Strength of Glass with Holes Including Stress Corrosion Cracking

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Introduction

This report describes a cooperative research project with the U.S. Department of Energy, Pacific Northwest National Laboratory (PNNL) and Visteon Automotive Systems (Glass Division) coordinated through the G+Plus program of the Glass Manufacturing Industry Council. The PNNL work built on existing data from past structural failure tests on glass specimens, which had been performed on samples of glass provided to PNNL by Visteon. The past tests included samples with holes and samples without holes, and included a range of fabrication procedures to produce the holes. The testing focused on conditions of high loading rates and did not provide data from static fatigue tests with a water environment.

The long range objective of the present project was to develop a design procedure, including recommendations for limits on design stresses, for automotive glazing subject to strength reductions caused by hole penetrations. The proposed design approach was to have a probabilistic basis which can relate proposed design stresses to defined levels of failure probabilities. Specific activities on the project were to:

- Assemble data from the prior PNNL tests and produce a data base that includes relevant information for each test such as size of hole, method used to produce holes, quality level of hole, lot or grade of glass specimen, loading rate used in testing, environmental conditions present during testing, location of fracture initiation (surface or edge), etc.
- Evaluate stress distributions in specimens and estimate peak stress levels associated with specimen failures,
- Develop plots relating failure probabilities to applied loads and levels of stresses,
- Identify the test conditions that were not adequately covered by the prior PNNL tests and propose additional tests to fill the gaps in the data,
- Obtain additional specimens from Visteon for use in supplementary tests and perform the needed tests at high and low loading rates and in static fatigue as appropriate,
- Reevaluate the test data including results of additional tests,
- Develop recommendations for design stress limits that will ensure low probabilities of failure for glass components with hole penetrations.

The results of the tests performed at PNNL are documented here for future applications to the design of automotive glazing systems. The data are evaluated in a systematic manner, to maximize the usefulness of the existing data for future applications. The test data fill critical gaps that exist from the previous PNNL work. The data can be applied to make statistically based recommendations for allowable stress levels for hole penetrations.

Ring-on-Ring Tests

The ring-on-ring tests of specimens with drilled holes as described in this report were performed to establish the degrading effects of long-term static stresses on subsequent short-term strengths. The present work used a ring-on-ring test to measure fracture loads for 12-inch by 12-inch specimens. In this test, the loading is applied in bending by a fixture that applied two concentric ring loads at diameters of 2.5 and 6.0 inches. Prior PNNL efforts to determine long-term strengths were only partially successful. It was difficult to estimate the threshold static loads needed to produce reductions in short-term strength without causing an excessive number of failures of specimens during the static testing. The discussion below describes a modified testing procedure and the number of specimens needed to accomplish the objectives of the present study.

Methodology

The following approach was used to perform static fatigue tests:

1. Visteon selected one specimen design/hole configuration and fabricated specimens for the tests to be performed at PNNL.
2. Testing procedures were such to ensure control and measurement of temperature and humidity for the tests - both for the short-term and long-term tests.
3. Testing began with a batch of specimens (30) to measure short-term breaking loads to establish the baseline strengths and the scatter in the measured strengths.
4. An Instron machine was used to perform long-term tests for test durations of several days. The test durations were as long feasible, and were several orders of magnitude longer than the short-term tests.
5. Stacks (five specimens) of ring-on-ring specimens for the long-term tests were loaded by an Instron machine with control such to remove the load after the first specimen fractured.
6. the long-term tests began at very low levels of load for which it was ensured that no failures would occur. After 10 hours the load was increased by 15 percent and the tests were continued for another 10 hours.
7. Tests were continued with the loads increased in steps of 15 percent until one specimen in the stack of five failed in static fatigue.
8. The remaining unfailed specimens from each batch of five were then continued under the sequence of load steps until all specimens had either failed by static fatigue or had survived for 10 hours at a load of 155 pounds.
9. The remaining unbroken specimens were tested in short-term loading to determine if there was a change in the statistical distribution of short term strengths.

Technical Basis for Selecting Loading Sequence

The selection of load levels and test durations were based on pretest analyses as follows. This approach was based in part on information presented during lectures by Suresh Gulati at PNNL August 27-28, 1998.

The pretest evaluations assumed short-term strength tests that gave a mean breaking load of 370 lbs. and a minimum load from 30 tests of 316 lbs.

The Gulati data on static fatigue and crack growth by stress corrosion cracking indicated (data from strength tests governed by surface flaws) that strengths at 10 hours are about 70% of the short-term strengths. A very long-term test (measured in years) would have strengths of about 33% of the short-term tests. These ratios could be somewhat different for edge strengths (relevant to specimens with holes) than

for surface strengths. Therefore the proposed testing allowed for uncertainty in the glass fracture behavior. The incremental loading tests load started at a load for which there is no expectation of failure of edge flaws. For the assumed test series it was recommend starting at 40% of the minimum failure load of 316 lbs (0.4x316 = 126 lb).

The Gulati information indicated that crack growth by stress corrosion cracking is governed by da/dt = Constant × K^{16} = A × (Applied Load)^{16}. The strategy was to ensure that each successive load step applied over a period of about 10 hours would produce a much higher (by a factor of 10) crack growth rate (da/dt) than the growth rate during the previous load period. Using the cited equation, required that each step should increase the load by a factor of ($10^{1/16}$) = 1.15 compared to the load from the previous test period.

The proposed sequence of loading steps was 126 lb, 145 lb, 166 lb, 191 lb, 220 lb, 253 lb, 291 lb, 335 lb, etc. It was initially expected that one specimen of the stack of 30 specimens would fracture at a load of 0.70 × 316 lb = 221 lb. Therefore the test sequence was expected to end after 5 load steps or after about 3 days of testing.

Requested Test Specimens

Visteon was requested to select one hole configuration and a drilling/chamfer preparation process of interest. Visteon fabricated a batch of specimens (12 inch by 12 inch) of the same general configuration used in the previous tests performed at PNNL. The specimens were of annealed glass rather than of tempered glass.

The test plan as described required a minimum of 2×30 = 60 specimens. The requested number of specimens was doubled to a total of 120 specimens to allow for testing difficulties and a possible need to repeat tests. Furthermore, an even larger number of specimens was suggested to allow for more tests if time and budget considerations allowed PNNL to expand the scope of the test matrix. In summary, PNNL requested a minimum of 120 specimens. Visteon provided a larger number (300) of specimens in consideration of future needs.

Results of Tests

A total of 60 specimens (listed in Table 1) were tested using the ring-on-ring test fixtures as shown in Figure 1. The first 30 tests were standard strength tests for short-term loading, whereas the final 30 tests were long terms tests performed with the specimens submerged in room temperature water.

Short-Term Baseline Strength Tests

The first 30 entries of Table 1 list the ultimate or fracture loads from short term tests, with specimens AS-1 through AS-15 loaded to put the air side of the glass in tension and with specimens TS-1 through TS-15 loaded to put the tin side of the glass in tension. The fracture conditions are described in terms of the applied load (units of either pounds or kips, where one kip equals 1,000 pounds). Failure conditions in terms of maximum applied stress (pounds per square inch) at the edge of the holes can be obtained by multiplying the load in pounds by the factor of 32.28.

These failure data are plotted in Figure 2 using the failure probability parameter of the Wiebull statistical distribution. All specimens were 12-inch by 12-inch plates with the same configuration of center hole. The data depart somewhat from a straight line that would define an ideal Weibull distribution, with some apparent differences in the plot for the air-side versus tin-side tests. These differences are believed to be due to the random scatter in the measured strengths and not a clear indication that air-side strengths are inherently superior. A third curve is plotted on Figure 2 that combines the data from all 30 short-term tests. These same three curves are plotted on Figure 2 along with the failure loads from prior set of fracture tests performed by PNNL using specimens from Visteon that had various procedures used to prepare the center holes in the specimens. The present test data fall within the range of data from the specimens tested in the prior PNNL study.

Tests for Sustained Static Fatigue Loading

Specimens from the same lot of specimens as tested for Figure 2 were tested under sustained load using water immersion to induce stress corrosion cracking (SCC) from naturally occurring flaws located at the edges of the drilled holes. The photographs of Figure 4 show the arrangement used to test five specimens at a time in an Instron test machine. The machine was initially programmed to begin with a load of 67 pounds sustained for 10 hours. After 10 hours the load was increased by about 15 percent and held for another 10 hours. The sequence of increased load was continued until one of the five specimens fractured during a ten-hour hold period. The machine was programmed to remove the load and stop the tests when the fracture of one of the five specimens occurred. In order to minimize the time to complete the tests, later tests started the test sequence at a higher level of load with no apparent effect on the SCC strengths of the specimens.

The specimens were covered with sheets of tape (except at the center hole) as indicated in Figures 5 and 6 to confine the fragmentation of glass at the time of final fracture. Figure 7 shows the load histories for three sets of five-specimen tests. As indicated fractures of specimens occurred at about 2 hour and at 5 hours at a load of 155 pound for specimen groups 1-5 and 6-10. All five of specimens 11-15 survived the full 10 hours at155 pounds.

The SCC tests were performed at PNNL for a total of 30 specimens as listed in Table 1. All of the unfailed specimens were tested for an accumulated test time of 10 hours at 155 pounds or until the specimen fractured. All of the unfailed specimens were then fractured in short term tests to establish a distribution of strengths to be compared with the baseline strengths of Figure 2. Six of the 30 specimens tested under static fatigue (specimens AS-16 through AS-30 and specimens TS-16 through TS-30) failed under static fatigue conditions, and the remaining 24 specimens were subsequently loaded to fracture under short-term loading conditions.

Evaluation of Test Data

The short-term fracture data for the unfailed specimens of the static fatigue tests were evaluated in terms of Weibull probability plots. The data were then compared with short-term strengths of specimens that had not been loaded in the water environment.

Figures 7, 8 and 9 present Weibull plots for probability of failure. The objective was to determine the extent (if any) that exposure of the specimens to SCC conditions caused a reduction in the subsequent short-term strengths of the specimens. Small cracks along the edges of the holes were expected to grow by SCC during the 100-hour period at the 155-pound load. Strength data were separated into subsets of specimens stressed on the air-side and on the tin-side, and also with both sets of data combined. There appears to be little or no difference in the strengths for air and tin side specimens.

Given the large scatter in the strength data, it is difficult to observe reductions in strengths of the SCC specimens relative to the set of baseline data from specimens not subjected to SCC. Depending on how the data were evaluated, the exposure to SCC can be interpreted to either increase or decrease the strength of the set of specimens. One statistical evaluation excluded the specimens that had failed before 10 hours at the 155-pound load, and this evaluation showed that the remaining set of specimens had higher strengths than the baseline specimens. Evidently the SCC tests served to eliminate the weak specimens (with large flaws along the edge of the drilled holes). The remaining unfailed specimens were those with smaller flaws which did not experience significant SCC growth. The second statistical evaluation included the specimens that had failed by SCC and treated these specimens as failing at zero load for short-term strength. In this evaluation the failure probabilities of the entire set of specimens tended to be higher than for the baseline (no SCC) tests. Again it should be noted that a sample of 30 SCC specimens is a relatively small sample for purposes of observing small effects of SCC on specimen strengths.

Fracture Mechanics Calculations

A fracture mechanics model and associated computer code were developed to predict the growth of preexisting edge flaws for sustained loads applied to specimens exposed to a water environment. The objective was to 1) determine if the measured effects of SCC as described by Figures 8-10 were consistent with the expected behavior as predicted by fracture mechanics theory, and 2) establish a method from predicting the long-term effects of static fatigue for time spans that are too long to study through laboratory static fatigue tests.

Crack growth rates from the literature (shown by Figure 11) for stress corrosion cracks were used as inputs to the fracture mechanics model of the test specimens. A computer code was developed to make fracture mechanics calculations for stress corrosion crack growth. Calculations were performed for a hypothetical set of 30 specimens with flaws identical to those of the baseline batch of specimens. Crack growth rates were conservatively taken from the upper curve of Figure 11 corresponding to 100 percent relative humidity or a water immersion environment.

For purposes of the present calculations a sustained load of 155 pounds was assumed to act on the specimens. The times to grow the SCC cracks to critical sizes were calculated. The calculations for the 30 specimens predicted that the specimens would survive from 1.978 hours to 163.009 hours at the 155-pound load. Only four of the 30 specimens were predicted to fracture before 10 hours at the 155-pound load compared to six specimens that actually fractured in the PNNL static fatigue tests.

Although each individual specimen will have its strength decreased by SCC (at least to some small extent), it is not possible measure the strengths (with and without SCC) on the same specimen. The fracture mechanics model was therefore applied to predict what changes in strengths would theoretically result from SCC for the baseline set of specimens, if these specimens had been exposed to 150 pounds for 10 hours. In these calculations the measured failure loads of the baseline specimens were used as an input to a fracture mechanics calculation that assigned a flaw size that would have caused the specimen to fail at the measured load. This flaw was then assumed to grow by SCC for a period of 10 hours at a load of 155 pounds. A distribution of failure loads was then calculated for the larger flaws. Figure 12 shows trends similar to those of the measured strength data. If the failed specimens are excluded from the failure probability calculation, the SCC specimens show a trend of higher predicted strengths (or lower failure probabilities) than those measured prior to the SCC tests. If the specimens failed by SCC are included (with zero residual strength), the predicted strengths are seen to decrease relative to the baseline strengths.

Probabilistic fracture mechanics calculations were next performed for an assumed distribution of strengths (or flaw sizes). This distribution was a smooth (linear correlation) that approximated the flaw distribution established from the short-term strength tests as indicated in the plot of Figure 13.

The first set of calculations predicted the probability that a specimen would fail as a function of time for SCC tests at loads at 150 and 100 pounds (Figure 14). It was predicted that about one specimen in ten would fail by SCC after ten hours at 150 pounds, as opposed to one specimen in 5 (=30/6) for the PNNL SCC tests of Table 1. It was concluded that the fracture mechanics model can predict reasonable trends for failure probabilities.

Calculations were then performed to predict the effects of SCC on residual short-term strengths for a large population of specimens with the results shown by Figure 15. This plot shows that the trends of PNNL tests data are consistent with behavior as predicted by a fracture mechanics model.

For a final set of calculations the probabilistic fracture mechanics model simulated the effects for a population of 1000 specimens with a sustained 155-pound load with SCC. Results of these calculations are shown by Figures 16, 17 and 18. These calculations assumed a periodic short-term “load bump” of 100, 200 or 300 pound in excess of the 155 pound sustained load. The load bump was assumed to occur at different time intervals (once per minute, once per hour and once per day) in the three plots. The higher

values of load tended to fail the weaker SCC specimens (with larger flaws), but only if the load is applied before the specimen otherwise fails by SCC (growth the crack to critical size for the 155-pound load). Also indicated are the failure probabilities for the various load levels (sustained 155 pound load plus the 100, 200 or 300 pound bump in load). These calculations identified three time domains: 1) failure is governed solely by the maximum load (e.g. t = 0.01 hour), 2) failure governed by an interaction of SCC and short term load (e.g. 0.1 to 10 hours), and 3) failure is governed solely by SCC (time greater than 10 hours). These results suggested an approach to setting design stresses for glazing systems that are subject to a combination of long-term (years) sustained stresses and other stresses that are of a relatively short-term duration (fractions of a second to hours). This approach is described in the next section of this report.

Proposed Structural Design Procedure

A design procedure for glazing systems with holes should define allowable loads or stresses, and should address failures both due to long-term failures by static fatigue under sustained loads and failures due to superimposed short-term loads. The results of the above tests and fracture mechanics calculations can be applied to develop a suitable design method. The recommended approach is to impose separate limits on the static loads and the short-term loads such that the expected failure probabilities are about the same for the two modes of failure.

Figures 16 through 18 indicate that interaction effects are relatively small between the two modes of failure (static fatigue and short-term fracture) unless the maximum level of short-term load is applied at very frequent intervals (e.g. once per minute). If the maximum load is applied relatively infrequently (once per 24 hours as in Figure 16), the failure probability curves tend to collapse into the curve corresponding to the curve for static fatigue. In effect, short-term overload failures enhanced by ongoing static fatigue would occur only for degraded specimens for which a static failures was about to occur even without the application of the overload condition.

The proposed approach is to set one design limit based on the sum of the static and short-term loads of concern and to base this limit on the data from short-term tests of strengths. The other design limit compares the applied static loads with the failure loads from static fatigue tests. In lieu of static fatigue tests, a fracture mechanics approach such as used to generate the curves of Figure 14 can be applied.

A simple example is used to illustrate the methodology. Based on design requirements, one must first decide on a design life (hours) and an acceptable failure probability. In this example we will assume a design life of 100 hours and a failure probability of 0.01. Figure 14 indicates the allowable static load is 100 pounds (corresponding to 100 hours and a probability of 0.01). Using the curve “Without SCC” Figure 13 indicates a short-term failure load of 291 pounds for the selected failure probability of 0.01. This means that the sum of the dynamic and static load must be limited to 291 pounds. If the actual static load is at the full design limit of 100 pounds, the dynamic load must then be limited to 191 pounds (= 291 pounds – 100 pounds). In this case the allowable static load is about one third (100/291=0.344) of the allowable short-term loading. This factor of about 33 percent is the same as suggested by Gulati in lectures presented to PNNL staff in 1998.

The above simple example needs to be extended to address parameters more relevant to the design of automotive glazing. In these applications failure probabilities of 1.0E-04 or less are desired and design lives may be 100,000 hours or greater. Designing to such conditions require extrapolations of failure probability curves (such as Figure 13) down to low levels of applied stress, and also extrapolations of static fatigue data to failure times well beyond practical test durations for laboratory tests. Interaction effects between the two failure modes could be addressed by application of results such as shown by Figure 16-18. Interaction effects are estimated to be relatively small compared to the uncertainties associated with extrapolations of failure probabilities beyond the range of the supporting test data. Therefore design values of applied load for the configuration of the test specimen with the 12x12 inch

plate with center hole were evaluated by neglecting interaction effects. The results the results are given in Table 2.

The calculations of Table 2 were performed to relate failure probabilities for short-term loads by application of the equation on Figure 13. Failure times for static fatigue were estimated by assuming that crack growth rates (da/dt) are proportional to the applied load raised to the $1/16^{th}$ power. As seen in Table 2, the allowable level for short-term load for a given target failure probability is independent of the design life. In contrast, the allowable level for sustained static load decreases if the specified design life is increased to 100,000 hours from 100 hours. The allowable loads of Table 2 have been compared with guidance for designing with glass as presented in lectures by Suresh Gulati at PNNL August 27-28, 1998. Gulati noted that the endurance limit for soda lime glass is 25-40% (or about $1/3^{rd}$) of the short term strength, which is consistent with the results presented in Table 2. Gulati also noted that the usable stress for glass is 1,000 to 1,200 psi when the account is taken for real-life flaws and for static fatigue. The allowable static loads of Table 2 are consistent with this level of allowable stress.

Summary and Conclusions

Tests have been performed to establish strengths of glass specimens for which the breaking strengths have been degraded by the presence of a drilled hole. The drilled hole introduces a stress concentration that elevates the local stress at the hole, and introduces a distribution of small flaws around the edges of the hole. Tests of specimens under sustained loads in the presence of a water environment showed a significant reduction in breaking loads compared to the loads for fracture of the specimens for short-term loading conditions. Fracture mechanics calculations were performed to predict failure times associated with the growth of small flaws at the edges of the holes by the mechanism of stress corrosion cracking. These predictions predicted failure loads and failure times that were consistent with the static fatigue tests of the present study. The fracture mechanics calculations and results of short-term strength tests of specimens degraded by static fatigue loadings showed minimal interactions between the failure modes of static fatigue and failure due to short-term loading. A method for the design of automotive glazing is proposed. This method sets independent limits on sustained and short-term stresses, and assumes that interaction effects between the two failure modes can be neglected.

Table 1 Summary of Data from Ring-on-Ring Tests of Square Glass Specimens with Center Holes Including Short-Term Strength Tests and Stress Corrosion Crack Tests

Sample Number	SCC	Tin/Air	Time at Load, Hr.							Ultimate Load lb	Date	Specimen Stack	Comment
			67.1 lb	77.1 lb	88.7 lb	102.0 lb	117.3 lb	134.9 lb	155.1 lb				
AS-1	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	501.4	10/3/2002	N/A	Baseline – Short Term Strength
AS-2	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	471.7	10/3/2002	N/A	Baseline – Short Term Strength
AS-3	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	518.9	10/3/2002	N/A	Baseline – Short Term Strength
AS-4	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	502.1	10/3/2002	N/A	Baseline – Short Term Strength
AS-5	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	475.2	10/3/2002	N/A	Baseline – Short Term Strength
AS-6	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	487.9	10/3/2002	N/A	Baseline – Short Term Strength
AS-7	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	506.1	10/3/2002	N/A	Baseline – Short Term Strength
AS-8	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	479.2	10/3/2002	N/A	Baseline – Short Term Strength
AS-9	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	335.3	10/3/2002	N/A	Baseline – Short Term Strength
AS-10	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	511.9	10/3/2002	N/A	Baseline – Short Term Strength
AS-11	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	338.1	10/3/2002	N/A	Baseline – Short Term Strength
AS-12	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	518.3	10/3/2002	N/A	Baseline – Short Term Strength
AS-13	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	459.3	10/3/2002	N/A	Baseline – Short Term Strength
AS-14	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	487.7	10/3/2002	N/A	Baseline – Short Term Strength
AS-15	No	Air	0.0	0.0	0.0	0.0	0.0	0.0	0.0	351.9	10/3/2002	N/A	Baseline – Short Term Strength
TS-1	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	504.4	10/3/2002	N/A	Baseline – Short Term Strength
TS-2	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	487.5	10/3/2002	N/A	Baseline – Short Term Strength
TS-3	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	501.3	10/3/2002	N/A	Baseline – Short Term Strength
TS-4	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	532.4	10/3/2002	N/A	Baseline – Short Term Strength
TS-5	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	465.6	10/3/2002	N/A	Baseline – Short Term Strength
TS-6	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	365.2	10/3/2002	N/A	Baseline – Short Term Strength
TS-7	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	497.1	10/3/2002	N/A	Baseline – Short Term Strength
TS-8	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	491.1	10/3/2002	N/A	Baseline – Short Term Strength
TS-9	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	408.9	10/3/2002	N/A	Baseline – Short Term Strength
TS-10	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	446.3	10/3/2002	N/A	Baseline – Short Term Strength
TS-11	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	426.0	10/3/2002	N/A	Baseline – Short Term Strength
TS-12	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	491.7	10/3/2002	N/A	Baseline – Short Term Strength
TS-13	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	414.2	10/3/2002	N/A	Baseline – Short Term Strength
TS-14	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	516.1	10/3/2002	N/A	Baseline – Short Term Strength
TS-15	No	Tin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	434.1	10/3/2002	N/A	Baseline – Short Term Strength
AS-16	Yes	Air	10.0	10.0	10.0	10.0	10.0	10.0	4.9		11/4/2002	1-5	Sample broke @ 4.9 hours @ 155 pounds
AS-17	Yes	Air	10.0	10.0	10.0	10.0	10.0	10.0	10.0	463.9	11/4/2002	1-5	Test complete 10 hours @ 155 pounds
AS-18	Yes	Air	10.0	10.0	10.0	10.0	10.0	10.0	10.0	532.5	11/4/2002	1-5	Test complete 10 hours @ 155 pounds
AS-19	Yes	Air	10.0	10.0	10.0	10.0	10.0	10.0	10.0	557.9	11/4/2002	6-10	Test complete 10 hours @ 155 pounds
AS-20	Yes	Air	10.0	10.0	10.0	10.0	10.0	10.0	10.0	511.5	11/4/2002	6-10	Test complete 10 hours @ 155 pounds
AS-21	Yes	Air	10.0	10.0	10.0	10.0	10.0	10.0	10.0	466.1	11/4/2002	11-15	Test complete 10 hours @ 155 pounds
AS-22	Yes	Air	10.0	10.0	10.0	10.0	10.0	10.0	10.0	526.4	11/4/2002	11-15	Test complete 10 hours @ 155 pounds
AS-23	Yes	Air	10.0	10.0	10.0	10.0	10.0	10.0	10.0	493.9	11/4/2002	11-15	Test complete 10 hours @ 155 pounds
AS-24	Yes	Air	0.0	0.0	0.0	0.0	10.0	10.0	10.0	470.4	11/4/2002	16-20	Test complete 10 hours @ 155 pounds
AS-25	Yes	Air	0.0	0.0	0.0	0.0	10.0	0.3	0.0		11/4/2002	16-20	Sample broke @ 0.3 hours @134 pounds
AS-26	Yes	Air	0.0	0.0	0.0	0.0	10.0	10.0	10.0	343.8	11/4/2002	16-20	Test complete 10 hours @ 155 pounds
AS-27	Yes	Air	0.0	0.0	0.0	0.0	2.8	0.0	0.0		11/4/2002	21-25	Sample broke @ 2.8 hours @ 117 pounds
AS-28	Yes	Air	0.0	0.0	0.0	0.0	10.0	10.0	10.0	483.3	11/4/2002	26-30	Test complete 10 hours @ 155 pounds
AS-29	Yes	Air	0.0	0.0	0.0	0.0	10.0	10.0	10.0	519.0	11/4/2002	26-30	Test complete 10 hours @ 155 pounds
AS-30	Yes	Air	0.0	0.0	0.0	0.0	10.0	10.0	10.0	532.6	11/4/2002	26-30	Test complete 10 hours @ 155 pounds
TS-16	Yes	Tin	10.0	10.0	10.0	10.0	10.0	10.0	10.0	448.2	11/4/2002	1-5	Test complete 10 hours @ 155 pounds
TS-17	Yes	Tin	10.0	10.0	10.0	10.0	10.0	10.0	10.0	471.2	11/4/2002	1-5	Test complete 10 hours @ 155 pounds
TS-18	Yes	Tin	10.0	10.0	10.0	10.0	10.0	10.0	10.0	517.1	11/4/2002	6-10	Test complete 10 hours @ 155 pounds
TS-19	Yes	Tin	10.0	10.0	10.0	10.0	10.0	10.0	10.0	449.5	11/4/2002	6-10	Test complete 10 hours @ 155 pounds
TS-20	Yes	Tin	10.0	10.0	10.0	10.0	10.0	10.0	2.0		11/4/2002	6-10	Sample broke @ 62.0 hours@155 pounds
TS-21	Yes	Tin	10.0	10.0	10.0	10.0	10.0	10.0	10.0	460.0	11/4/2002	11-15	Test complete 10 hours @ 155 pounds
TS-22	Yes	Tin	10.0	10.0	10.0	10.0	10.0	10.0	10.0	501.7	11/4/2002	11-15	Test complete 10 hours @ 155 pounds
TS-23	Yes	Tin	0.0	0.0	0.0	0.0	10.0	10.0	0.6		11/4/2002	16-20	Sample broke @ 0.6 hours @ 134 pounds
TS-24	Yes	Tin	0.0	0.0	0.0	0.0	10.0	10.0	10.0	544.4	11/4/2002	16-20	Test complete 10 hours @ 155 pounds
TS-25	Yes	Tin	0.0	0.0	0.0	0.0	10.0	10.0	10.0	533.9	11/4/2002	21-25	Test complete 10 hours @ 155 pounds
TS-26	Yes	Tin	0.0	0.0	0.0	0.0	10.0	10.0	10.0	479.6	11/4/2002	21-25	Test complete 10 hours @ 155 pounds
TS-27	Yes	Tin	0.0	0.0	0.0	0.0	10.0	4.4	0.0		11/4/2002	21-25	Sample broke @ 449 hours @ 117 pounds
TS-28	Yes	Tin	0.0	0.0	0.0	0.0	10.0	10.0	10.0	441.8	11/4/2002	21-25	Test complete 10 hours @ 155 pounds
TS-29	Yes	Tin	0.0	0.0	0.0	0.0	10.0	10.0	10.0	453.1	11/4/2002	26-30	Test complete 10 hours @ 155 pounds
TS-30	Yes	Tin	0.0	0.0	0.0	0.0	10.0	10.0	10.0	500.7	11/4/2002	26-30	Test complete 10 hours @ 155 pounds

Table 2 Design Stresses as Function of the Target Failure Probability and Design Lifetime

	Design for 100 hour life		Design for 100,000 hour life	
Target Failure Probability	Allowable Static Load , pounds	Allowable Total Load – Static Plus Short Term, pounds	Allowable Static Load , pounds	Allowable Total Load – Static Plus Short Term, pounds
10^{-2}	100	291	65	290
10^{-3}	77	223	50	223
10^{-4}	59	172	39	172
10^{-5}	46	132	30	132
10^{-6}	35	102	23	102

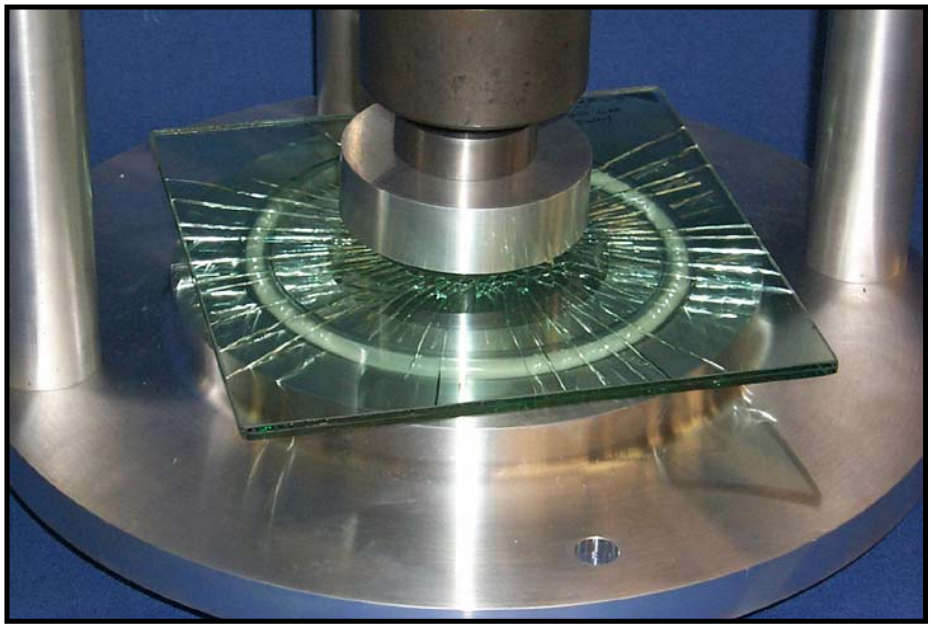


Figure 1 Ring-on-Ring Test

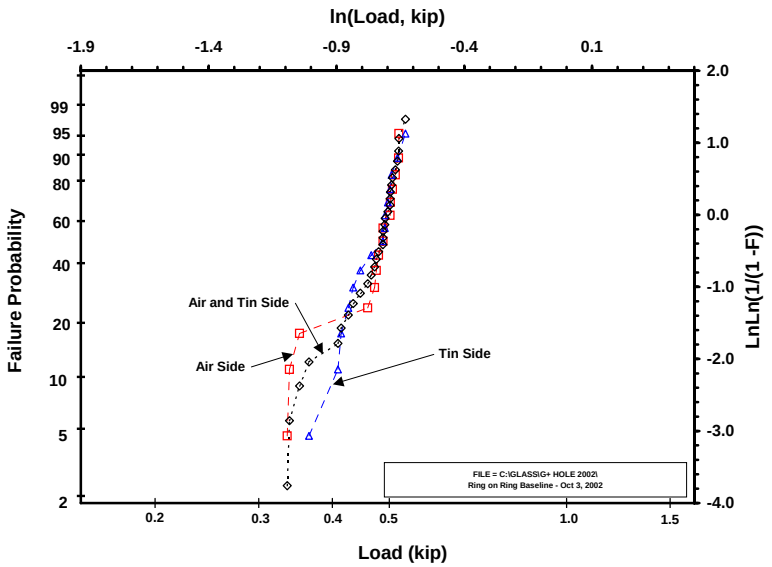


Figure 2 **Baseline Strength Data from Short Term Tests of 30 Specimens of Glass Specimens with Holes (kip = 1,000 lb.)**

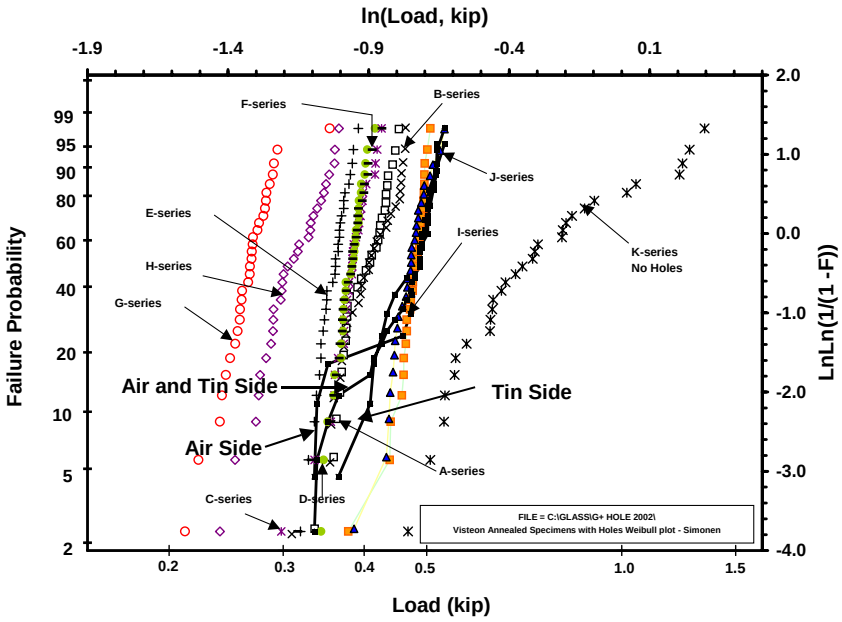
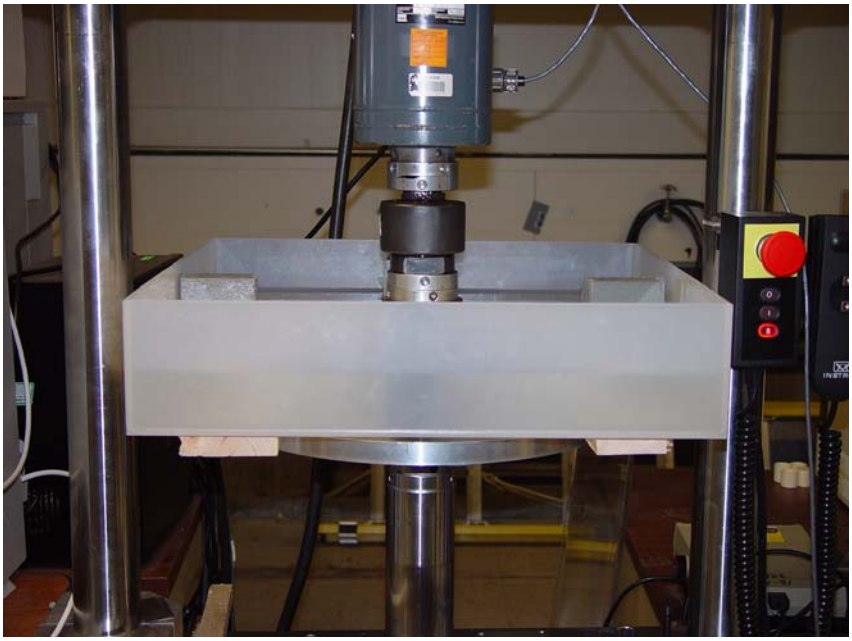


Figure 3 **Comparison of Baseline Strength Data from Short Term Tests of 30 Specimens of Glass Specimens with Data from Prior PNNL Tests on Visteon Glass (kip = 1,000 lb.)**



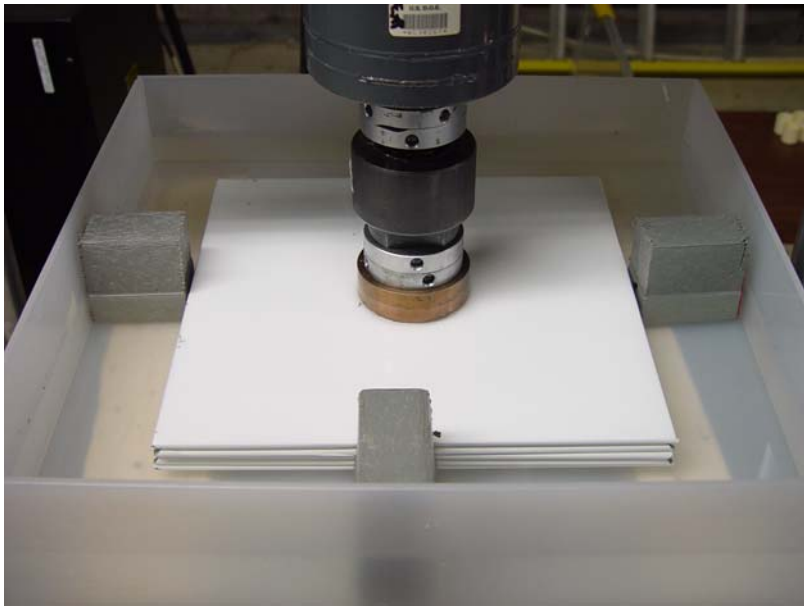


Figure 4 Stack of Five Specimens Ready for Water Immersion Tests of Stress Corrosion Cracking

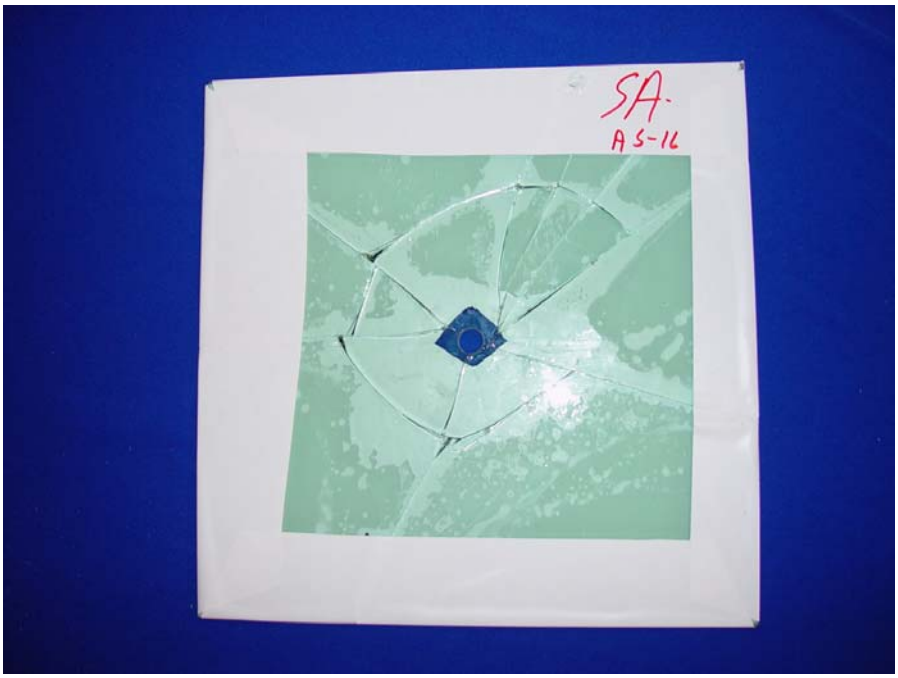


Figure 5 Fractured Specimen from Water Immersion Test and Collection of Specimens from Visteon

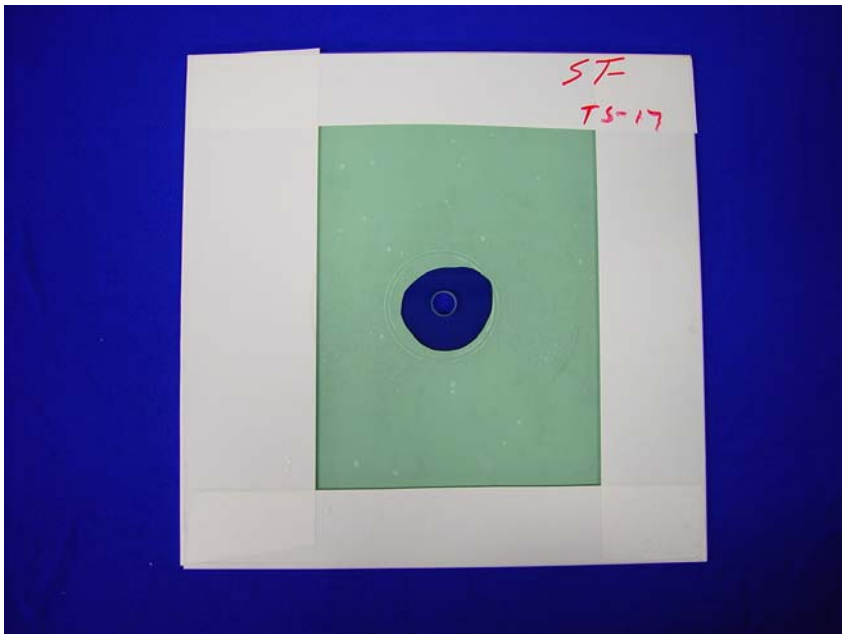


Figure 6 Water Immersion Specimen with Tape Applied to Confine Fragments of Fractured Glass

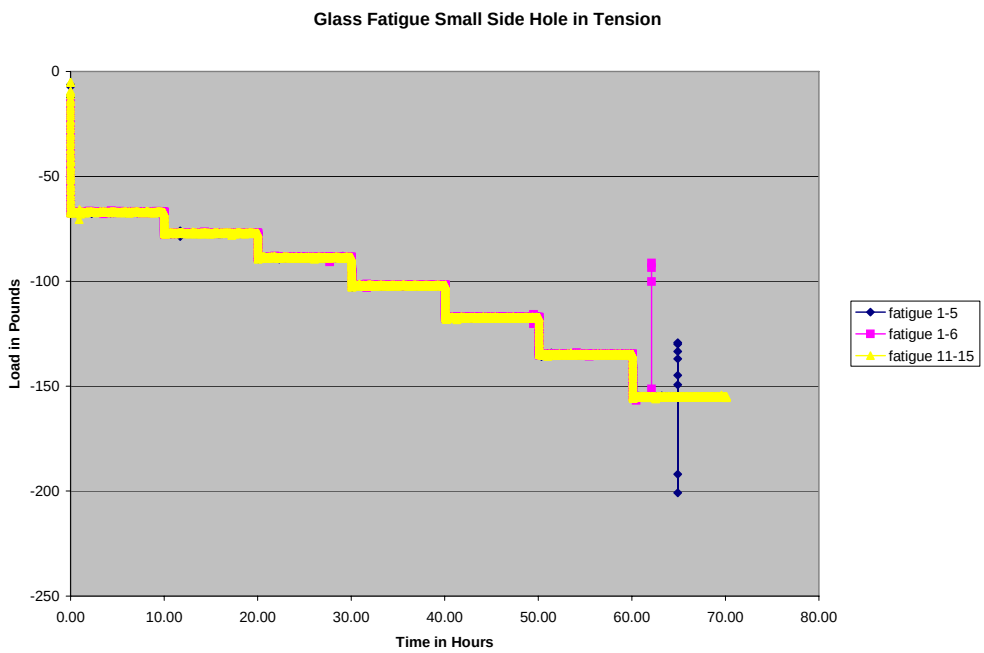


Figure 7 Static Fatigue Test Showing 1) Loading Sequence That Increased Load In Steps-to Maximum Load of 155 lb. and 2) Fracture of 2 of 15 Specimens During Final Load Step at 155 lb.

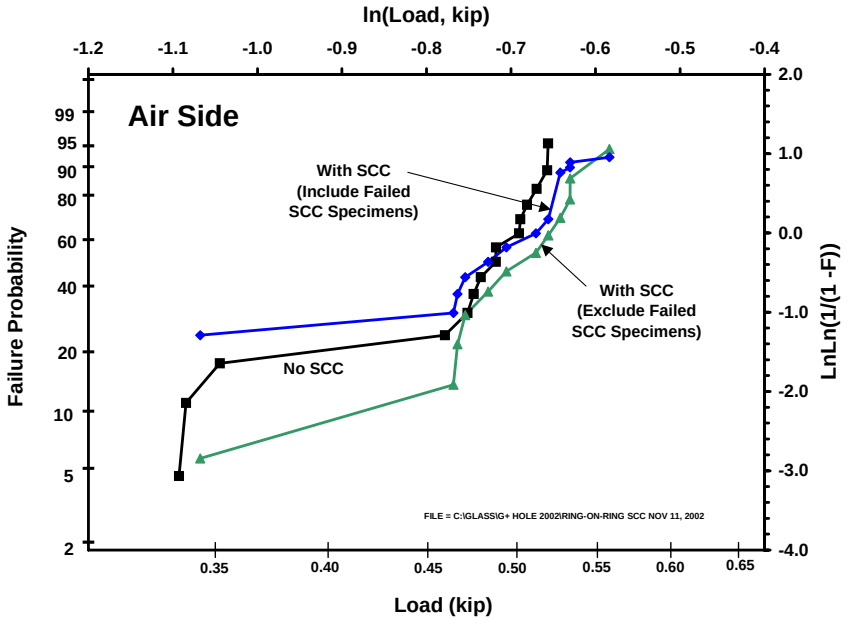


Figure 8 **Short-Term Strengths of Air Side Specimens After SCC Testing for 10 Hours at 155 lb Load (kip = 1,000 lb.)**

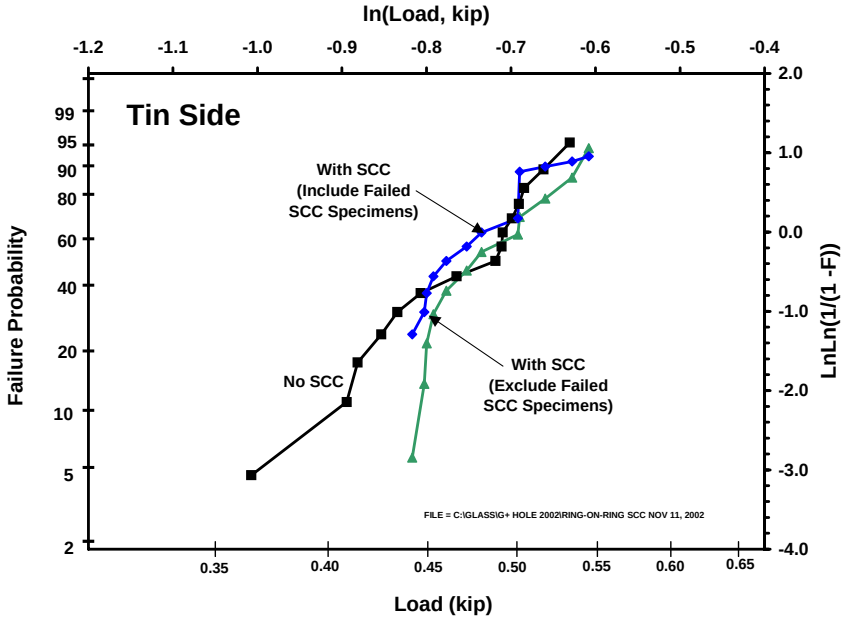


Figure 9 **Short-Term Strengths of Tin Side Specimens After SCC Testing for 10 Hours at 155 lb Load (kip = 1,000 lb.)**

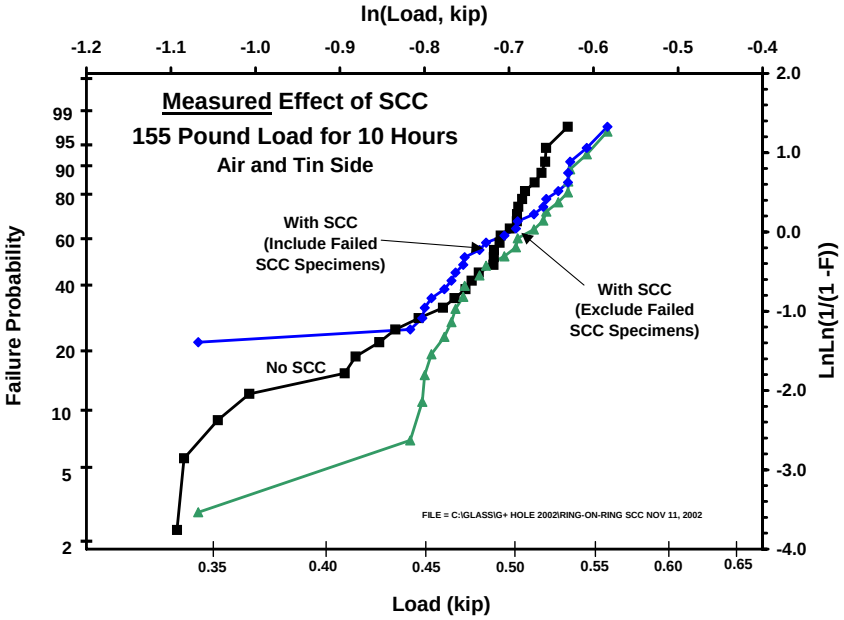


Figure 10 **Short-Term Strengths of Air and Tin Side Specimens After SCC Testing for 10 Hours at 155 lb Load (kip = 1,000 lb.)**

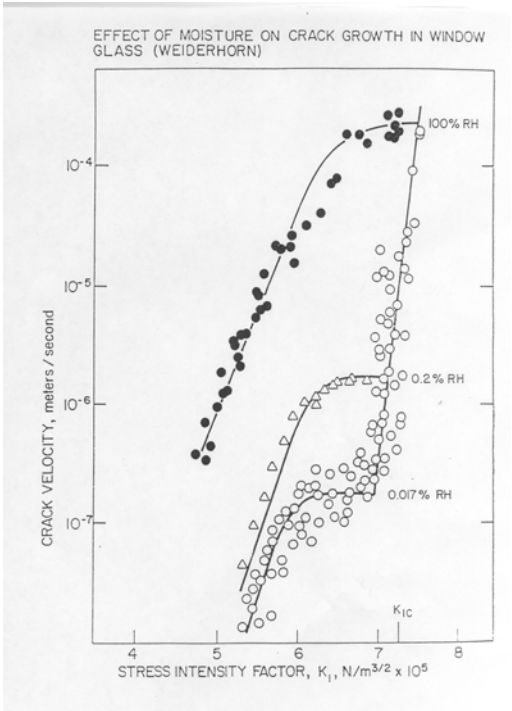


Figure 11 **Growth Rates (100% RH) for Stress Corrosion Cracks in Glass That Were Used in PNNL's Fracture Mechanics Calculations for Water Immersion Tests**

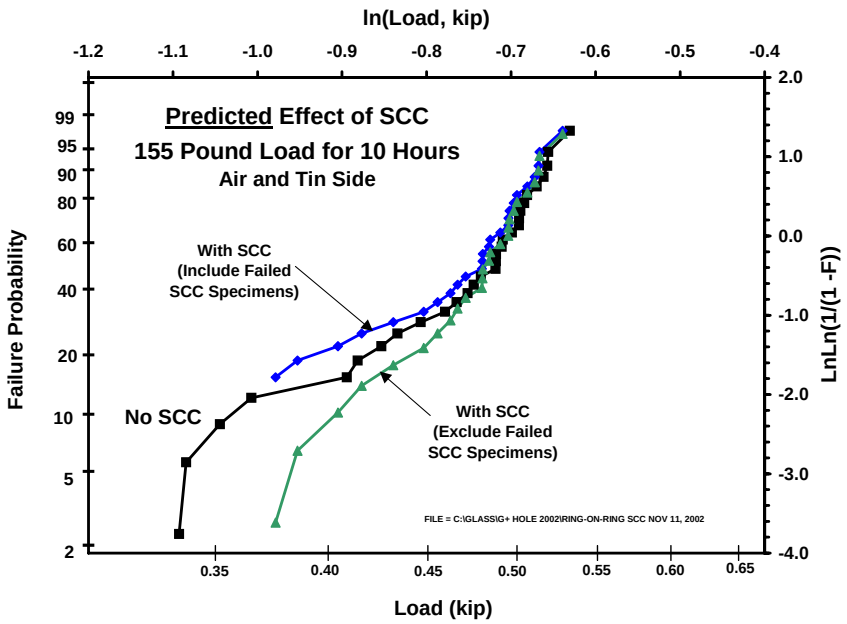


Figure 12 Predicted Short Term Strengths of Baseline Specimens After Crack Growth from SCC Testing for 10 Hours at 155 lb Load (kip = 1,000 lb.)

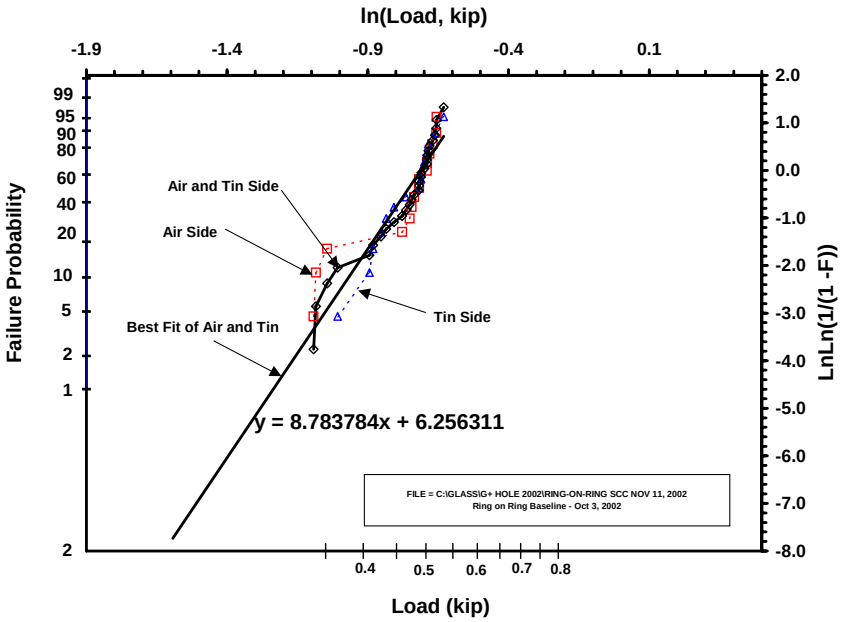


Figure 13 Best Fit of Short-Term Strengths of Baseline Specimens (kip = 1,000 lb.)

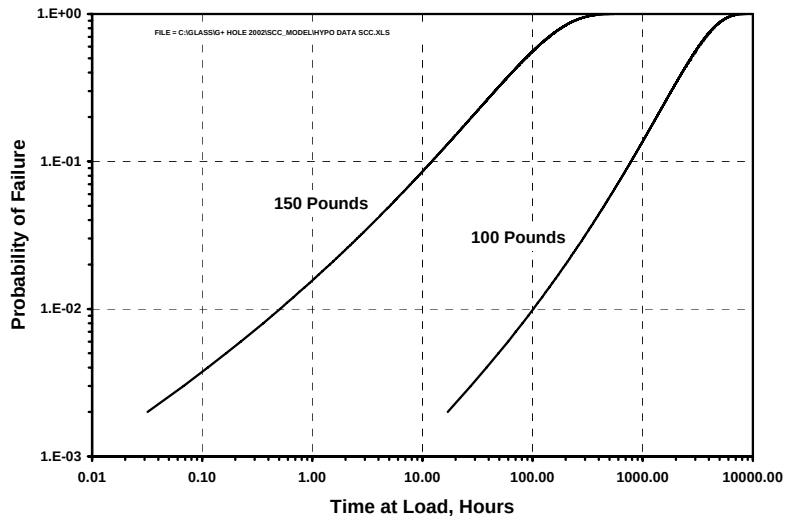


Figure 14 Predicted Time to Failure for "Best Fit" Set of Specimens for SCC at 100 and 155 lb Loadings

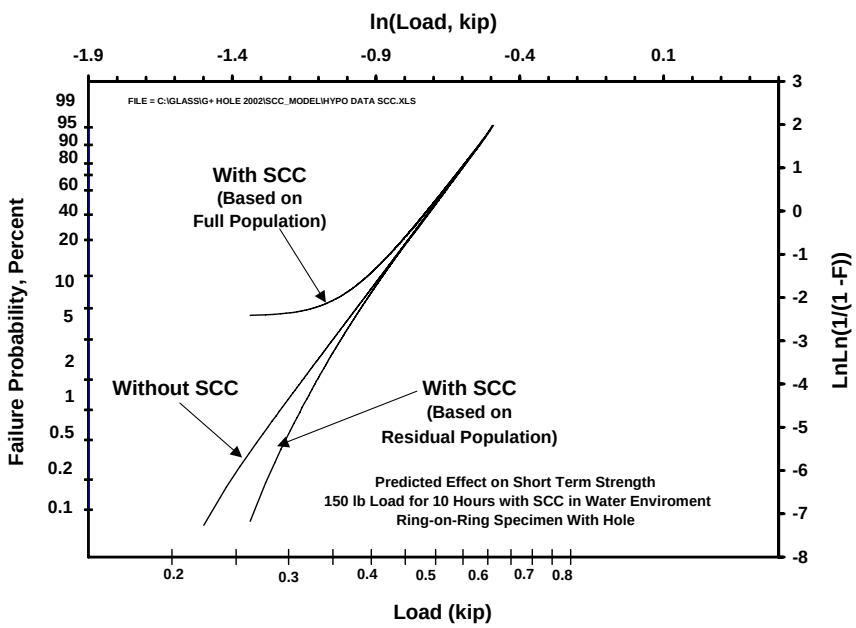


Figure 15 Predicted Effect of SCC on Short Term Residual Strength for "Best Fit" Population of Ring-on-Ring Specimens (kip = 1,000 lb.)

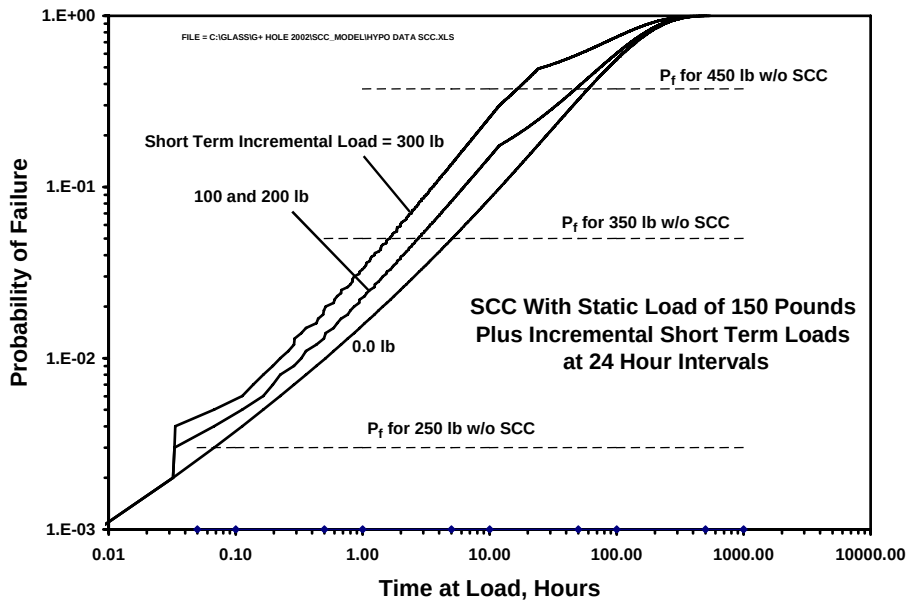


Figure 16 Effect of Short Term Overloads (Applied at 24 Hour Intervals) on Predicted Time to Failure for "Best Fit" Set of Specimens Tested at 155 lb Sustained Loadings

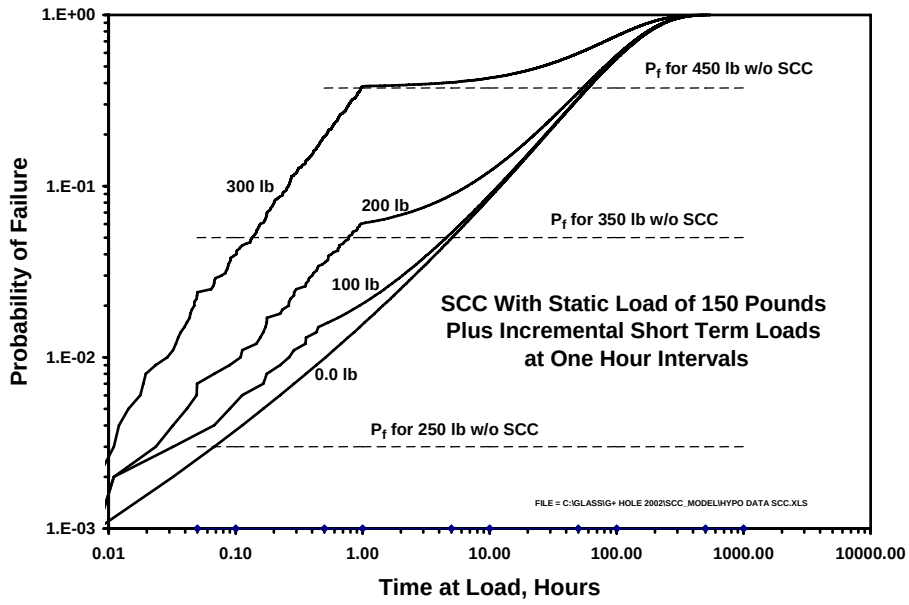


Figure 17 Effect of Short Term Overloads (Applied at One Hour Intervals) on Predicted Time to Failure for "Best Fit" Set of Specimens Tested at 155 lb Sustained Loadings

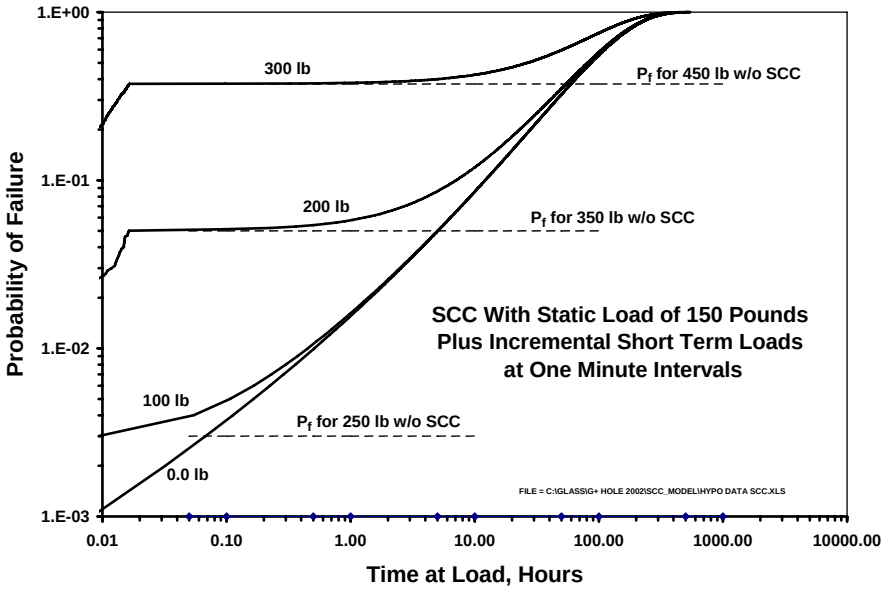


Figure 18 Effect of Short Term Overloads (Applied at One Minute Intervals) on Predicted Time to Failure for "Best Fit" Set of Specimens Tested at 155 lb Sustained Loadings