td>-1.246</td>
</tr>
<tr>
<td>9</td>
<td>180.66</td>
<td>0.28</td>
<td>5.197</td>
<td>-1.099</td>
</tr>
<tr>
<td>10</td>
<td>180.72</td>
<td>0.32</td>
<td>5.197</td>
<td>-0.966</td>
</tr>
<tr>
<td>11</td>
<td>180.96</td>
<td>0.35</td>
<td>5.198</td>
<td>-0.842</td>
</tr>
<tr>
<td>12</td>
<td>181.62</td>
<td>0.38</td>
<td>5.202</td>
<td>-0.727</td>
</tr>
<tr>
<td>13</td>
<td>181.83</td>
<td>0.42</td>
<td>5.203</td>
<td>-0.618</td>
</tr>
<tr>
<td>14</td>
<td>182.15</td>
<td>0.45</td>
<td>5.205</td>
<td>-0.514</td>
</tr>
<tr>
<td>15</td>
<td>182.51</td>
<td>0.48</td>
<td>5.207</td>
<td>-0.415</td>
</tr>
<tr>
<td>16</td>
<td>182.81</td>
<td>0.52</td>
<td>5.208</td>
<td>-0.319</td>
</tr>
<tr>
<td>17</td>
<td>183.16</td>
<td>0.55</td>
<td>5.210</td>
<td>-0.226</td>
</tr>
<tr>
<td>18</td>
<td>185.66</td>
<td>0.58</td>
<td>5.224</td>
<td>-0.133</td>
</tr>
<tr>
<td>19</td>
<td>187.18</td>
<td>0.62</td>
<td>5.232</td>
<td>-0.042</td>
</tr>
<tr>
<td>20</td>
<td>187.30</td>
<td>0.65</td>
<td>5.233</td>
<td>0.049</td>
</tr>
<tr>
<td>21</td>
<td>187.66</td>
<td>0.68</td>
<td>5.235</td>
<td>0.140</td>
</tr>
<tr>
<td>22</td>
<td>187.99</td>
<td>0.72</td>
<td>5.236</td>
<td>0.232</td>
</tr>
<tr>
<td>23</td>
<td>188.03</td>
<td>0.75</td>
<td>5.237</td>
<td>0.327</td>
</tr>
<tr>
<td>24</td>
<td>188.51</td>
<td>0.78</td>
<td>5.239</td>
<td>0.425</td>
</tr>
<tr>
<td>25</td>
<td>188.56</td>
<td>0.82</td>
<td>5.239</td>
<td>0.529</td>
</tr>
<tr>
<td>26</td>
<td>188.83</td>
<td>0.85</td>
<td>5.241</td>
<td>0.640</td>
</tr>
<tr>
<td>27</td>
<td>189.93</td>
<td>0.88</td>
<td>5.247</td>
<td>0.765</td>
</tr>
<tr>
<td>28</td>
<td>190.33</td>
<td>0.92</td>
<td>5.249</td>
<td>0.910</td>
</tr>
<tr>
<td>29</td>
<td>191.45</td>
<td>0.96</td>
<td>5.255</td>
<td>1.097</td>
</tr>
<tr>
<td>30</td>
<td>191.72</td>
<td>0.98</td>
<td>5.256</td>
<td>1.410</td>
</tr>
</tbody>
</table>
Weibull Plot

Material: Pyroceram
n: 30 Specimens
Average Failure Stress: 166.85 (MPa)
Std. Dev. +/-: 4.28 (MPa)
Environment: Distilled Water

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150.24</td>
<td>0.02</td>
<td>5.051</td>
<td>-4.086</td>
</tr>
<tr>
<td>2</td>
<td>150.63</td>
<td>0.05</td>
<td>5.067</td>
<td>-2.970</td>
</tr>
<tr>
<td>3</td>
<td>161.38</td>
<td>0.08</td>
<td>5.084</td>
<td>-2.442</td>
</tr>
<tr>
<td>4</td>
<td>161.76</td>
<td>0.12</td>
<td>5.086</td>
<td>-2.087</td>
</tr>
<tr>
<td>5</td>
<td>163.64</td>
<td>0.15</td>
<td>5.098</td>
<td>-1.817</td>
</tr>
<tr>
<td>6</td>
<td>163.66</td>
<td>0.16</td>
<td>5.098</td>
<td>-1.597</td>
</tr>
<tr>
<td>7</td>
<td>163.92</td>
<td>0.22</td>
<td>5.099</td>
<td>-1.410</td>
</tr>
<tr>
<td>8</td>
<td>164.28</td>
<td>0.25</td>
<td>5.102</td>
<td>-1.264</td>
</tr>
<tr>
<td>9</td>
<td>164.96</td>
<td>0.28</td>
<td>5.106</td>
<td>-1.099</td>
</tr>
<tr>
<td>10</td>
<td>165.14</td>
<td>0.32</td>
<td>5.107</td>
<td>-0.968</td>
</tr>
<tr>
<td>11</td>
<td>165.50</td>
<td>0.35</td>
<td>5.109</td>
<td>-0.842</td>
</tr>
<tr>
<td>12</td>
<td>165.63</td>
<td>0.38</td>
<td>5.110</td>
<td>-0.727</td>
</tr>
<tr>
<td>13</td>
<td>166.11</td>
<td>0.42</td>
<td>5.111</td>
<td>-0.618</td>
</tr>
<tr>
<td>14</td>
<td>166.42</td>
<td>0.45</td>
<td>5.115</td>
<td>-0.514</td>
</tr>
<tr>
<td>15</td>
<td>166.52</td>
<td>0.48</td>
<td>5.115</td>
<td>-0.415</td>
</tr>
<tr>
<td>16</td>
<td>166.95</td>
<td>0.52</td>
<td>5.118</td>
<td>-0.319</td>
</tr>
<tr>
<td>17</td>
<td>167.08</td>
<td>0.55</td>
<td>5.119</td>
<td>-0.225</td>
</tr>
<tr>
<td>18</td>
<td>167.73</td>
<td>0.58</td>
<td>5.122</td>
<td>-0.133</td>
</tr>
<tr>
<td>19</td>
<td>167.80</td>
<td>0.62</td>
<td>5.123</td>
<td>-0.042</td>
</tr>
<tr>
<td>20</td>
<td>168.14</td>
<td>0.65</td>
<td>5.125</td>
<td>0.049</td>
</tr>
<tr>
<td>21</td>
<td>168.43</td>
<td>0.68</td>
<td>5.127</td>
<td>0.140</td>
</tr>
<tr>
<td>22</td>
<td>169.29</td>
<td>0.72</td>
<td>5.132</td>
<td>0.232</td>
</tr>
<tr>
<td>23</td>
<td>170.11</td>
<td>0.75</td>
<td>5.136</td>
<td>0.327</td>
</tr>
<tr>
<td>24</td>
<td>170.68</td>
<td>0.78</td>
<td>5.140</td>
<td>0.425</td>
</tr>
<tr>
<td>25</td>
<td>170.95</td>
<td>0.82</td>
<td>5.141</td>
<td>0.529</td>
</tr>
<tr>
<td>26</td>
<td>171.43</td>
<td>0.85</td>
<td>5.144</td>
<td>0.640</td>
</tr>
<tr>
<td>27</td>
<td>171.67</td>
<td>0.88</td>
<td>5.146</td>
<td>0.765</td>
</tr>
<tr>
<td>28</td>
<td>173.49</td>
<td>0.92</td>
<td>5.156</td>
<td>0.910</td>
</tr>
<tr>
<td>29</td>
<td>174.86</td>
<td>0.95</td>
<td>5.158</td>
<td>1.097</td>
</tr>
<tr>
<td>30</td>
<td>174.53</td>
<td>0.98</td>
<td>5.162</td>
<td>1.410</td>
</tr>
</tbody>
</table>
Material: Pyroceram
n: 30 Specimens
Average Failure Stress: 150.51 (MPa)
Std. Dev. +/-: 4.06 (MPa)
Temperature: rt
Environment: Distilled Water

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>139.50</td>
<td>0.02</td>
<td>4.938</td>
<td>-4.088</td>
</tr>
<tr>
<td>2</td>
<td>144.37</td>
<td>0.05</td>
<td>4.972</td>
<td>-2.970</td>
</tr>
<tr>
<td>3</td>
<td>144.51</td>
<td>0.08</td>
<td>4.973</td>
<td>-2.442</td>
</tr>
<tr>
<td>4</td>
<td>145.46</td>
<td>0.12</td>
<td>4.980</td>
<td>-2.087</td>
</tr>
<tr>
<td>5</td>
<td>145.70</td>
<td>0.15</td>
<td>4.982</td>
<td>-1.817</td>
</tr>
<tr>
<td>6</td>
<td>146.30</td>
<td>0.18</td>
<td>4.986</td>
<td>-1.597</td>
</tr>
<tr>
<td>7</td>
<td>147.18</td>
<td>0.22</td>
<td>4.992</td>
<td>-1.410</td>
</tr>
<tr>
<td>8</td>
<td>147.97</td>
<td>0.25</td>
<td>4.997</td>
<td>-1.246</td>
</tr>
<tr>
<td>9</td>
<td>148.89</td>
<td>0.28</td>
<td>5.003</td>
<td>-1.099</td>
</tr>
<tr>
<td>10</td>
<td>149.16</td>
<td>0.32</td>
<td>5.005</td>
<td>-0.966</td>
</tr>
<tr>
<td>11</td>
<td>149.58</td>
<td>0.35</td>
<td>5.008</td>
<td>-0.842</td>
</tr>
<tr>
<td>12</td>
<td>149.91</td>
<td>0.38</td>
<td>5.010</td>
<td>-0.727</td>
</tr>
<tr>
<td>13</td>
<td>150.12</td>
<td>0.42</td>
<td>5.011</td>
<td>-0.618</td>
</tr>
<tr>
<td>14</td>
<td>150.33</td>
<td>0.45</td>
<td>5.013</td>
<td>-0.514</td>
</tr>
<tr>
<td>15</td>
<td>151.17</td>
<td>0.48</td>
<td>5.018</td>
<td>-0.415</td>
</tr>
<tr>
<td>16</td>
<td>151.63</td>
<td>0.52</td>
<td>5.021</td>
<td>-0.319</td>
</tr>
<tr>
<td>17</td>
<td>151.92</td>
<td>0.55</td>
<td>5.023</td>
<td>-0.225</td>
</tr>
<tr>
<td>18</td>
<td>152.12</td>
<td>0.58</td>
<td>5.025</td>
<td>-0.133</td>
</tr>
<tr>
<td>19</td>
<td>152.33</td>
<td>0.62</td>
<td>5.028</td>
<td>-0.042</td>
</tr>
<tr>
<td>20</td>
<td>152.44</td>
<td>0.65</td>
<td>5.027</td>
<td>0.049</td>
</tr>
<tr>
<td>21</td>
<td>152.70</td>
<td>0.68</td>
<td>5.028</td>
<td>0.140</td>
</tr>
<tr>
<td>22</td>
<td>153.19</td>
<td>0.72</td>
<td>5.032</td>
<td>0.232</td>
</tr>
<tr>
<td>23</td>
<td>153.25</td>
<td>0.75</td>
<td>5.032</td>
<td>0.327</td>
</tr>
<tr>
<td>24</td>
<td>153.96</td>
<td>0.78</td>
<td>5.037</td>
<td>0.425</td>
</tr>
<tr>
<td>25</td>
<td>154.01</td>
<td>0.82</td>
<td>5.037</td>
<td>0.529</td>
</tr>
<tr>
<td>26</td>
<td>154.24</td>
<td>0.85</td>
<td>5.039</td>
<td>0.640</td>
</tr>
<tr>
<td>27</td>
<td>154.25</td>
<td>0.88</td>
<td>5.039</td>
<td>0.765</td>
</tr>
<tr>
<td>28</td>
<td>154.47</td>
<td>0.92</td>
<td>5.040</td>
<td>0.910</td>
</tr>
<tr>
<td>29</td>
<td>156.79</td>
<td>0.95</td>
<td>5.055</td>
<td>1.097</td>
</tr>
<tr>
<td>30</td>
<td>157.77</td>
<td>0.98</td>
<td>5.061</td>
<td>1.410</td>
</tr>
</tbody>
</table>

**Weibull Plot**

**Weibull Analysis**

Pyroceram Flexure in Distilled Water
Without .17mm Fortification Layer Dimension
Stress Rate (MPa/s): 0.005

\[ y = 45.746x - 229.92 \]
\[ R^2 = 0.9852 \]
### Weibull Analysis

**Pyroceram Flexure in Distilled Water**

**Without .17mm Fortification Layer Dimension**

**Stress Rate (MPa/s):** 0.0005

**Temperature:** rt

**Environment:** Distilled Water

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>125.81</td>
<td>0.02</td>
<td>4.835</td>
<td>-3.773</td>
</tr>
<tr>
<td>2</td>
<td>127.71</td>
<td>0.07</td>
<td>4.850</td>
<td>-2.650</td>
</tr>
<tr>
<td>3</td>
<td>129.64</td>
<td>0.11</td>
<td>4.865</td>
<td>-2.115</td>
</tr>
<tr>
<td>4</td>
<td>130.92</td>
<td>0.16</td>
<td>4.875</td>
<td>-1.753</td>
</tr>
<tr>
<td>5</td>
<td>132.52</td>
<td>0.20</td>
<td>4.887</td>
<td>-1.475</td>
</tr>
<tr>
<td>6</td>
<td>132.57</td>
<td>0.25</td>
<td>4.887</td>
<td>-1.246</td>
</tr>
<tr>
<td>7</td>
<td>133.27</td>
<td>0.30</td>
<td>4.892</td>
<td>-1.049</td>
</tr>
<tr>
<td>8</td>
<td>133.93</td>
<td>0.34</td>
<td>4.897</td>
<td>-0.875</td>
</tr>
<tr>
<td>9</td>
<td>134.16</td>
<td>0.39</td>
<td>4.899</td>
<td>-0.717</td>
</tr>
<tr>
<td>10</td>
<td>134.44</td>
<td>0.43</td>
<td>4.901</td>
<td>-0.570</td>
</tr>
<tr>
<td>11</td>
<td>134.72</td>
<td>0.48</td>
<td>4.903</td>
<td>-0.433</td>
</tr>
<tr>
<td>12</td>
<td>135.24</td>
<td>0.52</td>
<td>4.907</td>
<td>-0.302</td>
</tr>
<tr>
<td>13</td>
<td>135.60</td>
<td>0.57</td>
<td>4.910</td>
<td>-0.175</td>
</tr>
<tr>
<td>14</td>
<td>136.86</td>
<td>0.61</td>
<td>4.919</td>
<td>-0.050</td>
</tr>
<tr>
<td>15</td>
<td>137.35</td>
<td>0.66</td>
<td>4.923</td>
<td>0.073</td>
</tr>
<tr>
<td>16</td>
<td>139.27</td>
<td>0.70</td>
<td>4.938</td>
<td>0.198</td>
</tr>
<tr>
<td>17</td>
<td>140.24</td>
<td>0.75</td>
<td>4.943</td>
<td>0.327</td>
</tr>
<tr>
<td>18</td>
<td>141.40</td>
<td>0.80</td>
<td>4.952</td>
<td>0.462</td>
</tr>
<tr>
<td>19</td>
<td>141.80</td>
<td>0.84</td>
<td>4.954</td>
<td>0.609</td>
</tr>
<tr>
<td>20</td>
<td>141.81</td>
<td>0.89</td>
<td>4.955</td>
<td>0.777</td>
</tr>
<tr>
<td>21</td>
<td>141.98</td>
<td>0.93</td>
<td>4.956</td>
<td>0.988</td>
</tr>
</tbody>
</table>

\[ y = 34.323x - 169.06 \]

\[ R^2 = 0.9519 \]
# FLEXURE DYNAMIC FATIGUE TEST

**Advanced Ceramics Test Lab**  
**NASA Glenn Research Center**  
**Cleveland, Ohio**

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Fracture Strength (MPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/6/2000</td>
<td>FI-1</td>
<td>50.0</td>
<td>Width 5.069</td>
<td>Depth 2.539</td>
<td>236.1</td>
<td>309.1</td>
<td>216.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50.0</td>
<td>Width 5.043</td>
<td>Depth 2.546</td>
<td>235.6</td>
<td>308.2</td>
<td>215.8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>50.0</td>
<td>Width 5.054</td>
<td>Depth 2.541</td>
<td>237.5</td>
<td>311.4</td>
<td>217.9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>50.0</td>
<td>Width 5.038</td>
<td>Depth 2.545</td>
<td>237.4</td>
<td>311.2</td>
<td>217.8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>50.0</td>
<td>Width 5.035</td>
<td>Depth 2.548</td>
<td>226.1</td>
<td>295.8</td>
<td>207.1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>50.0</td>
<td>Width 5.065</td>
<td>Depth 2.550</td>
<td>227.9</td>
<td>295.7</td>
<td>207.2</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>50.0</td>
<td>Width 5.025</td>
<td>Depth 2.536</td>
<td>231.3</td>
<td>306.5</td>
<td>214.3</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>50.0</td>
<td>Width 5.047</td>
<td>Depth 2.545</td>
<td>221.9</td>
<td>290.3</td>
<td>203.2</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>50.0</td>
<td>Width 5.043</td>
<td>Depth 2.546</td>
<td>241.4</td>
<td>315.8</td>
<td>221.1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>50.0</td>
<td>Width 5.037</td>
<td>Depth 2.548</td>
<td>235.2</td>
<td>307.5</td>
<td>215.3</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>50.0</td>
<td>Width 5.028</td>
<td>Depth 2.554</td>
<td>230.2</td>
<td>299.9</td>
<td>210.2</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>50.0</td>
<td>Width 5.084</td>
<td>Depth 2.550</td>
<td>225.2</td>
<td>291.0</td>
<td>204.0</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>50.0</td>
<td>Width 5.091</td>
<td>Depth 2.557</td>
<td>235.2</td>
<td>301.6</td>
<td>211.6</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>50.0</td>
<td>Width 5.029</td>
<td>Depth 2.547</td>
<td>228.7</td>
<td>299.8</td>
<td>209.9</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>50.0</td>
<td>Width 5.041</td>
<td>Depth 2.548</td>
<td>235.6</td>
<td>307.8</td>
<td>215.5</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>50.0</td>
<td>Width 5.043</td>
<td>Depth 2.547</td>
<td>239.7</td>
<td>313.3</td>
<td>219.4</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>50.0</td>
<td>Width 5.029</td>
<td>Depth 2.546</td>
<td>233.9</td>
<td>306.9</td>
<td>214.8</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>50.0</td>
<td>Width 5.036</td>
<td>Depth 2.586</td>
<td>243.4</td>
<td>307.6</td>
<td>216.4</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>50.0</td>
<td>Width 5.041</td>
<td>Depth 2.573</td>
<td>225.9</td>
<td>288.6</td>
<td>202.7</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>50.0</td>
<td>Width 5.032</td>
<td>Depth 2.547</td>
<td>225.7</td>
<td>295.7</td>
<td>207.0</td>
</tr>
<tr>
<td>4/10/2000</td>
<td>21</td>
<td>50.0</td>
<td>Width 4.994</td>
<td>Depth 2.536</td>
<td>220.8</td>
<td>294.6</td>
<td>205.8</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>50.0</td>
<td>Width 5.154</td>
<td>Depth 2.540</td>
<td>241.3</td>
<td>310.1</td>
<td>217.3</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>50.0</td>
<td>Width 5.055</td>
<td>Depth 2.540</td>
<td>233.7</td>
<td>306.6</td>
<td>214.6</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>50.0</td>
<td>Width 5.049</td>
<td>Depth 2.557</td>
<td>232.9</td>
<td>301.3</td>
<td>211.2</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>50.0</td>
<td>Width 5.168</td>
<td>Depth 2.540</td>
<td>236</td>
<td>302.4</td>
<td>211.9</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>50.0</td>
<td>Width 5.031</td>
<td>Depth 2.543</td>
<td>223.4</td>
<td>293.8</td>
<td>205.6</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>50.0</td>
<td>Width 5.071</td>
<td>Depth 2.550</td>
<td>235.5</td>
<td>305.2</td>
<td>213.8</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>50.0</td>
<td>Width 5.040</td>
<td>Depth 2.543</td>
<td>238.8</td>
<td>313.5</td>
<td>219.4</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>50.0</td>
<td>Width 5.087</td>
<td>Depth 2.533</td>
<td>229.7</td>
<td>301.3</td>
<td>210.7</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>50.0</td>
<td>Width 5.045</td>
<td>Depth 2.486</td>
<td>219.5</td>
<td>303.3</td>
<td>210.8</td>
</tr>
</tbody>
</table>

Avg: 303.2  
StDev +/-: 7.42  
n: 30
### FLEXURE DYNAMIC FATIGUE TEST

**Advanced Ceramics Test Lab**

**NASA Glenn Research Center**  Cleveland, Ohio

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size Width (mm)</th>
<th>Specimen Size Depth (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength Without (MPa)</th>
<th>Fracture Strength With (MPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDF50-1</td>
<td>50.0</td>
<td>5.060</td>
<td>2.547</td>
<td>175.9</td>
<td>229.1</td>
<td>160.4</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>50.0</td>
<td>5.062</td>
<td>2.555</td>
<td>171.5</td>
<td>221.7</td>
<td>155.4</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>50.0</td>
<td>5.037</td>
<td>2.543</td>
<td>175.6</td>
<td>230.6</td>
<td>161.4</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>50.0</td>
<td>5.031</td>
<td>2.543</td>
<td>173.2</td>
<td>227.8</td>
<td>159.4</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>50.0</td>
<td>5.063</td>
<td>2.518</td>
<td>168.3</td>
<td>222.2</td>
<td>155.1</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>50.0</td>
<td>5.049</td>
<td>2.486</td>
<td>170.3</td>
<td>235.1</td>
<td>163.4</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>50.0</td>
<td>5.066</td>
<td>2.543</td>
<td>173.8</td>
<td>226.9</td>
<td>158.8</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>50.0</td>
<td>5.060</td>
<td>2.548</td>
<td>177.2</td>
<td>230.6</td>
<td>161.5</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>50.0</td>
<td>5.057</td>
<td>2.539</td>
<td>177.4</td>
<td>232.9</td>
<td>162.9</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>50.0</td>
<td>5.068</td>
<td>2.503</td>
<td>172.3</td>
<td>233.2</td>
<td>162.5</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>50.0</td>
<td>5.000</td>
<td>2.529</td>
<td>173.8</td>
<td>233.0</td>
<td>162.7</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>50.0</td>
<td>5.040</td>
<td>2.532</td>
<td>169.6</td>
<td>224.9</td>
<td>157.2</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td>50.0</td>
<td>4.999</td>
<td>2.532</td>
<td>175.6</td>
<td>234.9</td>
<td>164.1</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>50.0</td>
<td>5.015</td>
<td>2.544</td>
<td>171.9</td>
<td>226.6</td>
<td>158.6</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>50.0</td>
<td>5.055</td>
<td>2.483</td>
<td>161.3</td>
<td>223.0</td>
<td>155.0</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>50.0</td>
<td>5.026</td>
<td>2.538</td>
<td>167.3</td>
<td>221.3</td>
<td>154.7</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>17</td>
<td>50.0</td>
<td>5.028</td>
<td>2.522</td>
<td>167.1</td>
<td>224.2</td>
<td>156.4</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>18</td>
<td>50.0</td>
<td>5.055</td>
<td>2.549</td>
<td>171.1</td>
<td>222.7</td>
<td>156.0</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>19</td>
<td>50.0</td>
<td>5.143</td>
<td>2.536</td>
<td>167.7</td>
<td>216.8</td>
<td>151.8</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>20</td>
<td>50.0</td>
<td>5.132</td>
<td>2.533</td>
<td>182.7</td>
<td>237.4</td>
<td>166.1</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>21</td>
<td>50.0</td>
<td>5.010</td>
<td>2.531</td>
<td>167.2</td>
<td>223.3</td>
<td>156.0</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>22</td>
<td>50.0</td>
<td>5.060</td>
<td>2.543</td>
<td>172.2</td>
<td>225.1</td>
<td>157.6</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>23</td>
<td>50.0</td>
<td>5.022</td>
<td>2.544</td>
<td>167.9</td>
<td>221.0</td>
<td>154.7</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>24</td>
<td>50.0</td>
<td>5.039</td>
<td>2.535</td>
<td>173.7</td>
<td>229.7</td>
<td>160.6</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>25</td>
<td>50.0</td>
<td>5.020</td>
<td>2.564</td>
<td>177.9</td>
<td>230.1</td>
<td>161.4</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>26</td>
<td>50.0</td>
<td>5.047</td>
<td>2.551</td>
<td>175.6</td>
<td>228.5</td>
<td>160.1</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>27</td>
<td>50.0</td>
<td>5.044</td>
<td>2.523</td>
<td>177.5</td>
<td>237.1</td>
<td>165.5</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>28</td>
<td>50.0</td>
<td>5.012</td>
<td>2.528</td>
<td>172.6</td>
<td>231.1</td>
<td>161.3</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>29</td>
<td>50.0</td>
<td>5.034</td>
<td>2.542</td>
<td>174.6</td>
<td>229.7</td>
<td>160.7</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>30</td>
<td>50.0</td>
<td>5.053</td>
<td>2.545</td>
<td>178.6</td>
<td>233.4</td>
<td>163.4</td>
<td></td>
<td>30</td>
</tr>
</tbody>
</table>

Avg 228.1 159.5
StDev +/- 5.29 3.66

n 30 30
### FLEXURE DYNAMIC FATIGUE TEST

**Advanced Ceramics Test Lab**

**NASA Glenn Research Center**  
**Cleveland, Ohio**

**Material:** Pyroceram  
**Environment:** Distilled H2O  
**Load:** 328.0 N/min  
**Load Frame:** M-2 Instron  
**Rate:** 5.0 Mpa/sec  
**Specimen Prep.:** as received  
**Annealing:** as received  
**Support Span (mm):** 40.026  
**Load Span (mm):** 20.065  
**Fortification Layer Thickness (mm):** 0.17

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size Width (mm)</th>
<th>Specimen Size Depth (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength Without (MPa)</th>
<th>Fracture Strength With (MPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>5.015 2.532</td>
<td>152.5 203.3 142.0</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>5.0</td>
<td>5.029 2.549</td>
<td>148 193.7 135.6</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>5.0</td>
<td>5.060 2.549</td>
<td>154.5 200.8 140.7</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>5.0</td>
<td>5.025 2.538</td>
<td>155.1 205.2 143.5</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>5.0</td>
<td>5.034 2.542</td>
<td>155 203.9 142.7</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>5.0</td>
<td>5.067 2.530</td>
<td>158.5 209.3 146.3</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>5.0</td>
<td>5.046 2.535</td>
<td>158.8 209.7 146.6</td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>5.0</td>
<td>5.061 2.545</td>
<td>157.1 204.9 143.5</td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>5.0</td>
<td>5.042 2.529</td>
<td>156.1 207.4 144.9</td>
<td></td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>5.0</td>
<td>5.055 2.538</td>
<td>153.2 201.4 140.9</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>5.0</td>
<td>5.059 2.476</td>
<td>151.4 210.5 146.2</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>5.0</td>
<td>5.078 2.548</td>
<td>152.5 197.7 138.5</td>
<td></td>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>5.0</td>
<td>5.061 2.544</td>
<td>155.8 203.4 142.4</td>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>5.0</td>
<td>5.060 2.552</td>
<td>155.2 201.2 141.0</td>
<td></td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>5.0</td>
<td>5.031 2.571</td>
<td>148.8 190.8 134.0</td>
<td></td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>5.0</td>
<td>5.022 2.535</td>
<td>150.1 199.2 139.3</td>
<td></td>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>5.0</td>
<td>5.039 2.543</td>
<td>157.5 206.8 144.7</td>
<td></td>
<td></td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>5.0</td>
<td>5.041 2.523</td>
<td>155 207.2 144.6</td>
<td></td>
<td></td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>5.0</td>
<td>5.153 2.476</td>
<td>152.7 208.2 144.7</td>
<td></td>
<td></td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>5.0</td>
<td>5.017 2.538</td>
<td>156.2 207.0 144.7</td>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>5.0</td>
<td>5.082 2.547</td>
<td>157.7 204.4 143.2</td>
<td></td>
<td></td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>5.0</td>
<td>5.017 2.532</td>
<td>150.6 200.7 140.2</td>
<td></td>
<td></td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>5.0</td>
<td>5.062 2.477</td>
<td>145 201.3 139.8</td>
<td></td>
<td></td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>5.0</td>
<td>5.144 2.529</td>
<td>157 204.2 142.9</td>
<td></td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>5.0</td>
<td>5.042 2.544</td>
<td>158.3 207.5 145.3</td>
<td></td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td>5.0</td>
<td>5.057 2.552</td>
<td>152.5 197.8 138.6</td>
<td></td>
<td></td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>5.0</td>
<td>5.032 2.576</td>
<td>154.9 197.7 138.9</td>
<td></td>
<td></td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>5.0</td>
<td>5.170 2.535</td>
<td>150.2 193.3 135.4</td>
<td></td>
<td></td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>5.0</td>
<td>5.085 2.550</td>
<td>157.3 203.2 142.4</td>
<td></td>
<td></td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>5.0</td>
<td>5.193 2.533</td>
<td>154.5 198.2 138.8</td>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
</tbody>
</table>

| Avg  | 202.7  | 141.7  |
| StDev +/- | 5.04 | 3.34 |
| n   | 30     | 30     |
# FLEXURE DYNAMIC FATIGUE TEST

**Advanced Ceramics Test Lab**

**NASA Glenn Research Center**  
**Cleveland, Ohio**

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Fortification Layer Thickness (mm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDF0.5-1</td>
<td>0.5</td>
<td>5.049</td>
<td>2.539</td>
<td>130</td>
<td>170.9</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>5.042</td>
<td>2.536</td>
<td>142.8</td>
<td>188.6</td>
<td>131.9</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>5.027</td>
<td>2.539</td>
<td>142.3</td>
<td>188.0</td>
<td>131.5</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>5.025</td>
<td>2.535</td>
<td>136.2</td>
<td>180.7</td>
<td>126.3</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>5.035</td>
<td>2.529</td>
<td>139.5</td>
<td>185.7</td>
<td>129.7</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>5.022</td>
<td>2.532</td>
<td>143</td>
<td>190.3</td>
<td>133.0</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>0.5</td>
<td>5.056</td>
<td>2.487</td>
<td>135.9</td>
<td>187.2</td>
<td>130.1</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
<td>5.112</td>
<td>2.532</td>
<td>144.6</td>
<td>188.8</td>
<td>132.1</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>5.023</td>
<td>2.546</td>
<td>135.5</td>
<td>178.0</td>
<td>124.6</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>5.035</td>
<td>2.545</td>
<td>142.8</td>
<td>187.3</td>
<td>131.1</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>0.5</td>
<td>5.140</td>
<td>2.528</td>
<td>138.7</td>
<td>180.7</td>
<td>126.4</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>0.5</td>
<td>5.041</td>
<td>2.525</td>
<td>136.3</td>
<td>181.8</td>
<td>127.0</td>
<td>11</td>
</tr>
<tr>
<td>13</td>
<td>0.5</td>
<td>5.167</td>
<td>2.537</td>
<td>138</td>
<td>177.3</td>
<td>124.2</td>
<td>12</td>
</tr>
<tr>
<td>14</td>
<td>0.5</td>
<td>5.024</td>
<td>2.545</td>
<td>136.2</td>
<td>179.1</td>
<td>125.3</td>
<td>13</td>
</tr>
<tr>
<td>15</td>
<td>0.5</td>
<td>5.026</td>
<td>2.534</td>
<td>135.2</td>
<td>179.5</td>
<td>125.4</td>
<td>14</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>5.044</td>
<td>2.488</td>
<td>136.3</td>
<td>188.0</td>
<td>130.7</td>
<td>15</td>
</tr>
<tr>
<td>17</td>
<td>0.5</td>
<td>5.046</td>
<td>2.551</td>
<td>147.1</td>
<td>191.5</td>
<td>134.1</td>
<td>16</td>
</tr>
<tr>
<td>18</td>
<td>0.5</td>
<td>5.034</td>
<td>2.553</td>
<td>132.8</td>
<td>173.0</td>
<td>121.2</td>
<td>17</td>
</tr>
<tr>
<td>19</td>
<td>0.5</td>
<td>5.060</td>
<td>2.548</td>
<td>140.5</td>
<td>182.8</td>
<td>128.1</td>
<td>18</td>
</tr>
<tr>
<td>20</td>
<td>0.5</td>
<td>5.052</td>
<td>2.541</td>
<td>144.8</td>
<td>189.9</td>
<td>132.9</td>
<td>19</td>
</tr>
<tr>
<td>21</td>
<td>0.5</td>
<td>5.051</td>
<td>2.475</td>
<td>135.2</td>
<td>188.5</td>
<td>130.8</td>
<td>20</td>
</tr>
<tr>
<td>22</td>
<td>0.5</td>
<td>5.046</td>
<td>2.550</td>
<td>140.6</td>
<td>183.2</td>
<td>128.3</td>
<td>21</td>
</tr>
<tr>
<td>23</td>
<td>0.5</td>
<td>5.034</td>
<td>2.531</td>
<td>135.3</td>
<td>179.8</td>
<td>125.6</td>
<td>22</td>
</tr>
<tr>
<td>24</td>
<td>0.5</td>
<td>5.037</td>
<td>2.541</td>
<td>145.7</td>
<td>191.7</td>
<td>134.1</td>
<td>23</td>
</tr>
<tr>
<td>25</td>
<td>0.5</td>
<td>5.061</td>
<td>2.551</td>
<td>140.4</td>
<td>182.2</td>
<td>127.6</td>
<td>24</td>
</tr>
<tr>
<td>26</td>
<td>0.5</td>
<td>5.165</td>
<td>2.533</td>
<td>137.2</td>
<td>177.0</td>
<td>124.0</td>
<td>25</td>
</tr>
<tr>
<td>27</td>
<td>0.5</td>
<td>5.049</td>
<td>2.542</td>
<td>138.5</td>
<td>181.6</td>
<td>127.1</td>
<td>26</td>
</tr>
<tr>
<td>28</td>
<td>0.5</td>
<td>5.142</td>
<td>2.527</td>
<td>140</td>
<td>182.5</td>
<td>127.7</td>
<td>27</td>
</tr>
<tr>
<td>29</td>
<td>0.5</td>
<td>5.046</td>
<td>2.538</td>
<td>142.5</td>
<td>187.7</td>
<td>131.3</td>
<td>28</td>
</tr>
<tr>
<td>30</td>
<td>0.5</td>
<td>5.062</td>
<td>2.550</td>
<td>139.4</td>
<td>181.0</td>
<td>126.8</td>
<td>29</td>
</tr>
</tbody>
</table>

Avg 183.5 128.3  
StDev +/- 5.41 3.70  
n 30 30
# FLEXURE DYNAMIC FATIGUE TEST

**Advanced Ceramics Test Lab**  
NASA Glenn Research Center  
Cleveland, Ohio

**Material:** Pyroceram  
**Environment:** Distilled H2O  
**Load:** 3280 N/min

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Temperature (°C)</td>
<td>rt</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td></td>
</tr>
<tr>
<td>Support Span (mm)</td>
<td>40.026</td>
</tr>
<tr>
<td>Load Span (mm)</td>
<td>20.065</td>
</tr>
</tbody>
</table>

**Load Frame:** M-2 Instron  
**Load Cell:** 1Kn Instron  
**Instron Rate:** 0.050 Mpa/sec  
**Specimen Prep.:** as received  
**Annealing:** as received  
**Fortification Layer Thickness (mm):** 0.17

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength Without (MPa)</th>
<th>Fracture Strength With (MPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.05</td>
<td>Width (mm)</td>
<td>Depth (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.086</td>
<td>2.549</td>
<td>122.7</td>
<td>158.6</td>
<td>111.2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.05</td>
<td>5.085</td>
<td>2.547</td>
<td>120.6</td>
<td>156.2</td>
<td>109.5</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.05</td>
<td>5.044</td>
<td>2.542</td>
<td>132.4</td>
<td>173.8</td>
<td>121.6</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.05</td>
<td>5.091</td>
<td>2.531</td>
<td>128.3</td>
<td>168.4</td>
<td>117.8</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.05</td>
<td>5.056</td>
<td>2.472</td>
<td>118.1</td>
<td>165.0</td>
<td>114.5</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.05</td>
<td>5.081</td>
<td>2.539</td>
<td>127.5</td>
<td>166.5</td>
<td>116.5</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.05</td>
<td>5.035</td>
<td>2.554</td>
<td>131.4</td>
<td>171.0</td>
<td>119.8</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.05</td>
<td>5.065</td>
<td>2.543</td>
<td>123.6</td>
<td>161.4</td>
<td>113.0</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.05</td>
<td>5.052</td>
<td>2.543</td>
<td>125</td>
<td>163.7</td>
<td>114.6</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.05</td>
<td>5.058</td>
<td>2.544</td>
<td>126.4</td>
<td>161.5</td>
<td>115.6</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>0.05</td>
<td>5.083</td>
<td>2.540</td>
<td>128.6</td>
<td>167.7</td>
<td>117.4</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>0.05</td>
<td>5.015</td>
<td>2.537</td>
<td>128.2</td>
<td>170.1</td>
<td>118.9</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>0.05</td>
<td>5.144</td>
<td>2.528</td>
<td>131.1</td>
<td>170.7</td>
<td>119.4</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>0.05</td>
<td>5.021</td>
<td>2.528</td>
<td>124.1</td>
<td>165.8</td>
<td>115.8</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>0.05</td>
<td>5.054</td>
<td>2.539</td>
<td>126.1</td>
<td>165.6</td>
<td>115.9</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>0.05</td>
<td>5.046</td>
<td>2.541</td>
<td>132.1</td>
<td>173.5</td>
<td>121.4</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>0.05</td>
<td>5.058</td>
<td>2.481</td>
<td>121.2</td>
<td>167.8</td>
<td>116.6</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>0.05</td>
<td>5.024</td>
<td>2.539</td>
<td>126.4</td>
<td>167.1</td>
<td>116.9</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>0.05</td>
<td>5.067</td>
<td>2.548</td>
<td>130.3</td>
<td>169.3</td>
<td>118.6</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.05</td>
<td>5.187</td>
<td>2.538</td>
<td>128.2</td>
<td>163.9</td>
<td>114.9</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>0.05</td>
<td>5.037</td>
<td>2.543</td>
<td>130.7</td>
<td>171.7</td>
<td>120.1</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>0.05</td>
<td>5.044</td>
<td>2.544</td>
<td>126.3</td>
<td>165.5</td>
<td>115.8</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>0.05</td>
<td>5.062</td>
<td>2.544</td>
<td>127.9</td>
<td>167.0</td>
<td>116.9</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>0.05</td>
<td>5.031</td>
<td>2.541</td>
<td>124.2</td>
<td>163.6</td>
<td>114.5</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>0.05</td>
<td>5.016</td>
<td>2.542</td>
<td>124.4</td>
<td>164.3</td>
<td>114.9</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td>0.05</td>
<td>5.049</td>
<td>2.551</td>
<td>131.8</td>
<td>171.4</td>
<td>120.1</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>0.05</td>
<td>5.169</td>
<td>2.535</td>
<td>125.7</td>
<td>161.8</td>
<td>113.3</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>0.05</td>
<td>5.014</td>
<td>2.530</td>
<td>124.6</td>
<td>166.4</td>
<td>116.2</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>0.05</td>
<td>5.010</td>
<td>2.551</td>
<td>129.2</td>
<td>168.1</td>
<td>117.7</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>0.05</td>
<td>5.067</td>
<td>2.537</td>
<td>133</td>
<td>174.5</td>
<td>122.1</td>
</tr>
</tbody>
</table>

Avg 166.9 116.7  
StDev +/- 4.28 3.00  
n 30 30
## FLEXURE DYNAMIC FATIGUE TEST

**Advanced Ceramics Test Lab**

**NASA Glenn Research Center**  
**Cleveland, Ohio**

- **Material:** Pyroceram  
- **Environment:** Distilled H₂O  
- **Load:** 3280 N/min  
- **Rate:** 0.005 Mpa/sec  

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Fracture Strength (MPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDF.005-1</td>
<td>0.005</td>
<td>5.030 2.540</td>
<td>113.4</td>
<td>149.6</td>
<td>104.6</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
<td>5.052 2.547</td>
<td>111.5</td>
<td>145.5</td>
<td>101.9</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.005</td>
<td>5.147 2.545</td>
<td>118</td>
<td>151.2</td>
<td>106.0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.005</td>
<td>5.166 2.532</td>
<td>113.3</td>
<td>146.3</td>
<td>102.4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.005</td>
<td>5.037 2.551</td>
<td>117.1</td>
<td>152.7</td>
<td>107.0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.005</td>
<td>5.028 2.531</td>
<td>116.1</td>
<td>154.5</td>
<td>107.9</td>
<td>80%PL (90N)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.005</td>
<td>5.041 2.532</td>
<td>115</td>
<td>152.4</td>
<td>106.5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.005</td>
<td>5.054 2.489</td>
<td>114</td>
<td>156.8</td>
<td>109.0</td>
<td>60%PL (69N)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.005</td>
<td>5.076 2.550</td>
<td>113.7</td>
<td>147.2</td>
<td>103.1</td>
<td>70%PL (80N)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.005</td>
<td>5.056 2.480</td>
<td>113.8</td>
<td>157.8</td>
<td>109.6</td>
<td>90%PL</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.005</td>
<td>5.152 2.530</td>
<td>117.1</td>
<td>151.9</td>
<td>106.3</td>
<td>90%PL</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.005</td>
<td>5.148 2.475</td>
<td>112.9</td>
<td>154.2</td>
<td>107.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.005</td>
<td>5.064 2.547</td>
<td>116.9</td>
<td>152.1</td>
<td>106.5</td>
<td>60%PL</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.005</td>
<td>5.043 2.484</td>
<td>111.2</td>
<td>154.0</td>
<td>107.0</td>
<td>90%PL</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.005</td>
<td>5.037 2.548</td>
<td>116.5</td>
<td>152.3</td>
<td>106.7</td>
<td>90%PL</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0.005</td>
<td>5.063 2.551</td>
<td>115.6</td>
<td>149.9</td>
<td>105.1</td>
<td>90%PL</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.005</td>
<td>5.014 2.531</td>
<td>114.8</td>
<td>153.2</td>
<td>107.0</td>
<td>80%PL</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0.005</td>
<td>5.044 2.548</td>
<td>111.6</td>
<td>145.7</td>
<td>102.0</td>
<td>80%PL</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0.005</td>
<td>5.011 2.538</td>
<td>115.5</td>
<td>153.2</td>
<td>107.1</td>
<td>80%PL</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.005</td>
<td>5.051 2.546</td>
<td>114</td>
<td>148.9</td>
<td>104.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.005</td>
<td>5.046 2.549</td>
<td>118.3</td>
<td>154.2</td>
<td>108.0</td>
<td>60%PL</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>0.005</td>
<td>5.027 2.537</td>
<td>112.7</td>
<td>149.2</td>
<td>104.3</td>
<td>80%PL</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>0.005</td>
<td>5.039 2.523</td>
<td>113.4</td>
<td>151.6</td>
<td>105.9</td>
<td>70%PL</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>0.005</td>
<td>5.013 2.541</td>
<td>113.5</td>
<td>150.1</td>
<td>105.0</td>
<td>70%PL</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.005</td>
<td>5.032 2.534</td>
<td>113.4</td>
<td>150.3</td>
<td>105.1</td>
<td>70%PL</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>0.005</td>
<td>5.020 2.545</td>
<td>117</td>
<td>154.0</td>
<td>107.7</td>
<td>70%PL</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>0.005</td>
<td>5.066 2.542</td>
<td>110.6</td>
<td>144.5</td>
<td>101.2</td>
<td>60%PL</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>0.005</td>
<td>5.178 2.537</td>
<td>108.8</td>
<td>139.5</td>
<td>97.7</td>
<td>60%PL</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>0.005</td>
<td>5.032 2.545</td>
<td>110</td>
<td>144.4</td>
<td>101.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.005</td>
<td>5.027 2.533</td>
<td>111.4</td>
<td>148.0</td>
<td>103.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Avg | 150.5 | 105.2 |
| StDev +/- | 4.06 | 2.68 |
| n   | 30    | 30    |

---

**FORTIFICATION LAYER THICKNESS (mm): 0.17**
# FLEXURE DYNAMIC FATIGUE TEST

Advanced Ceramics Test Lab  
NASA Glenn Research Center  
Cleveland, Ohio

<table>
<thead>
<tr>
<th>Material: Pyroceram</th>
<th>Environment: Distilled H2O</th>
<th>Load Rate: 3280 N/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Temperature (C): rt</td>
<td>Load Frame: M-2 Instron</td>
<td>Rate: 0005 Mpa/sec</td>
</tr>
<tr>
<td>Poissons Ratio:</td>
<td>Load Cell: 1Kn Instron</td>
<td>Notes:</td>
</tr>
<tr>
<td>Support Span (mm): 40.026</td>
<td>Specimen Prep.: as received</td>
<td></td>
</tr>
<tr>
<td>Load Span (mm): 20.065</td>
<td>Annealing: as received</td>
<td></td>
</tr>
<tr>
<td>Fortification Layer Thickness (mm): 0.17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size Width (mm)</th>
<th>Depth (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Fracture Strength Without (MPa)</th>
<th>Fracture Strength With (MPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDF0005-1</td>
<td>0.0005</td>
<td>5.003</td>
<td>2.531</td>
<td>100.3</td>
<td>134.2</td>
<td>93.7</td>
<td>20 N PL</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.0005</td>
<td>5.090</td>
<td>2.531</td>
<td>108</td>
<td>141.8</td>
<td>99.2</td>
<td>80%PL</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.0005</td>
<td>5.054</td>
<td>2.550</td>
<td>101.9</td>
<td>132.5</td>
<td>92.8</td>
<td>80%PL</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.0005</td>
<td>5.012</td>
<td>2.536</td>
<td>106.7</td>
<td>141.8</td>
<td>99.1</td>
<td>20 N PL</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.0005</td>
<td>5.082</td>
<td>2.548</td>
<td>102.9</td>
<td>133.3</td>
<td>93.4</td>
<td>80%PL</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.0005</td>
<td>5.041</td>
<td>2.535</td>
<td>101.7</td>
<td>134.4</td>
<td>94.0</td>
<td>80%PL</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.0005</td>
<td>5.025</td>
<td>2.549</td>
<td>104.5</td>
<td>136.9</td>
<td>95.8</td>
<td>20 N PL</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.0005</td>
<td>5.040</td>
<td>2.531</td>
<td>94.8</td>
<td>125.8</td>
<td>87.9</td>
<td>90%PL</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.0005</td>
<td>5.038</td>
<td>2.539</td>
<td>96.9</td>
<td>127.7</td>
<td>89.3</td>
<td>90%PL</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.0005</td>
<td>5.053</td>
<td>2.487</td>
<td>102.6</td>
<td>141.4</td>
<td>98.3</td>
<td>90%PL</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.0005</td>
<td>5.057</td>
<td>2.545</td>
<td>99.3</td>
<td>129.6</td>
<td>90.8</td>
<td>90%PL</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.0005</td>
<td>5.042</td>
<td>2.539</td>
<td>102.7</td>
<td>135.2</td>
<td>94.6</td>
<td>90%PL</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.0005</td>
<td>5.042</td>
<td>2.541</td>
<td>99.6</td>
<td>130.9</td>
<td>91.6</td>
<td>80%PL</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.0005</td>
<td>5.033</td>
<td>2.540</td>
<td>101.6</td>
<td>133.9</td>
<td>93.7</td>
<td>95% PL</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.0005</td>
<td>5.035</td>
<td>2.539</td>
<td>105.6</td>
<td>139.3</td>
<td>97.4</td>
<td>95% PL</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0.0005</td>
<td>5.067</td>
<td>2.540</td>
<td>101.3</td>
<td>132.6</td>
<td>92.8</td>
<td>95% PL</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.0005</td>
<td>5.065</td>
<td>2.540</td>
<td>102.9</td>
<td>134.7</td>
<td>94.3</td>
<td>95% PL</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0.0005</td>
<td>5.030</td>
<td>2.546</td>
<td>106.9</td>
<td>140.2</td>
<td>98.2</td>
<td>95% PL</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0.0005</td>
<td>5.057</td>
<td>2.488</td>
<td>103.3</td>
<td>142.1</td>
<td>98.8</td>
<td>20 N PL</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.0005</td>
<td>5.060</td>
<td>2.550</td>
<td>104.4</td>
<td>135.6</td>
<td>95.0</td>
<td>20 N PL</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.0005</td>
<td>5.061</td>
<td>2.486</td>
<td>103.1</td>
<td>142.0</td>
<td>98.7</td>
<td>20 N PL</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>0.0005</td>
<td>5.054</td>
<td>2.484</td>
<td>99.4</td>
<td>137.3</td>
<td>95.4</td>
<td>20 N PL</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Avg</td>
<td>135.6</td>
<td>94.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>StDev +/-</td>
<td>4.78</td>
<td>3.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>22</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure A1-1.—Typical fracture pattern of a Pyroceram specimen tested in constant stress-rate (“dynamic fatigue”) testing in flexure at room-temperature distilled water.

Figure A1-2.—Surface appearances of as-received Pyroceram flexure specimens: (a) Unfortified (as-machined) and (b) ‘fortified’ specimens. Machining marks are seen in both specimens; however, for the ‘fortified’ specimens, their machining marks were etched away from the specimens’ surfaces leaving a soft, protective layer.
2. Individual Weibull Plots and Raw Strength Data in Slow Crack Growth Testing in Flexure: ‘Unfortified’ Pyroceram Test Specimens

Material: Pyroceram

n: 20 Specimens
Average Failure Stress: 235.72 (MPa)
Std. Dev. +/-: 30.87 (MPa)
Temperature: rt
Environment: Silicon Oil

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>160.73</td>
<td>0.03</td>
<td>5.080</td>
<td>-3.676</td>
</tr>
<tr>
<td>2</td>
<td>185.64</td>
<td>0.08</td>
<td>5.224</td>
<td>-2.952</td>
</tr>
<tr>
<td>3</td>
<td>196.10</td>
<td>0.13</td>
<td>5.279</td>
<td>-2.013</td>
</tr>
<tr>
<td>4</td>
<td>204.01</td>
<td>0.18</td>
<td>5.318</td>
<td>-1.648</td>
</tr>
<tr>
<td>5</td>
<td>210.20</td>
<td>0.23</td>
<td>5.348</td>
<td>-1.367</td>
</tr>
<tr>
<td>6</td>
<td>214.20</td>
<td>0.28</td>
<td>5.367</td>
<td>-1.134</td>
</tr>
<tr>
<td>7</td>
<td>227.16</td>
<td>0.33</td>
<td>5.426</td>
<td>-0.934</td>
</tr>
<tr>
<td>8</td>
<td>229.60</td>
<td>0.38</td>
<td>5.436</td>
<td>-0.755</td>
</tr>
<tr>
<td>9</td>
<td>242.06</td>
<td>0.43</td>
<td>5.489</td>
<td>-0.592</td>
</tr>
<tr>
<td>10</td>
<td>249.67</td>
<td>0.48</td>
<td>5.520</td>
<td>-0.440</td>
</tr>
<tr>
<td>11</td>
<td>252.01</td>
<td>0.53</td>
<td>5.529</td>
<td>-0.295</td>
</tr>
<tr>
<td>12</td>
<td>252.67</td>
<td>0.58</td>
<td>5.532</td>
<td>-0.156</td>
</tr>
<tr>
<td>13</td>
<td>255.90</td>
<td>0.63</td>
<td>5.545</td>
<td>0.019</td>
</tr>
<tr>
<td>14</td>
<td>256.10</td>
<td>0.68</td>
<td>5.546</td>
<td>0.117</td>
</tr>
<tr>
<td>15</td>
<td>258.15</td>
<td>0.73</td>
<td>5.554</td>
<td>0.255</td>
</tr>
<tr>
<td>16</td>
<td>260.15</td>
<td>0.78</td>
<td>5.561</td>
<td>0.400</td>
</tr>
<tr>
<td>17</td>
<td>262.29</td>
<td>0.83</td>
<td>5.570</td>
<td>0.556</td>
</tr>
<tr>
<td>18</td>
<td>262.90</td>
<td>0.88</td>
<td>5.572</td>
<td>0.732</td>
</tr>
<tr>
<td>19</td>
<td>265.29</td>
<td>0.93</td>
<td>5.581</td>
<td>0.952</td>
</tr>
<tr>
<td>20</td>
<td>269.50</td>
<td>0.98</td>
<td>5.597</td>
<td>1.305</td>
</tr>
</tbody>
</table>

Weibull Plot

Weibull Analysis
Pyroceram Flexure in Silicon Oil
Without Fortification Layer
Stress Rate (MPa/s): 70.0

\[ y = 8.5737x - 47.321 \]
\[ R^2 = 0.9536 \]
Material: Pyroceram

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>167.07</td>
<td>0.03</td>
<td>5.118</td>
<td>-3.676</td>
</tr>
<tr>
<td>2</td>
<td>171.20</td>
<td>0.08</td>
<td>5.143</td>
<td>-2.552</td>
</tr>
<tr>
<td>3</td>
<td>181.15</td>
<td>0.13</td>
<td>5.199</td>
<td>-2.013</td>
</tr>
<tr>
<td>4</td>
<td>190.33</td>
<td>0.18</td>
<td>5.251</td>
<td>-1.548</td>
</tr>
<tr>
<td>5</td>
<td>201.52</td>
<td>0.23</td>
<td>5.306</td>
<td>-1.367</td>
</tr>
<tr>
<td>6</td>
<td>207.50</td>
<td>0.28</td>
<td>5.335</td>
<td>-1.134</td>
</tr>
<tr>
<td>7</td>
<td>214.42</td>
<td>0.33</td>
<td>5.368</td>
<td>-0.934</td>
</tr>
<tr>
<td>8</td>
<td>218.22</td>
<td>0.38</td>
<td>5.376</td>
<td>-0.765</td>
</tr>
<tr>
<td>9</td>
<td>219.53</td>
<td>0.43</td>
<td>5.391</td>
<td>-0.592</td>
</tr>
<tr>
<td>10</td>
<td>221.06</td>
<td>0.46</td>
<td>5.398</td>
<td>-0.440</td>
</tr>
<tr>
<td>11</td>
<td>223.26</td>
<td>0.53</td>
<td>5.408</td>
<td>-0.298</td>
</tr>
<tr>
<td>12</td>
<td>223.72</td>
<td>0.58</td>
<td>5.410</td>
<td>-0.156</td>
</tr>
<tr>
<td>13</td>
<td>228.51</td>
<td>0.63</td>
<td>5.432</td>
<td>-0.019</td>
</tr>
<tr>
<td>14</td>
<td>228.59</td>
<td>0.68</td>
<td>5.432</td>
<td>0.117</td>
</tr>
<tr>
<td>15</td>
<td>232.84</td>
<td>0.73</td>
<td>5.450</td>
<td>0.255</td>
</tr>
<tr>
<td>16</td>
<td>234.64</td>
<td>0.78</td>
<td>5.458</td>
<td>0.400</td>
</tr>
<tr>
<td>17</td>
<td>236.76</td>
<td>0.83</td>
<td>5.467</td>
<td>0.556</td>
</tr>
<tr>
<td>18</td>
<td>238.67</td>
<td>0.86</td>
<td>5.475</td>
<td>0.732</td>
</tr>
<tr>
<td>19</td>
<td>240.82</td>
<td>0.93</td>
<td>5.484</td>
<td>0.952</td>
</tr>
<tr>
<td>20</td>
<td>252.84</td>
<td>0.98</td>
<td>5.533</td>
<td>1.305</td>
</tr>
</tbody>
</table>

Weibull Analysis
Pyroceram Flexure in Distilled Water
Without Fortification Layer
Stress Rate (MPa/s): 70.0

Weibull Plot

Weibull Analysis
Pyroceram Flexure in Distilled Water
Without Fortification Layer
Stress Rate (MPa/s): 70.0

y = 10.656x - 57.806
R² = 0.9641
Material: Pyroceram  
Specimens: 20  
Average Failure Stress: 153.34 (MPa)  
Stress Rate (MPa/s): 0.07  
Std. Dev. +/-: 9.33 (MPa)  
Temperature: rt  
Environment: Distilled Water  

### Failure Stress and Weibull Plot

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>134.86</td>
<td>0.03</td>
<td>4.904</td>
<td>-3.676</td>
</tr>
<tr>
<td>2</td>
<td>135.57</td>
<td>0.08</td>
<td>4.910</td>
<td>-2.952</td>
</tr>
<tr>
<td>3</td>
<td>136.59</td>
<td>0.13</td>
<td>4.910</td>
<td>-2.073</td>
</tr>
<tr>
<td>4</td>
<td>141.23</td>
<td>0.18</td>
<td>4.962</td>
<td>-1.648</td>
</tr>
<tr>
<td>5</td>
<td>146.11</td>
<td>0.23</td>
<td>4.984</td>
<td>-1.367</td>
</tr>
<tr>
<td>6</td>
<td>150.71</td>
<td>0.28</td>
<td>5.015</td>
<td>-1.134</td>
</tr>
<tr>
<td>7</td>
<td>154.33</td>
<td>0.33</td>
<td>5.039</td>
<td>-0.934</td>
</tr>
<tr>
<td>8</td>
<td>154.81</td>
<td>0.38</td>
<td>5.042</td>
<td>-0.750</td>
</tr>
<tr>
<td>9</td>
<td>154.92</td>
<td>0.43</td>
<td>5.043</td>
<td>-0.592</td>
</tr>
<tr>
<td>10</td>
<td>155.97</td>
<td>0.48</td>
<td>5.050</td>
<td>-0.440</td>
</tr>
<tr>
<td>11</td>
<td>156.26</td>
<td>0.53</td>
<td>5.052</td>
<td>-0.299</td>
</tr>
<tr>
<td>12</td>
<td>157.82</td>
<td>0.58</td>
<td>5.061</td>
<td>-0.156</td>
</tr>
<tr>
<td>13</td>
<td>158.40</td>
<td>0.63</td>
<td>5.065</td>
<td>-0.019</td>
</tr>
<tr>
<td>14</td>
<td>160.26</td>
<td>0.68</td>
<td>5.077</td>
<td>0.117</td>
</tr>
<tr>
<td>15</td>
<td>160.54</td>
<td>0.73</td>
<td>5.079</td>
<td>0.255</td>
</tr>
<tr>
<td>16</td>
<td>160.60</td>
<td>0.78</td>
<td>5.079</td>
<td>0.400</td>
</tr>
<tr>
<td>17</td>
<td>160.87</td>
<td>0.83</td>
<td>5.081</td>
<td>0.556</td>
</tr>
<tr>
<td>18</td>
<td>161.06</td>
<td>0.88</td>
<td>5.082</td>
<td>0.732</td>
</tr>
<tr>
<td>19</td>
<td>161.72</td>
<td>0.93</td>
<td>5.086</td>
<td>0.952</td>
</tr>
<tr>
<td>20</td>
<td>163.66</td>
<td>0.98</td>
<td>5.098</td>
<td>1.305</td>
</tr>
</tbody>
</table>

Weibull Analysis

Pyroceram Flexure in Distilled Water  
Without Fortification Layer  
Stress Rate (MPa/s): 0.07

![Weibull Plot](Weibull.png)

Weibull Plot

Pyroceram Flexure in Distilled Water  
Without Fortification Layer  
Stress Rate (MPa/s): 0.07

\[ y = 18.798x - 95.133 \]
## FLEXURE DYNAMIC FATIGUE TEST

**Advanced Ceramics Test Lab**

**NASA Glenn Research Center**

**Cleveland, Ohio**

---

**Not Fortified**

**Material:** Pyroceram  
**Environment:** Silicon Oil  
**Load:** 80 N/s = 4800 N/min  
**Rate:** 70 MPa/s  
**Support Span (mm):** 40.026  
**Load Span (mm):** 20.065  
**Poissons Ratio:**  
**Load Cell:** 5Kn Instron  
**Instron Rate:**  
**Specimen Prep.:** see comments  
**Annealing:** as received  
**Fortification Layer Thickness (mm):** 0

### Completion Date | Specimen Number | Stress Rate (MPa/sec) | Specimen Size Width (mm) | Specimen Size Depth (mm) | Fracture Load (N) | Fracture Strength Without (MPa) | Fracture Strength With (MPa) | Comments
---|---|---|---|---|---|---|---|---
NFI-1 | | 0.070 | 5.082 | 2.600 | 225 | 196.1 | 196.1 | 1
2 | | 0.070 | 5.100 | 2.519 | 220.5 | 204.0 | 204.0 | 2
3 | | 0.070 | 5.085 | 2.563 | 288 | 258.2 | 258.2 | 3
4 | | 0.070 | 5.081 | 2.591 | 299.5 | 262.9 | 262.9 | 4
5 | | 0.070 | 5.120 | 2.522 | 274.1 | 252.0 | 252.0 | 5
6 | | 0.070 | 5.116 | 2.585 | 302.9 | 265.3 | 265.3 | 6
7 | | 0.070 | 5.116 | 2.526 | 263.9 | 242.1 | 242.1 | 7
8 | | 0.070 | 5.087 | 2.599 | 260.7 | 227.2 | 227.2 | 8
9 | | 0.070 | 5.087 | 2.586 | 306.2 | 269.5 | 269.5 | 9
10 | | 0.070 | 5.077 | 2.577 | 241.2 | 214.2 | 214.2 | 10
11 | | 0.070 | 5.102 | 2.517 | 200.4 | 185.6 | 185.6 | 11
12 | | 0.070 | 5.096 | 2.557 | 289.5 | 260.2 | 260.2 | 12
13 | | 0.070 | 5.098 | 2.509 | 274.5 | 256.1 | 256.1 | 13
14 | | 0.070 | 5.083 | 2.614 | 293.1 | 252.7 | 252.7 | 14
15 | | 0.070 | 5.090 | 2.517 | 275.6 | 255.9 | 255.9 | 15
16 | | 0.070 | 5.096 | 2.516 | 282.7 | 262.4 | 262.4 | 16
17 | | 0.070 | 5.093 | 2.547 | 275.5 | 249.7 | 249.7 | 17
18 | | 0.070 | 5.100 | 2.534 | 229.9 | 210.2 | 210.2 | 18
19 | | 0.070 | 5.111 | 2.514 | 173.4 | 160.7 | 160.7 | 19
20 | | 0.070 | 5.122 | 2.535 | 252.4 | 229.6 | 229.6 | 20

**Avg** 235.7 235.7  
**StDev +/-** 30.87 30.87  
**n** 20 20
# FLEXURE DYNAMIC FATIGUE TEST

**Advanced Ceramics Test Lab**

NASA Glenn Research Center  Cleveland, Ohio

---

**Material:** Not Fortified

**Environment:** Distilled H2O

**Load:** 80 N/s = 4800 N/min

**Test Temperature (C):** rt

**Load Frame:** M-1 Instron

**Rate:**

**Poissons Ratio:**

**Load Cell:** 5Kn Instron

**Support Span (mm):** 40.026

**Specimen Prep.:** as received

**Annealing:** as received

**Fortification Layer Thickness (mm):** 0

---

### FLEXURE DYNAMIC FATIGUE TEST

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size Width (mm)</th>
<th>Specimen Size Depth (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Fracture Strength (MPa) Without</th>
<th>Fracture Strength (MPa) With</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/14/2000</td>
<td>70NFDF-1</td>
<td>70.0</td>
<td>5.103</td>
<td>2.505</td>
<td>270.4</td>
<td>252.8</td>
<td>252.8</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>70.0</td>
<td>5.089</td>
<td>2.549</td>
<td>184.5</td>
<td>167.1</td>
<td>167.1</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>70.0</td>
<td>5.070</td>
<td>2.562</td>
<td>245.7</td>
<td>221.1</td>
<td>221.1</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>70.0</td>
<td>5.094</td>
<td>2.497</td>
<td>181.6</td>
<td>171.2</td>
<td>171.2</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>70.0</td>
<td>5.094</td>
<td>2.510</td>
<td>235.3</td>
<td>219.5</td>
<td>219.5</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>70.0</td>
<td>5.094</td>
<td>2.515</td>
<td>245.9</td>
<td>228.5</td>
<td>228.5</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>70.0</td>
<td>5.084</td>
<td>2.576</td>
<td>233.8</td>
<td>207.5</td>
<td>207.5</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>70.0</td>
<td>5.108</td>
<td>2.519</td>
<td>254</td>
<td>234.6</td>
<td>234.6</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>70.0</td>
<td>5.092</td>
<td>2.545</td>
<td>262.9</td>
<td>238.7</td>
<td>238.7</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>70.0</td>
<td>5.093</td>
<td>2.524</td>
<td>234.3</td>
<td>216.2</td>
<td>216.2</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>70.0</td>
<td>5.085</td>
<td>2.554</td>
<td>211.4</td>
<td>190.8</td>
<td>190.8</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>70.0</td>
<td>5.076</td>
<td>2.592</td>
<td>265.2</td>
<td>232.8</td>
<td>232.8</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>70.0</td>
<td>5.085</td>
<td>2.576</td>
<td>251.6</td>
<td>223.3</td>
<td>223.3</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>70.0</td>
<td>5.096</td>
<td>2.520</td>
<td>255.9</td>
<td>236.8</td>
<td>236.8</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>70.0</td>
<td>5.095</td>
<td>2.503</td>
<td>243.7</td>
<td>228.6</td>
<td>228.6</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>70.0</td>
<td>5.102</td>
<td>2.518</td>
<td>241.7</td>
<td>223.7</td>
<td>223.7</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>70.0</td>
<td>5.097</td>
<td>2.520</td>
<td>231.8</td>
<td>214.4</td>
<td>214.4</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>70.0</td>
<td>5.106</td>
<td>2.504</td>
<td>257.5</td>
<td>240.8</td>
<td>240.8</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>70.0</td>
<td>5.079</td>
<td>2.565</td>
<td>224.9</td>
<td>201.5</td>
<td>201.5</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>70.0</td>
<td>5.094</td>
<td>2.507</td>
<td>193.7</td>
<td>181.1</td>
<td>181.1</td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>

**Avg:** 216.6 216.6

**StDev +/-:** 23.56 23.56

**n:** 20 20
### FLEXURE DYNAMIC FATIGUE TEST

**Advanced Ceramics Test Lab**

**NASA Glenn Research Center, Cleveland, Ohio**

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Fracture Strength (MPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/14/2000</td>
<td>NFDF-7</td>
<td>0.070</td>
<td>5.068, 2.587</td>
<td>161.8</td>
<td>142.8</td>
<td>142.8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>NFDF-8</td>
<td>0.070</td>
<td>5.083, 2.536</td>
<td>168.5</td>
<td>154.3</td>
<td>154.3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>NFDF-9</td>
<td>0.070</td>
<td>5.100, 2.531</td>
<td>170.5</td>
<td>156.3</td>
<td>156.3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>NFDF-10</td>
<td>0.070</td>
<td>5.118, 2.510</td>
<td>146</td>
<td>135.6</td>
<td>135.6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>NFDF-11</td>
<td>0.070</td>
<td>5.099, 2.548</td>
<td>177.5</td>
<td>160.5</td>
<td>160.5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>NFDF-12</td>
<td>0.070</td>
<td>5.105, 2.517</td>
<td>171.1</td>
<td>158.4</td>
<td>158.4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>NFDF-13</td>
<td>0.070</td>
<td>5.098, 2.506</td>
<td>144.2</td>
<td>134.9</td>
<td>134.9</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>NFDF-14</td>
<td>0.070</td>
<td>5.104, 2.503</td>
<td>171.8</td>
<td>160.9</td>
<td>160.9</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>NFDF-15</td>
<td>0.070</td>
<td>5.080, 2.542</td>
<td>171</td>
<td>156.0</td>
<td>156.0</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>NFDF-16</td>
<td>0.070</td>
<td>5.079, 2.592</td>
<td>184.3</td>
<td>161.7</td>
<td>161.7</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>NFDF-17</td>
<td>0.070</td>
<td>5.102, 2.541</td>
<td>177.2</td>
<td>161.1</td>
<td>161.1</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>NFDF-18</td>
<td>0.070</td>
<td>5.093, 2.607</td>
<td>179.1</td>
<td>154.9</td>
<td>154.9</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>NFDF-19</td>
<td>0.070</td>
<td>5.083, 2.510</td>
<td>171.4</td>
<td>160.3</td>
<td>160.3</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>NFDF-20</td>
<td>0.070</td>
<td>5.081, 2.596</td>
<td>167.1</td>
<td>146.1</td>
<td>146.1</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>NFDF-21</td>
<td>0.070</td>
<td>5.105, 2.595</td>
<td>187.9</td>
<td>163.7</td>
<td>163.7</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>NFDF-22</td>
<td>0.070</td>
<td>5.079, 2.581</td>
<td>170.3</td>
<td>150.7</td>
<td>150.7</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>NFDF-23</td>
<td>0.070</td>
<td>5.086, 2.555</td>
<td>175</td>
<td>157.8</td>
<td>157.8</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>NFDF-24</td>
<td>0.070</td>
<td>5.085, 2.560</td>
<td>172.3</td>
<td>154.8</td>
<td>154.8</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>NFDF-25</td>
<td>0.070</td>
<td>5.097, 2.517</td>
<td>173.2</td>
<td>160.6</td>
<td>160.6</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>NFDF-26</td>
<td>0.070</td>
<td>5.092, 2.499</td>
<td>144</td>
<td>135.6</td>
<td>135.6</td>
<td>20</td>
</tr>
</tbody>
</table>

**Avg** 153.3 153.3

**StDev +/-** 9.33 9.33

**n** 20 20
3. Individual Weibull Plots and Raw Strength Data in Tension: ‘Fortified’ Pyroceram Test Specimens

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>164.39</td>
<td>0.03</td>
<td>5.102</td>
<td>-3.450</td>
</tr>
<tr>
<td>2</td>
<td>165.82</td>
<td>0.09</td>
<td>5.111</td>
<td>-2.318</td>
</tr>
<tr>
<td>3</td>
<td>166.32</td>
<td>0.16</td>
<td>5.114</td>
<td>-1.773</td>
</tr>
<tr>
<td>4</td>
<td>169.01</td>
<td>0.22</td>
<td>5.130</td>
<td>-1.399</td>
</tr>
<tr>
<td>5</td>
<td>170.16</td>
<td>0.28</td>
<td>5.137</td>
<td>-1.106</td>
</tr>
<tr>
<td>6</td>
<td>170.21</td>
<td>0.34</td>
<td>5.137</td>
<td>-0.865</td>
</tr>
<tr>
<td>7</td>
<td>170.54</td>
<td>0.41</td>
<td>5.139</td>
<td>-0.651</td>
</tr>
<tr>
<td>8</td>
<td>171.62</td>
<td>0.47</td>
<td>5.145</td>
<td>-0.456</td>
</tr>
<tr>
<td>9</td>
<td>172.47</td>
<td>0.53</td>
<td>5.150</td>
<td>-0.277</td>
</tr>
<tr>
<td>10</td>
<td>173.99</td>
<td>0.59</td>
<td>5.159</td>
<td>-0.104</td>
</tr>
<tr>
<td>11</td>
<td>174.76</td>
<td>0.66</td>
<td>5.163</td>
<td>0.066</td>
</tr>
<tr>
<td>12</td>
<td>176.12</td>
<td>0.72</td>
<td>5.171</td>
<td>0.238</td>
</tr>
<tr>
<td>13</td>
<td>176.53</td>
<td>0.78</td>
<td>5.174</td>
<td>0.419</td>
</tr>
<tr>
<td>14</td>
<td>176.98</td>
<td>0.84</td>
<td>5.176</td>
<td>0.619</td>
</tr>
<tr>
<td>15</td>
<td>178.78</td>
<td>0.91</td>
<td>5.186</td>
<td>0.862</td>
</tr>
<tr>
<td>16</td>
<td>178.97</td>
<td>0.97</td>
<td>5.187</td>
<td>1.243</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Weibull Analysis
Pyroceram Tensile in Distilled Water Room Temp
Without .214mm Fortification Layer Dimension
Stress Rate (MPa/s): 50.0

\[
y = 45.296x - 233.78
\]
\[
R^2 = 0.9482
\]
Material: Pyroceram  

Specimens: 15  

Average Failure Stress: 133.08 (MPa)  

Stress Rate (MPa/s): 60.0000  

Std. Dev. +/-: 20.42 (MPa)  

Temperature: 200 F (93 C)  

Environment: Distilled Water

<table>
<thead>
<tr>
<th>Rank</th>
<th>Failure Stress (MPa)</th>
<th>F</th>
<th>ln(Failure Stress)</th>
<th>lnln[1/(1-F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91.21</td>
<td>0.03</td>
<td>4.513</td>
<td>-3.384</td>
</tr>
<tr>
<td>2</td>
<td>102.34</td>
<td>0.10</td>
<td>4.828</td>
<td>-2.250</td>
</tr>
<tr>
<td>3</td>
<td>109.62</td>
<td>0.17</td>
<td>4.897</td>
<td>-1.702</td>
</tr>
<tr>
<td>4</td>
<td>124.58</td>
<td>0.23</td>
<td>4.925</td>
<td>-1.329</td>
</tr>
<tr>
<td>5</td>
<td>128.59</td>
<td>0.30</td>
<td>4.857</td>
<td>-1.031</td>
</tr>
<tr>
<td>6</td>
<td>128.67</td>
<td>0.37</td>
<td>4.857</td>
<td>-0.784</td>
</tr>
<tr>
<td>7</td>
<td>132.95</td>
<td>0.43</td>
<td>4.890</td>
<td>-0.566</td>
</tr>
<tr>
<td>8</td>
<td>133.82</td>
<td>0.50</td>
<td>4.926</td>
<td>-0.387</td>
</tr>
<tr>
<td>9</td>
<td>138.97</td>
<td>0.57</td>
<td>4.934</td>
<td>-0.179</td>
</tr>
<tr>
<td>10</td>
<td>139.14</td>
<td>0.63</td>
<td>4.935</td>
<td>0.003</td>
</tr>
<tr>
<td>11</td>
<td>139.63</td>
<td>0.70</td>
<td>4.939</td>
<td>0.186</td>
</tr>
<tr>
<td>12</td>
<td>148.52</td>
<td>0.77</td>
<td>5.001</td>
<td>0.375</td>
</tr>
<tr>
<td>13</td>
<td>154.76</td>
<td>0.83</td>
<td>5.042</td>
<td>0.583</td>
</tr>
<tr>
<td>14</td>
<td>158.80</td>
<td>0.90</td>
<td>5.068</td>
<td>0.834</td>
</tr>
<tr>
<td>15</td>
<td>164.55</td>
<td>0.97</td>
<td>5.103</td>
<td>1.224</td>
</tr>
</tbody>
</table>

Weibull Plot

Weibull Analysis  
Pyroceram Tensile in Distilled Water 200F  
Without .214mm Fortification Layer Dimension  
Stress Rate (MPa/s): 50.0  

\[ y = 7.5042x - 37.172 \]  
\[ R^2 = 0.9787 \]
Weibull Plot

Weibull Analysis
Pyroceram Tensile in Air 525F
Without .214mm Fortification Layer Dimension
Stress Rate (MPa/s): 60.000
Temperature: 525 F (274 C)
Environment: Air

y = 5.8213x - 31.657
R² = 0.8945
# Tensile Dynamic Fatigue Test

## ADVANCED CERAMICS TEST LAB
NASA Glenn Research Center      Cleveland, Ohio

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size Width (mm)</th>
<th>Specimen Size Depth (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Load Strength (MPa)</th>
<th>Load Rate N/s</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>2.543</td>
<td>3.178</td>
<td>983</td>
<td>169.0</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>2.548</td>
<td>3.182</td>
<td>1002</td>
<td>171.6</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>2.549</td>
<td>3.186</td>
<td>997.6</td>
<td>170.5</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>2.551</td>
<td>3.172</td>
<td>968.9</td>
<td>166.3</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>TC1</td>
<td>2.549</td>
<td>3.189</td>
<td>1010</td>
<td>172.5</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>T9</td>
<td>2.549</td>
<td>3.188</td>
<td>996.4</td>
<td>170.2</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>T11</td>
<td>3.170</td>
<td>2.525</td>
<td>1028</td>
<td>178.8</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>T12</td>
<td>2.764</td>
<td>2.197</td>
<td>1072</td>
<td>176.5</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2 Actmeas</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>T13</td>
<td>3.179</td>
<td>2.548</td>
<td>967.1</td>
<td>165.8</td>
<td>0.00</td>
<td></td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>T14</td>
<td>3.169</td>
<td>2.548</td>
<td>1040</td>
<td>179.0</td>
<td>0.00</td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>T15</td>
<td>2.180</td>
<td>2.750</td>
<td>1061</td>
<td>177.0</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2 Actmeas</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>T16</td>
<td>3.180</td>
<td>2.552</td>
<td>1017</td>
<td>174.0</td>
<td>0.00</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>T17</td>
<td>3.184</td>
<td>2.548</td>
<td>1029</td>
<td>176.1</td>
<td>0.00</td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>T18</td>
<td>3.190</td>
<td>2.548</td>
<td>962.6</td>
<td>164.4</td>
<td>0.00</td>
<td></td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>T19</td>
<td>2.731</td>
<td>2.167</td>
<td>1007</td>
<td>170.2</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2 Actmeas</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>T20</td>
<td>2.716</td>
<td>2.170</td>
<td>1030</td>
<td>174.8</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2 Actmeas</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

**Avg 172.3**

**StDev +/- 4.57**

| n | 16 |

---

NASA/TM—2003-212487  58
## Tensile Dynamic Fatigue Test

**ADVANCED CERAMICS TEST LAB**

NASA Glenn Research Center  Cleveland, Ohio

### Material: Pyroceram  Environment: H2O  Load: 70 Mpa/sec

Test Temperature (C): 93C (200F)  Load Frame: M2  Rate: 400 N/sec

Poissons Ratio :  

Specimen Prep.: none  Notes:  

Annealing:

**Fortification Layer Thickness (mm nominal):** 0.214

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size Width (mm)</th>
<th>Specimen Size Depth (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Load Rate N/s</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2-1</td>
<td>2.672</td>
<td>2.184</td>
<td>727</td>
<td>124.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>T2-2</td>
<td>2.782</td>
<td>2.182</td>
<td>847.6</td>
<td>139.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>T2-3</td>
<td>3.186</td>
<td>2.535</td>
<td>747.7</td>
<td>128.7</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>T2-4</td>
<td>3.247</td>
<td>2.477</td>
<td>802.7</td>
<td>139.0</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>T2-5</td>
<td>3.167</td>
<td>2.553</td>
<td>924.3</td>
<td>158.8</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>T2-6</td>
<td>3.242</td>
<td>2.541</td>
<td>883.1</td>
<td>148.5</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>T2-7</td>
<td>3.238</td>
<td>2.548</td>
<td>828.9</td>
<td>139.1</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>T2-8</td>
<td>3.226</td>
<td>2.554</td>
<td>764.9</td>
<td>128.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>T2-9</td>
<td>3.135</td>
<td>2.555</td>
<td>765.5</td>
<td>133.0</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>T2-10</td>
<td>3.227</td>
<td>2.555</td>
<td>543</td>
<td>91.2</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>T2-11</td>
<td>3.224</td>
<td>2.557</td>
<td>609.2</td>
<td>102.3</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>T2-12</td>
<td>3.252</td>
<td>2.553</td>
<td>657.8</td>
<td>109.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>T2-13</td>
<td>3.244</td>
<td>2.550</td>
<td>983.3</td>
<td>164.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>T2-14</td>
<td>3.246</td>
<td>2.555</td>
<td>802.1</td>
<td>133.8</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>T2-15</td>
<td>3.244</td>
<td>2.548</td>
<td>923.9</td>
<td>154.8</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Avg 133.1</td>
<td>StDev +/- 20.42</td>
<td>n 15</td>
</tr>
</tbody>
</table>

**ADVANCED CERAMICS TEST LAB**

NASA Glenn Research Center  Cleveland, Ohio

**Tensile Dynamic Fatigue Test**

- Material: Pyroceram
- Environment: H2O
- Test Temperature (C): 93C (200F)
- Load: 70 Mpa/sec
- Load Frame: M2
- Rate: 400 N/sec
- Poissons Ratio:
- Specimen Prep.: none
- Annealing:
- Fortification Layer Thickness (mm nominal): 0.214

### Table

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size Width (mm)</th>
<th>Specimen Size Depth (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Load Rate N/s</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2-1</td>
<td>2.672</td>
<td>2.184</td>
<td>727</td>
<td>124.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>T2-2</td>
<td>2.782</td>
<td>2.182</td>
<td>847.6</td>
<td>139.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>T2-3</td>
<td>3.186</td>
<td>2.535</td>
<td>747.7</td>
<td>128.7</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>T2-4</td>
<td>3.247</td>
<td>2.477</td>
<td>802.7</td>
<td>139.0</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>T2-5</td>
<td>3.167</td>
<td>2.553</td>
<td>924.3</td>
<td>158.8</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>T2-6</td>
<td>3.242</td>
<td>2.541</td>
<td>883.1</td>
<td>148.5</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>T2-7</td>
<td>3.238</td>
<td>2.548</td>
<td>828.9</td>
<td>139.1</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>T2-8</td>
<td>3.226</td>
<td>2.554</td>
<td>764.9</td>
<td>128.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>T2-9</td>
<td>3.135</td>
<td>2.555</td>
<td>765.5</td>
<td>133.0</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>T2-10</td>
<td>3.227</td>
<td>2.555</td>
<td>543</td>
<td>91.2</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>T2-11</td>
<td>3.224</td>
<td>2.557</td>
<td>609.2</td>
<td>102.3</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>T2-12</td>
<td>3.252</td>
<td>2.553</td>
<td>657.8</td>
<td>109.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>T2-13</td>
<td>3.244</td>
<td>2.550</td>
<td>983.3</td>
<td>164.6</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>T2-14</td>
<td>3.246</td>
<td>2.555</td>
<td>802.1</td>
<td>133.8</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>T2-15</td>
<td>3.244</td>
<td>2.548</td>
<td>923.9</td>
<td>154.8</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Avg 133.1</td>
<td>StDev +/- 20.42</td>
<td>n 15</td>
</tr>
</tbody>
</table>

- **Avg**: 133.1
- **StDev +/-**: 20.42
- **n**: 15
### Tensile Dynamic Fatigue Test

**ADVANCED CERAMICS TEST LAB**  
NASA Glenn Research Center  
Cleveland, Ohio

**Material:** Pyroceram  
**Environment:** Air  
**Load:** 70 Mpa/sec  
**Load Frame:** M2  
**Rate:** 400 N/s  
**Test Temperature (C):** 274C (525F)  
**Poissons Ratio:**  
**Specimen Prep.:** none  
**Notes:**  
**Annealing:**  
**Fortification Layer Thickness (mm nominal):** 0.214

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Size (mm)</th>
<th>Fracture Width</th>
<th>Fracture Depth</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Load Rate N/s</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>T5-1</td>
<td></td>
<td></td>
<td></td>
<td>2.551</td>
<td>3.188</td>
<td>863.1</td>
<td>147.3</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-2</td>
<td></td>
<td></td>
<td></td>
<td>2.569</td>
<td>3.182</td>
<td>939</td>
<td>159.3</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-3</td>
<td></td>
<td></td>
<td></td>
<td>2.544</td>
<td>3.198</td>
<td>765.1</td>
<td>130.5</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-4</td>
<td></td>
<td></td>
<td></td>
<td>2.549</td>
<td>3.172</td>
<td>1343</td>
<td>230.8</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-5</td>
<td></td>
<td></td>
<td></td>
<td>2.550</td>
<td>3.184</td>
<td>1352</td>
<td>231.2</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-6</td>
<td></td>
<td></td>
<td></td>
<td>2.549</td>
<td>3.180</td>
<td>1186</td>
<td>203.2</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-7</td>
<td></td>
<td></td>
<td></td>
<td>2.547</td>
<td>3.180</td>
<td>1259</td>
<td>215.9</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-8</td>
<td></td>
<td></td>
<td></td>
<td>2.554</td>
<td>3.214</td>
<td>1343</td>
<td>226.7</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-9</td>
<td></td>
<td></td>
<td></td>
<td>2.551</td>
<td>3.181</td>
<td>1345</td>
<td>230.1</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-10</td>
<td></td>
<td></td>
<td></td>
<td>2.547</td>
<td>3.172</td>
<td>1384</td>
<td>238.0</td>
<td>0.00</td>
<td>BL#9-028-2035-15.2</td>
</tr>
<tr>
<td>T5-11</td>
<td></td>
<td></td>
<td></td>
<td>2.547</td>
<td>3.245</td>
<td>1371</td>
<td>229.7</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
</tr>
<tr>
<td>T5-12</td>
<td></td>
<td></td>
<td></td>
<td>2.539</td>
<td>3.113</td>
<td>1182</td>
<td>208.5</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
</tr>
<tr>
<td>T5-13</td>
<td></td>
<td></td>
<td></td>
<td>2.547</td>
<td>3.165</td>
<td>1475</td>
<td>254.3</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
</tr>
<tr>
<td>T5-14</td>
<td></td>
<td></td>
<td></td>
<td>2.560</td>
<td>3.172</td>
<td>1463</td>
<td>250.1</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
</tr>
<tr>
<td>T5-15</td>
<td></td>
<td></td>
<td></td>
<td>2.548</td>
<td>3.236</td>
<td>1386</td>
<td>232.8</td>
<td>0.00</td>
<td>BL#9-028-2035-14.7</td>
</tr>
</tbody>
</table>

Avg 212.6  
StDev +/-37.45  
n15
Comparison of Strength Between Tension And Flexure

Test Rate = 70 MPa/s

Figure A3-1.—Comparison of strength as a function of test temperature between tension and flexure in Pyroceram.
## 4. Raw Strength Data in Compression Testing

### Compression Strength Test

**ADVANCED CERAMICS TEST LAB**  
NASA Glenn Research Center  
Cleveland, Ohio

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/sec)</th>
<th>Specimen Width (mm)</th>
<th>Fracture Depth (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Load Rate N/s</th>
<th>Notes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-1</td>
<td>12.769</td>
<td>2.555</td>
<td>12970</td>
<td></td>
<td>500.2</td>
<td>0.00</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>C1-2</td>
<td>12.774</td>
<td>2.549</td>
<td>23480</td>
<td></td>
<td>907.7</td>
<td>0.00</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>C1-3</td>
<td>12.785</td>
<td>2.545</td>
<td>19580</td>
<td></td>
<td>757.7</td>
<td>0.00</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>C1-4</td>
<td>12.754</td>
<td>2.534</td>
<td>21200</td>
<td></td>
<td>826.8</td>
<td>0.00</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>C2-1</td>
<td>12.774</td>
<td>2.542</td>
<td>22990</td>
<td></td>
<td>891.7</td>
<td>0.00</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>C2-2</td>
<td>12.761</td>
<td>2.544</td>
<td>21250</td>
<td></td>
<td>824.3</td>
<td>0.00</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>C2-3</td>
<td>12.762</td>
<td>2.531</td>
<td>16350</td>
<td></td>
<td>638.1</td>
<td>0.00</td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>C2-4</td>
<td>12.750</td>
<td>2.536</td>
<td>13740</td>
<td></td>
<td>535.5</td>
<td>0.00</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>C3-1</td>
<td>12.763</td>
<td>2.550</td>
<td>21400</td>
<td></td>
<td>827.6</td>
<td>0.00</td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>C3-2</td>
<td>12.756</td>
<td>2.553</td>
<td>24250</td>
<td></td>
<td>937.0</td>
<td>0.00</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>C3-3</td>
<td>12.772</td>
<td>2.578</td>
<td>23890</td>
<td></td>
<td>911.1</td>
<td>0.00</td>
<td></td>
<td></td>
<td>11</td>
</tr>
</tbody>
</table>

**Material:** Pyroceram  
**Environment:** H2O  
**Test Temperature (C):** RT  
**Load Frame:** M2  
**Poissons Ratio:**  
**Load Cell:**  
**Specimen Prep.:**  
**Notes:**  

**Annealing:**  
**Fortification Layer Thickness (mm nominal):** 0.225
5. Raw Strength Data in Shear Testing

### Shear Strength Test

**Advanced Ceramics Test Lab**  
NASA Glenn Research Center  
Cleveland, Ohio

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Specimen Number</th>
<th>Stress Rate (MPa/ps)</th>
<th>Specimen Size Width (mm)</th>
<th>Specimen Size Height (mm)</th>
<th>Fracture Load (N)</th>
<th>Fracture Strength (MPa)</th>
<th>Load Rate (N/s)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>11.622</td>
<td>2.531</td>
<td>1834</td>
<td></td>
<td>77.8</td>
<td>0.00</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>11.621</td>
<td>2.602</td>
<td>2070</td>
<td></td>
<td>85.0</td>
<td>0.00</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>11.584</td>
<td>2.550</td>
<td>2083</td>
<td></td>
<td>87.9</td>
<td>0.00</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>11.635</td>
<td>2.551</td>
<td>2220</td>
<td></td>
<td>93.2</td>
<td>0.00</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>11.561</td>
<td>2.544</td>
<td>2019</td>
<td></td>
<td>85.6</td>
<td>0.00</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>11.600</td>
<td>2.548</td>
<td>2044</td>
<td></td>
<td>86.2</td>
<td>0.00</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

**Average** 86.0

**StDev +/- 4.97**

---

NASA/TM—2003-212487  
63
6. Raw Fracture Toughness Data

### S.E.P.B. TEST

**NASA CERAMICS TESTING LAB**

- **Material:** Pyroceram
- **Loading Rate:** 1/2 mm/min
- **Load Frame:** M2
- **Temperature:** RT
- **Load Cell:** 1KN Instron
- **Environment:** DOW 704 Oil
- **Date:** 6/12/00
- **Average:** 2.3
- **St.Dev. +/-:** 0.0533
- **n:** 10

Specimens are without fortification layer

<table>
<thead>
<tr>
<th>Spec #</th>
<th>P (N)</th>
<th>B (mm)</th>
<th>W (mm)</th>
<th>a1 (mm)</th>
<th>a2 (mm)</th>
<th>a3 (mm)</th>
<th>awg (mm)</th>
<th>a/w</th>
<th>F(a/w)</th>
<th>Klc E+6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPNF-1</td>
<td>48.170</td>
<td>2.541</td>
<td>5.094</td>
<td>2.221</td>
<td>2.031</td>
<td>1.738</td>
<td>1.997</td>
<td>0.392</td>
<td>1.2494</td>
<td>2.3</td>
</tr>
<tr>
<td>SPNF-2</td>
<td>47.140</td>
<td>2.507</td>
<td>5.095</td>
<td>2.174</td>
<td>2.076</td>
<td>1.932</td>
<td>2.061</td>
<td>0.404</td>
<td>1.2709</td>
<td>2.3</td>
</tr>
<tr>
<td>SPNF-3</td>
<td>42.990</td>
<td>2.5</td>
<td>5.097</td>
<td>2.378</td>
<td>2.282</td>
<td>2.036</td>
<td>2.232</td>
<td>0.438</td>
<td>1.3361</td>
<td>2.3</td>
</tr>
<tr>
<td>SPNF-4</td>
<td>44.600</td>
<td>2.498</td>
<td>5.089</td>
<td>2.230</td>
<td>2.123</td>
<td>2.033</td>
<td>2.129</td>
<td>0.418</td>
<td>1.2965</td>
<td>2.3</td>
</tr>
<tr>
<td>SPNF-5</td>
<td>43.690</td>
<td>2.516</td>
<td>5.092</td>
<td>2.206</td>
<td>2.143</td>
<td>2.031</td>
<td>2.127</td>
<td>0.418</td>
<td>1.2953</td>
<td>2.2</td>
</tr>
<tr>
<td>SPNF-6</td>
<td>46.110</td>
<td>2.539</td>
<td>5.093</td>
<td>1.987</td>
<td>2.120</td>
<td>2.193</td>
<td>2.100</td>
<td>0.412</td>
<td>1.2853</td>
<td>2.3</td>
</tr>
<tr>
<td>SPNF-7</td>
<td>46.130</td>
<td>2.505</td>
<td>5.102</td>
<td>2.177</td>
<td>2.063</td>
<td>1.854</td>
<td>2.031</td>
<td>0.398</td>
<td>1.2599</td>
<td>2.2</td>
</tr>
<tr>
<td>SPNF-8</td>
<td>41.6</td>
<td>2.503</td>
<td>5.102</td>
<td>2.310</td>
<td>2.222</td>
<td>2.010</td>
<td>2.181</td>
<td>0.427</td>
<td>1.3144</td>
<td>2.2</td>
</tr>
<tr>
<td>SPNF-9</td>
<td>46.2</td>
<td>2.501</td>
<td>5.101</td>
<td>1.910</td>
<td>1.824</td>
<td>2.262</td>
<td>1.999</td>
<td>0.392</td>
<td>1.2492</td>
<td>2.2</td>
</tr>
<tr>
<td>SPNF-10</td>
<td>47.3</td>
<td>2.507</td>
<td>5.1</td>
<td>1.802</td>
<td>1.962</td>
<td>2.071</td>
<td>1.945</td>
<td>0.381</td>
<td>1.2322</td>
<td>2.2</td>
</tr>
</tbody>
</table>
**S.E.V.N.B. TEST**

**NASA CERAMICS TESTING LAB**

Material: Pyroceram  
Load Frame: M2  
Temperature: RT  
Load Cell: 1KN Instron  
Actual upper span (mm): 20.065  
Environment: DOW 704 Oil  
Actual lower span (mm): 40.026  
Date: 6/12/2000  
Actual fixture Wgt (g): 227.000  
Specimens have fortification layer  
St.Dev. +/-: 0.079808032  
Linear measurements are without fortification layer  

<table>
<thead>
<tr>
<th>Spec #</th>
<th>P (N)</th>
<th>B (mm)</th>
<th>W (mm)</th>
<th>a1 (mm)</th>
<th>a2 (mm)</th>
<th>a3 (mm)</th>
<th>a(avg) (mm)</th>
<th>a/w</th>
<th>F(a/w)</th>
<th>KIC (E+6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEVNB-1</td>
<td>23.3</td>
<td>2.142</td>
<td>3.255</td>
<td>1.120</td>
<td>1.129</td>
<td>1.116</td>
<td>1.122</td>
<td>0.345</td>
<td>1.1793</td>
<td>2.4</td>
</tr>
<tr>
<td>SEVNB-2</td>
<td>26.7</td>
<td>2.149</td>
<td>3.241</td>
<td>1.019</td>
<td>1.020</td>
<td>1.017</td>
<td>1.019</td>
<td>0.314</td>
<td>1.1426</td>
<td>2.5</td>
</tr>
<tr>
<td>SEVNB-3</td>
<td>23.3</td>
<td>2.19</td>
<td>3.168</td>
<td>1.051</td>
<td>1.080</td>
<td>1.061</td>
<td>1.064</td>
<td>0.336</td>
<td>1.1681</td>
<td>2.3</td>
</tr>
<tr>
<td>SEVNB-4</td>
<td>26.6</td>
<td>2.193</td>
<td>3.197</td>
<td>0.921</td>
<td>0.933</td>
<td>0.932</td>
<td>0.929</td>
<td>0.290</td>
<td>1.1179</td>
<td>2.3</td>
</tr>
<tr>
<td>SEVNB-5</td>
<td>21.4</td>
<td>2.149</td>
<td>3.176</td>
<td>1.102</td>
<td>1.047</td>
<td>1.082</td>
<td>1.077</td>
<td>0.339</td>
<td>1.1722</td>
<td>2.2</td>
</tr>
<tr>
<td>SEVNB-6</td>
<td>27.8</td>
<td>2.24</td>
<td>3.26</td>
<td>0.955</td>
<td>0.978</td>
<td>0.958</td>
<td>0.964</td>
<td>0.296</td>
<td>1.1229</td>
<td>2.3</td>
</tr>
<tr>
<td>SEVNB-7</td>
<td>22.9</td>
<td>2.159</td>
<td>3.214</td>
<td>1.088</td>
<td>1.097</td>
<td>1.095</td>
<td>1.093</td>
<td>0.340</td>
<td>1.1735</td>
<td>2.3</td>
</tr>
<tr>
<td>SEVNB-8</td>
<td>27.0</td>
<td>2.165</td>
<td>3.225</td>
<td>0.933</td>
<td>0.949</td>
<td>0.980</td>
<td>0.954</td>
<td>0.296</td>
<td>1.1231</td>
<td>2.4</td>
</tr>
<tr>
<td>SEVNB-9</td>
<td>28.0</td>
<td>2.149</td>
<td>3.355</td>
<td>1.067</td>
<td>1.065</td>
<td>1.065</td>
<td>1.066</td>
<td>0.318</td>
<td>1.1464</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Figure A6-1.—Average fracture toughness of Pyroceram at room temperature, determined by SEPB and SEVNB methods. Error bars indicate ±1.0 standard deviation.
### 6. Raw Elastic Modulus Data

#### Youngs Modulus by Impulse Excitation of Vibration

*Flexure Beam*

<table>
<thead>
<tr>
<th>Date</th>
<th>Specimen</th>
<th>Temperature</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Mass (g)</th>
<th>Frequency (Hz)</th>
<th>Density (g/cm³)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/20/2000</td>
<td>NF-1</td>
<td>rt</td>
<td>91.54</td>
<td>2.563</td>
<td>5.079</td>
<td>3.0985</td>
<td>2170</td>
<td>2.60</td>
<td>124.58</td>
</tr>
<tr>
<td></td>
<td>NF-2</td>
<td>rt</td>
<td>91.52</td>
<td>2.553</td>
<td>5.081</td>
<td>3.1071</td>
<td>2170</td>
<td>2.62</td>
<td>126.26</td>
</tr>
<tr>
<td></td>
<td>NF-3</td>
<td>rt</td>
<td>91.53</td>
<td>2.512</td>
<td>5.093</td>
<td>3.0293</td>
<td>2100</td>
<td>2.59</td>
<td>120.75</td>
</tr>
<tr>
<td></td>
<td>NF-4</td>
<td>rt</td>
<td>91.54</td>
<td>2.52</td>
<td>5.118</td>
<td>3.0507</td>
<td>2110</td>
<td>2.58</td>
<td>121.05</td>
</tr>
<tr>
<td></td>
<td>NF-5</td>
<td>rt</td>
<td>91.51</td>
<td>2.522</td>
<td>5.102</td>
<td>3.044</td>
<td>2120</td>
<td>2.59</td>
<td>121.91</td>
</tr>
<tr>
<td></td>
<td>NF-6</td>
<td>rt</td>
<td>91.52</td>
<td>2.557</td>
<td>5.092</td>
<td>3.0825</td>
<td>2140</td>
<td>2.59</td>
<td>120.99</td>
</tr>
<tr>
<td></td>
<td>NF-7</td>
<td>rt</td>
<td>91.51</td>
<td>2.552</td>
<td>5.079</td>
<td>3.101</td>
<td>2170</td>
<td>2.61</td>
<td>126.17</td>
</tr>
<tr>
<td></td>
<td>NF-8</td>
<td>rt</td>
<td>91.53</td>
<td>2.589</td>
<td>5.081</td>
<td>3.1037</td>
<td>2170</td>
<td>2.58</td>
<td>120.99</td>
</tr>
<tr>
<td></td>
<td>NF-9</td>
<td>rt</td>
<td>91.52</td>
<td>2.563</td>
<td>5.076</td>
<td>3.0963</td>
<td>2180</td>
<td>2.60</td>
<td>125.63</td>
</tr>
<tr>
<td></td>
<td>NF-10</td>
<td>rt</td>
<td>91.53</td>
<td>2.529</td>
<td>5.094</td>
<td>3.0387</td>
<td>2120</td>
<td>2.58</td>
<td>120.96</td>
</tr>
<tr>
<td></td>
<td>NF-11</td>
<td>rt</td>
<td>91.53</td>
<td>2.52</td>
<td>5.094</td>
<td>3.0313</td>
<td>2110</td>
<td>2.58</td>
<td>120.81</td>
</tr>
<tr>
<td></td>
<td>NF-12</td>
<td>rt</td>
<td>91.53</td>
<td>2.567</td>
<td>5.076</td>
<td>3.1049</td>
<td>2170</td>
<td>2.60</td>
<td>124.29</td>
</tr>
<tr>
<td></td>
<td>NF-13</td>
<td>rt</td>
<td>91.52</td>
<td>2.567</td>
<td>5.082</td>
<td>3.0813</td>
<td>2150</td>
<td>2.58</td>
<td>120.90</td>
</tr>
<tr>
<td></td>
<td>NF-14</td>
<td>rt</td>
<td>91.53</td>
<td>2.523</td>
<td>5.108</td>
<td>3.034</td>
<td>2100</td>
<td>2.57</td>
<td>119.02</td>
</tr>
<tr>
<td></td>
<td>NF-15</td>
<td>rt</td>
<td>91.53</td>
<td>2.503</td>
<td>5.097</td>
<td>3.0372</td>
<td>2110</td>
<td>2.60</td>
<td>123.45</td>
</tr>
<tr>
<td></td>
<td>NF-16</td>
<td>rt</td>
<td>91.56</td>
<td>2.567</td>
<td>5.103</td>
<td>3.1241</td>
<td>2180</td>
<td>2.60</td>
<td>125.66</td>
</tr>
<tr>
<td></td>
<td>NF-17</td>
<td>rt</td>
<td>91.53</td>
<td>2.512</td>
<td>5.098</td>
<td>3.0285</td>
<td>2120</td>
<td>2.58</td>
<td>122.91</td>
</tr>
<tr>
<td></td>
<td>NF-18</td>
<td>rt</td>
<td>91.53</td>
<td>2.541</td>
<td>5.091</td>
<td>3.0818</td>
<td>2150</td>
<td>2.60</td>
<td>124.47</td>
</tr>
<tr>
<td></td>
<td>NF-19</td>
<td>rt</td>
<td>91.53</td>
<td>2.545</td>
<td>5.095</td>
<td>3.0816</td>
<td>2150</td>
<td>2.60</td>
<td>123.78</td>
</tr>
<tr>
<td></td>
<td>NF-20</td>
<td>rt</td>
<td>91.53</td>
<td>2.606</td>
<td>5.094</td>
<td>3.1052</td>
<td>2160</td>
<td>2.56</td>
<td>117.31</td>
</tr>
<tr>
<td></td>
<td>NF-21</td>
<td>rt</td>
<td>91.54</td>
<td>2.504</td>
<td>5.096</td>
<td>3.0314</td>
<td>2110</td>
<td>2.60</td>
<td>123.13</td>
</tr>
<tr>
<td></td>
<td>NF-22</td>
<td>rt</td>
<td>91.52</td>
<td>2.526</td>
<td>5.097</td>
<td>3.0405</td>
<td>2110</td>
<td>2.58</td>
<td>120.21</td>
</tr>
<tr>
<td></td>
<td>NF-23</td>
<td>rt</td>
<td>91.53</td>
<td>2.608</td>
<td>5.082</td>
<td>3.1295</td>
<td>2190</td>
<td>2.58</td>
<td>121.54</td>
</tr>
<tr>
<td></td>
<td>NF-24</td>
<td>rt</td>
<td>91.56</td>
<td>2.515</td>
<td>5.097</td>
<td>3.0517</td>
<td>2140</td>
<td>2.60</td>
<td>125.90</td>
</tr>
<tr>
<td></td>
<td>NF-25</td>
<td>rt</td>
<td>91.52</td>
<td>2.5</td>
<td>5.098</td>
<td>3.0319</td>
<td>2120</td>
<td>2.60</td>
<td>124.78</td>
</tr>
<tr>
<td></td>
<td>NF-26</td>
<td>rt</td>
<td>91.56</td>
<td>2.509</td>
<td>5.109</td>
<td>3.0456</td>
<td>2110</td>
<td>2.59</td>
<td>122.74</td>
</tr>
<tr>
<td></td>
<td>NF-27</td>
<td>rt</td>
<td>91.53</td>
<td>2.539</td>
<td>5.081</td>
<td>3.0565</td>
<td>2140</td>
<td>2.59</td>
<td>122.83</td>
</tr>
<tr>
<td></td>
<td>NF-28</td>
<td>rt</td>
<td>91.55</td>
<td>2.545</td>
<td>5.147</td>
<td>3.0915</td>
<td>2130</td>
<td>2.58</td>
<td>120.73</td>
</tr>
<tr>
<td></td>
<td>NF-29</td>
<td>rt</td>
<td>91.59</td>
<td>2.501</td>
<td>5.094</td>
<td>3.018</td>
<td>2100</td>
<td>2.59</td>
<td>122.11</td>
</tr>
<tr>
<td></td>
<td>NF-30</td>
<td>rt</td>
<td>91.53</td>
<td>2.563</td>
<td>5.076</td>
<td>3.1018</td>
<td>2160</td>
<td>2.60</td>
<td>123.59</td>
</tr>
<tr>
<td></td>
<td>NF-31</td>
<td>rt</td>
<td>91.53</td>
<td>2.596</td>
<td>5.077</td>
<td>3.1091</td>
<td>2170</td>
<td>2.58</td>
<td>120.32</td>
</tr>
<tr>
<td></td>
<td>NF-32</td>
<td>rt</td>
<td>91.52</td>
<td>2.596</td>
<td>5.077</td>
<td>3.1095</td>
<td>2160</td>
<td>2.58</td>
<td>119.19</td>
</tr>
<tr>
<td></td>
<td>NF-33</td>
<td>rt</td>
<td>91.52</td>
<td>2.513</td>
<td>5.083</td>
<td>3.0252</td>
<td>2110</td>
<td>2.59</td>
<td>121.80</td>
</tr>
<tr>
<td></td>
<td>NF-34</td>
<td>rt</td>
<td>91.57</td>
<td>2.525</td>
<td>5.096</td>
<td>3.046</td>
<td>2120</td>
<td>2.59</td>
<td>121.94</td>
</tr>
<tr>
<td></td>
<td>NF-35</td>
<td>rt</td>
<td>91.52</td>
<td>2.511</td>
<td>5.095</td>
<td>3.0251</td>
<td>2100</td>
<td>2.58</td>
<td>120.64</td>
</tr>
<tr>
<td></td>
<td>NF-36</td>
<td>rt</td>
<td>91.52</td>
<td>2.512</td>
<td>5.091</td>
<td>3.0413</td>
<td>2120</td>
<td>2.60</td>
<td>123.56</td>
</tr>
<tr>
<td></td>
<td>NF-37</td>
<td>rt</td>
<td>91.53</td>
<td>2.51</td>
<td>5.098</td>
<td>3.0271</td>
<td>2100</td>
<td>2.58</td>
<td>120.83</td>
</tr>
<tr>
<td></td>
<td>NF-38</td>
<td>rt</td>
<td>91.53</td>
<td>2.591</td>
<td>5.069</td>
<td>3.091</td>
<td>2170</td>
<td>2.57</td>
<td>120.50</td>
</tr>
<tr>
<td></td>
<td>NF-39</td>
<td>rt</td>
<td>91.52</td>
<td>2.593</td>
<td>5.078</td>
<td>3.1045</td>
<td>2180</td>
<td>2.58</td>
<td>121.61</td>
</tr>
</tbody>
</table>

Avg: 122.30  
St.Dev: 2.14  
n: 39  

Poisson's: 0.29
### Youngs Modulus by Impulse Excitation of Vibration

**Flexure Beam**

Poisson's: 0.29

<table>
<thead>
<tr>
<th>Date</th>
<th>Specimen</th>
<th>Temperature (F)</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Mass (g)</th>
<th>Frequency (Hz)</th>
<th>Density (g/cm³)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/20/2000</td>
<td>NF-1</td>
<td>200</td>
<td>91.54</td>
<td>2.563</td>
<td>5.079</td>
<td>3.0985</td>
<td>2095</td>
<td>2.60</td>
<td>116.11</td>
</tr>
<tr>
<td></td>
<td>NF-2</td>
<td>200</td>
<td>91.52</td>
<td>2.553</td>
<td>5.081</td>
<td>3.1071</td>
<td>2101</td>
<td>2.62</td>
<td>118.36</td>
</tr>
<tr>
<td></td>
<td>NF-3</td>
<td>200</td>
<td>91.53</td>
<td>2.512</td>
<td>5.093</td>
<td>3.0293</td>
<td>2029</td>
<td>2.59</td>
<td>112.73</td>
</tr>
<tr>
<td></td>
<td>NF-4</td>
<td>200</td>
<td>91.54</td>
<td>2.52</td>
<td>5.118</td>
<td>3.0507</td>
<td>2040</td>
<td>2.58</td>
<td>113.15</td>
</tr>
<tr>
<td></td>
<td>NF-5</td>
<td>200</td>
<td>91.51</td>
<td>2.522</td>
<td>5.102</td>
<td>3.044</td>
<td>2041</td>
<td>2.59</td>
<td>112.99</td>
</tr>
<tr>
<td></td>
<td>NF-6</td>
<td>200</td>
<td>91.52</td>
<td>2.557</td>
<td>5.092</td>
<td>3.0625</td>
<td>2080</td>
<td>2.59</td>
<td>114.30</td>
</tr>
<tr>
<td></td>
<td>NF-7</td>
<td>200</td>
<td>91.51</td>
<td>2.552</td>
<td>5.079</td>
<td>3.101</td>
<td>2098</td>
<td>2.61</td>
<td>117.93</td>
</tr>
<tr>
<td></td>
<td>NF-8</td>
<td>200</td>
<td>91.53</td>
<td>2.589</td>
<td>5.081</td>
<td>3.1037</td>
<td>2095</td>
<td>2.58</td>
<td>112.77</td>
</tr>
<tr>
<td></td>
<td>NF-9</td>
<td>200</td>
<td>91.52</td>
<td>2.563</td>
<td>5.076</td>
<td>3.0963</td>
<td>2092</td>
<td>2.60</td>
<td>115.69</td>
</tr>
<tr>
<td></td>
<td>NF-10</td>
<td>200</td>
<td>91.53</td>
<td>2.529</td>
<td>5.094</td>
<td>3.0387</td>
<td>2037</td>
<td>2.58</td>
<td>111.67</td>
</tr>
</tbody>
</table>

Avg: 114.57

St.Dev: 2.33

n: 10
# Youngs Modulus by Impulse Excitation of Vibration

**Flexure Beam**

Poisson's: 0.29

<table>
<thead>
<tr>
<th>Date</th>
<th>Specimen</th>
<th>Temperature (F)</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Mass (g)</th>
<th>Frequency (Hz)</th>
<th>Density (g/cm³)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/20/2000</td>
<td>NF-1</td>
<td>525</td>
<td>91.54</td>
<td>2.563</td>
<td>5.079</td>
<td>3.0985</td>
<td>2160</td>
<td>2.60</td>
<td>123.43</td>
</tr>
<tr>
<td></td>
<td>NF-2</td>
<td>525</td>
<td>91.52</td>
<td>2.553</td>
<td>5.081</td>
<td>3.1071</td>
<td>2164</td>
<td>2.62</td>
<td>125.56</td>
</tr>
<tr>
<td></td>
<td>NF-3</td>
<td>525</td>
<td>91.53</td>
<td>2.512</td>
<td>5.093</td>
<td>3.0293</td>
<td>2092</td>
<td>2.59</td>
<td>119.83</td>
</tr>
<tr>
<td></td>
<td>NF-4</td>
<td>525</td>
<td>91.54</td>
<td>2.52</td>
<td>5.118</td>
<td>3.0507</td>
<td>2103</td>
<td>2.58</td>
<td>120.25</td>
</tr>
<tr>
<td></td>
<td>NF-5</td>
<td>525</td>
<td>91.51</td>
<td>2.522</td>
<td>5.102</td>
<td>3.044</td>
<td>2103</td>
<td>2.59</td>
<td>119.96</td>
</tr>
<tr>
<td></td>
<td>NF-6</td>
<td>525</td>
<td>91.52</td>
<td>2.557</td>
<td>5.092</td>
<td>3.0825</td>
<td>2143</td>
<td>2.59</td>
<td>121.33</td>
</tr>
<tr>
<td></td>
<td>NF-7</td>
<td>525</td>
<td>91.51</td>
<td>2.552</td>
<td>5.079</td>
<td>3.101</td>
<td>2162</td>
<td>2.61</td>
<td>125.24</td>
</tr>
<tr>
<td></td>
<td>NF-8</td>
<td>525</td>
<td>91.53</td>
<td>2.589</td>
<td>5.081</td>
<td>3.1037</td>
<td>2160</td>
<td>2.58</td>
<td>119.88</td>
</tr>
<tr>
<td></td>
<td>NF-9</td>
<td>525</td>
<td>91.52</td>
<td>2.563</td>
<td>5.076</td>
<td>3.0963</td>
<td>2157</td>
<td>2.60</td>
<td>122.99</td>
</tr>
<tr>
<td></td>
<td>NF-10</td>
<td>525</td>
<td>91.53</td>
<td>2.529</td>
<td>5.094</td>
<td>3.0387</td>
<td>2100</td>
<td>2.58</td>
<td>118.69</td>
</tr>
</tbody>
</table>

Avg: 121.72  
St.Dev: 2.43  
n: 10
### Youngs Modulus by Impulse Excitation of Vibration

*(High-temperature rig used)*

**Flexure**

**Room temperature**

Poisson's: 0.29

<table>
<thead>
<tr>
<th>Date</th>
<th>Specimen</th>
<th>Temperature</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Mass (g)</th>
<th>Frequency (Hz)</th>
<th>Density (g/cm³)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/14/2000</td>
<td>NF-1</td>
<td>rt</td>
<td>91.54</td>
<td>2.563</td>
<td>5.079</td>
<td>3.0985</td>
<td>2130</td>
<td>2.60</td>
<td>120.03</td>
</tr>
<tr>
<td></td>
<td>NF-2</td>
<td>rt</td>
<td>91.52</td>
<td>2.553</td>
<td>5.081</td>
<td>3.1071</td>
<td>2133</td>
<td>2.62</td>
<td>121.99</td>
</tr>
<tr>
<td></td>
<td>NF-3</td>
<td>rt</td>
<td>91.53</td>
<td>2.512</td>
<td>5.093</td>
<td>3.0293</td>
<td>2063</td>
<td>2.59</td>
<td>116.54</td>
</tr>
<tr>
<td></td>
<td>NF-4</td>
<td>rt</td>
<td>91.54</td>
<td>2.52</td>
<td>5.118</td>
<td>3.0507</td>
<td>2065</td>
<td>2.58</td>
<td>115.94</td>
</tr>
<tr>
<td></td>
<td>NF-5</td>
<td>rt</td>
<td>91.51</td>
<td>2.522</td>
<td>5.102</td>
<td>3.044</td>
<td>2074</td>
<td>2.59</td>
<td>116.67</td>
</tr>
<tr>
<td></td>
<td>NF-6</td>
<td>rt</td>
<td>91.52</td>
<td>2.557</td>
<td>5.092</td>
<td>3.0825</td>
<td>2107</td>
<td>2.59</td>
<td>117.29</td>
</tr>
<tr>
<td></td>
<td>NF-7</td>
<td>rt</td>
<td>91.51</td>
<td>2.552</td>
<td>5.079</td>
<td>3.101</td>
<td>2132</td>
<td>2.61</td>
<td>121.79</td>
</tr>
<tr>
<td></td>
<td>NF-8</td>
<td>rt</td>
<td>91.53</td>
<td>2.589</td>
<td>5.081</td>
<td>3.1037</td>
<td>2130</td>
<td>2.58</td>
<td>116.57</td>
</tr>
<tr>
<td></td>
<td>NF-9</td>
<td>rt</td>
<td>91.52</td>
<td>2.563</td>
<td>5.076</td>
<td>3.0963</td>
<td>2120</td>
<td>2.60</td>
<td>118.81</td>
</tr>
<tr>
<td></td>
<td>NF-10</td>
<td>rt</td>
<td>91.53</td>
<td>2.529</td>
<td>5.094</td>
<td>3.0387</td>
<td>2070</td>
<td>2.58</td>
<td>115.32</td>
</tr>
</tbody>
</table>

Avg: 118.09  
St.Dev: 2.42  
n: 10
Pyroceram
Compression Direction 2 run 2

\[ y = 0.1127x + 3.1485 \]
\[ R^2 = 1 \]

Pyroceram
Compression Direction 2 run 3

\[ y = 0.113x + 3.1679 \]
\[ R^2 = 1 \]
Pyroceram
Flexure Compression Direction 1 run 1

\[ y = 0.1172x - 1.535 \]
\[ R^2 = 1 \]

Pyroceram
Flexure Compression Direction 1 run 2

\[ y = 0.1168x - 1.177 \]
\[ R^2 = 1 \]
Pyroceram
Flexure Compression Direction 2 run 2

\[ y = 0.1098x - 0.4406 \]
\[ R^2 = 0.9998 \]

Pyroceram
Flexure Compression Direction 2 run 3

\[ y = 0.1098x - 0.5646 \]
\[ R^2 = 1 \]
Pyroceram
Flexure Tensile Direction 1 run 2

\[ y = 0.1141x - 0.5508 \]
\[ R^2 = 1 \]

Pyroceram
Flexure Tensile Direction 1 run 3

\[ y = 0.1142x - 0.7775 \]
\[ R^2 = 1 \]
Pyroceram
Flexure Tensile Direction 2 run 1

\[ y = 0.1091x - 1.1022 \]

\[ R^2 = 1 \]

Pyroceram
Flexure Tensile Direction 2 run 2

\[ y = 0.1091x - 1.0708 \]

\[ R^2 = 1 \]
Pyroceram
Flexure Tensile Direction 2 run 3

\[ y = 0.109x - 1.2517 \]
\[ R^2 = 1 \]

Pyroceram
Flexure Tensile Direction 3 run 1

\[ y = 0.114x - 0.6563 \]
\[ R^2 = 1 \]
**Title:** Results of Mechanical Testing for Pyroceram™ Glass-Ceramic

**Authors:** Sung R. Choi and John P. Gyekenyesi

**Abstract:**
Mechanical testing for Pyroceram™ 9606 glass-ceramic fabricated by Corning was conducted to determine mechanical properties of the material including slow crack growth (or life prediction parameters), flexure strength, tensile strength, compressive strength, shear strength, fracture toughness, and elastic modulus. Significantly high Weibull modulus in flexure strength, ranging from \( m = 34 \) to 52, was observed for the ‘fortified’ test specimens; while relatively low Weibull modulus (but comparable to most ceramics) of \( m = 9 \) to 19 were obtained from the ‘unfortified’ as-machined test specimens. The high Weibull modulus for the ‘fortified’ test specimens was attributed to the chemical etching process. The slow crack growth parameter \( n \) were found to be \( n = 21.5 \) from constant stress-rate (‘dynamic fatigue’) testing in flexure in room-temperature distilled water. Fracture toughness was determined as \( K_{IC} = 2.3 \) to 2.4 MPa√m (an average of 2.35 MPa√m) both by SEPB and SEVNB methods. Elastic modulus, ranging from \( E = 109 \) to 122 GPa, was almost independent of test temperature, material direction, and test method (strain gaging or impulse excitation technique) within the experimental scope, indicating that the material was homogeneous and isotropic. The existence of the ‘fortified’ layer played a crucial role in controlling and determining strength, strength distribution, and slow crack growth behavior. It also acted as a protective layer. Valid testing was not achieved in tension, compression, and shear testing due to inappropriate test specimen configurations (in compression and shear) provided and primarily due to the existence of ‘fortified’ layer (in tension).

**Keywords:** Mechanical testing; Glass ceramic; Pyroceram; Strength; Fracture toughness; Elastic modulus; Slow crack growth; Dynamic fatigue; Life prediction.