Strength of Tempered Glass with Holes Including Stress Corrosion Cracking

Prepared by

F.A. Simonen, M.E. Dahl and A.D. Guzman
Pacific Northwest National Laboratory
Richland, Washington 99352

February 2005

Prepared for
Visteon Automotive Systems
Glass Division
Detroit, Michigan

Strength of Tempered Glass with Holes Including Stress Corrosion Cracking

Prepared by

F.A. Simonen, M.E. Dahl and A.D. Guzman
Pacific Northwest National Laboratory

February 2005

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). The project 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, samples without holes, and samples using a range of fabrication procedures to produce the holes. The initial testing focused on high loading rates, whereas the more recent work (Reference 1) provided data from static fatigue tests with a water environment. However, these prior tests were only for non-tempered glass. The work of the present report expands on the testing to address tempered glass, both for short-term loading and for long-term static fatigue loadings.

The long range objective of the past and present studies has been 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 as described in Reference 1 has a probabilistic basis which relates proposed design stresses to selected levels of failure probabilities. Specific activities at PNNL have included:

- Assemble data from the series of 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 specimens, loading rates 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 stresses,
- Develop recommendations for design-stress limits that will ensure low probabilities of failure for glass components with hole penetrations.

Results of the most recent tests for tempered glass 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 a gap that existed from the previous PNNL work.

Test Methods

Ring-on-ring specimens with drilled holes were tested to establish short-term strengths and degrading effects of long-term static stresses on subsequent short-term strengths. The tests measured fracture loads for 12-inch by 12-inch specimens. Loadings were applied in bending by a fixture that used two concentric ring loads at diameters of 2.5 and 6.0 inches. The discussion below describes modified testing procedures and the specimens needed to accomplish the objectives of the study.

Test Method for Short-Term Strengths

Figure 1 shows a specimen placed into loading fixtures and ready for a short-term strength test. The two steel platens have integral machined loading rings with diameters 6.0 and 2.5 inches. Specimens are loaded to failure over a time period of a minute or less. The load time history and maximum load at specimen fracture are recorded. Figure 2 shows a fractured specimen with cracks radiating outward from the machined center hole. One side of the specimen is seen to have a sheet of paper tape that restrained the fragments of fractured glass.

Test Method for Static Fatigue Tests

Figure 3 shows a stack of five specimens ready of static fatigue testing. Loading fixtures apply loads at the diameters of 6.0 and 2.5 inches. The specimens were submerged in a bath of tap water at ambient laboratory temperature.

Loads were applied by the Instron testing machine according to a programmed schedule. Figure 4 shows a typical loading schedule that gradually increased the load in a stepwise manner with each load held for ten hours. Loading steps were selected so that failure at the initial load was highly unlikely, but sufficiently high that failure of some specimens (one specimen of the stack of five) was considered likely after a few steps in loading. Figure 2 shows a fractured specimen with cracks radiating outward from the center hole. The final failure in the case of tempered glass (Figure 5) consisting of large number of glass fragments held together by the adhesive tape applied to one surface.

The following approach was used to perform the static fatigue tests:

1. Visteon fabricated tempered and non-tempered specimens for the tests to be performed at PNNL; the selected configuration matched as closely as possible the non-tempered specimens of previous tests.
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 by measuring short-term breaking loads for both tempered and non-tempered specimens to establish the baseline strengths and the scatter in the measured strengths.
4. The Instron machine was used to perform long-term tests of the tempered specimens 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 into an Instron machine that was controlled such to remove the load after the first specimen fractured.
6. The long-term tests began at low levels of load for which it was clear that no failures would occur. After 10 hours the load was increased and the tests were continued for another 10 hours.
7. Tests were continued with the local stress increased in steps until one specimen from the stack of five failed in static fatigue.

8. The remaining unfailed specimens from the 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 about 1,100 pounds.
9. The remaining unfailed specimens were broken in short-term loading to determine if there was a change in the statistical distribution of short term strengths.

Selection of Loading Sequence

The selection of load levels and test durations were based on pretest analyses for non-tempered specimens and described in Reference 1. This approach was based in part on information on static fatigue of non-tempered glass presented during lectures by Suresh Gulati at PNNL August 27-28, 1998.

The Gulati data on static fatigue and crack growth by stress corrosion cracking indicated (data for non-tempered glass from strength tests governed by surface flaws) that failure stresses at 10 hours are about 70% of the short-term failure stresses. On the other hand a very long-term test (measured in years) would have failure stresses of about 33% of the short-term tests. These ratios may be different for edge strengths (relevant to the current specimens with holes) than for surface strengths as addressed by Gulati. Therefore the proposed testing allowed for some uncertainty in the glass fracture behavior. The incremental loading tests started at loads for which there is no expectation of failures from edge flaws. The Gulati information indicated that crack growth by stress corrosion cracking is governed by da/dt = Constant × K^{16} = A × $(\text{Stress})^{16}$. For tempered glass the stress includes both the local residual stress from the tempering process and the stress produced by the applied load. The test 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, each step should increase the stress by a factor of $(10^{1/16})$ = 1.15 compared to the load from the previous test period.

The strategy was to establish a load level such that a small fraction of the specimens (one of five) would fail in 10 hours by static fatigue and then to assume that the other specimens exposed to the same load for 10 hours would experience sufficient damage (growth of fabrication flaws) that short-term static strengths could be degraded compared to the strength of specimens not exposed to static fatigue. In the case of non-tempered specimens, preliminary tests quickly established the desired load to be about 155 pounds, and subsequent tests were performed on this basis. For the tempered specimens, even after considerable experimentation, it was not possible to establish a “desired load” with any precision, although it was estimated to be between 1,000 and 1,100 pounds.

The average short-term breaking load (air and tin side) of the tempered specimens was 1,335 pounds. Past static fatigue tests of non-tempered specimens showed ten-hour static fatigue strengths that were about 300 pounds less than the corresponding short-term strengths. Accordingly, the expected ten-hour static fatigue strength for tempered specimens was calculated to be 1,335 – 300 = 1035 pounds, which is consistent with the empirically established load of 1,000 to 1,100 pounds.

A much more extensive series of tests, beyond the budget of the present project, would have been required to establish a more precise “desired load”. The failure loads for the tempered specimens, although much greater than the failure loads for the non-tempered specimens, exhibited much more scatter. It was difficult with a limited number of tests to establish the “one-of-five” failure load for the static fatigue tests. For the tempered specimens the scatter in failure loads is due not only to the random sizes of the flaws at the edge of the drilled hole, but also on the variability of the tempering residual stress at the location of the largest flaw.

Requested Test Specimens

For the study of tempered glass, Visteon was requested to use the same selected hole configuration (drilling/chamfer preparation process) as for the previous static fatigue tests of non-tempered glass. Visteon then fabricated a batch of specimens (12 inch by 12 inch) of this configuration. Some specimens were of non-tempered glass, whereas most were of tempered glass. Tests of the non-tempered glass were to establish any batch-to-batch differences between the supposedly identical specimens.

Difficulties for Static Fatigue Tests

Complications appeared as the static fatigue tests were performed. Modifications during the testing program eventually established a satisfactory set of loading fixtures. Therefore early test data, although provided in the present report, are of questionable value. Final conclusions are based on the later tests that used the final configuration of fixtures.

Loads needed to fail the tempered glass in static fatigue were about seven times greater than the corresponding loads for the non-tempered glass. These higher loads significantly increased the bending deflections in the tempered specimens compared to the defections for non-tempered specimens that failed at much lower loads. The data as reported below correspond to loading fixtures of Type 1, Type 2 and Type 3 as follows:

Type 1 Fixtures - These fixtures were the same fixtures as for the prior PNNL testing of non-tempered glass and used the five specimen stack configuration. The upper and lower surfaces of the stacks were loaded by the same steel platens as used for the short-term strength tests. O-rings of 2.5 and 6.0 diameters were placed between the plates of glass in a manner to nominally apply the same state of stress to all specimens. For the higher loads applied to the tempered specimens it was soon noted that the top specimen of the stack was always the first specimen to fail in static fatigue. This indicated that the top specimens were subjected to higher than average stresses. Stress calculations were performed to establish the sensitivity of the applied stresses to the flattening of the O-rings and to the rotation of the contact point of the glass with the steel platens as the plate specimens deflected under load. The calculations showed that the loading diameter could shift sufficiently to increase the stress in the top specimen by a few percent, which could increase the probability of failure for the top specimen sufficiently such that failure of the top most specimens would usually fail first.

Type 2 Fixtures - This configuration replaced the machined steel contact surfaces of the top and bottom platens with platens having flat surfaces. O-rings identical to those used between the glass plates were placed at the top and bottom platens. Failures no longer occurred only at the top most specimens. A second concern then became evident. Contact at the outer edges of the defecting glass plates was observed at the high load levels, such that the applied stresses were no longer ensured to be proportional to the applied load.

Type 3 Fixtures - These fixtures prevented glass-to-glass contact by placing aluminum spacer plates between adjacent glass plates. Two thicknesses of O-rings then separated the glass plates and the deflections of the glass specimens were then far below the levels needed to cause contact at the outer edges of the glass specimens. The final set of static tests used the improved loading fixtures.

Results of Tests

The discussion below summarizes results from both the current the tests of tempered glass and the prior tests of non-tempered glass. Data were from standard strength tests for short-term loading of unfatigued specimens and from specimens that were subjected to long static fatigue for submersion in room temperature water.

Short Term Strength Tests

The initial tests of the present project were of unfatigued specimens to measure short-term breaking loads. Specimens were loaded in bending in PNNL's ring-on-ring tests fixtures. There were 15 tests of non-tempered glass from the 2003 batch of specimens, and 30 tests of tempered specimens, with 15 specimens stressed in tension on the tin-side and 15 stressed on the air-side. Tables 1 and 2 present the results of these tests.

Results of prior tests for non-tempered specimens that were performed by PNNL during 2002 using nominally identical specimens are listed in Table 3. The first 30 entries of Table 3 list the 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.

Average strengths for tempered specimens are listed in Table 1 on the basis of whether the tin or air side of the glass was stressed in tension and whether the tension side had the "small" or "large" diameter of the drilled hole. In this regard, it is noted that the holes were drilled from both surfaces of the plate, but with slightly different hole diameters that met at the mid section of the plates. Except for the very small differences in diameters, the holes appeared to be identical. The results as listed in Table 1 showed very little effect of hole diameter on breaking strength as indicated by the average failure loads as listed in Table 4. In contrast the specimens stressed on the tin-side had about 10 percent higher strengths than specimens stressed on the air-side. PNNL can propose no explanations for the differences in the measured air-side versus tin-side strengths.

Table 5 summarizes the results of the various tests. The following trends are noted:

1. The unfatigued tempered specimens had about 3.5 times the short-term strengths of the non-tempered specimens.
2. The variability in the strengths of the tempered specimens (difference between maximum and minimum strengths) was about 2 times the variability for the non-tempered specimens, due possibly to specimen-to-specimen differences in residual stresses from the tempering process.
3. The current batch of non-tempered specimens was about 15 percent weaker than the prior batch of specimens that were tested during 2002.

The short-term failure data for unfatigued specimens are plotted in Figures 6 through 10 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. Data were separated by air-side and tin-side and also with air and tin-side data combined (Figure 8). The data depart somewhat from the straight line that defines an ideal Weibull distribution. There are some differences in the plots for the air-side versus tin-side tests. These differences are in part to be due to the random scatter in the measured strengths and may not be a conclusive indication that air-side or tin-side strengths are inherently superior. Data from the 2002 specimens show air and tin-side strengths that are nearly identical, whereas the 2003 specimens

(Table 4 and Figure 6) show tin-side strengths that are about 10 percent greater than the corresponding air-side strengths.

Figure 7 present Weibull plots that show lower strengths for the non-tempered specimens that were tested by PNNL in 2003 along with the higher strengths of the specimens tested in 2002. Figures 8 and 9 individually address the 2003 and 2002 specimens and indicate the differences between tin and air side strengths.

Figure 10 shows the clearly higher measured strengths of the tempered glass compared to the non-tempered glass. The tempered glass has about 3.5 times the short-term strength of the non-tempered glass. Both sets of data show nearly linear trends, which indicates that the Weibull statistical distribution provides a good characterization of the scatter in the measured strengths.

Fatigue/SCC Tests in Water

Specimens of the 2003 specimens were tested under sustained load using water immersion to induce stress corrosion crack growth (SCC) of the naturally occurring flaws located at the edges of the drilled holes. The Instron testing machine was programmed to increase the load incrementally and to hold the loads for 10 hours at each load level. The load was increased until one of the five specimens fractured during a ten-hour hold period. The Instron machine was programmed to immediately remove the load if one of the five specimens fractured.

The 2002 SCC tests for non-tempered glass were performed for a total of 30 specimens as listed in Table 3. All of the unfailed specimens of this series were subjected to 10 hours at 155 pounds or until the specimen fractured.

The 2003 tests for tempered glass were again performed in submerged water with a 10 hour time period at each load step. Tables 6 through 10 give results for tests that stressed the air-side of the specimens. Tables 11 through 15 give the corresponding results for tests that stressed the tin-side of the specimens. As discussed above, the loading fixtures for the static fatigue tests were perfected during the testing program. Ideally the static fatigue tests would have been performed only with the final (Type 3) loading fixture design. The most definitive data are therefore those from the Type 3 tests. Data from the combined Type 2 and 3 tests are also plotted, because this data set gives a larger statistical sample for purposes of identifying trends. Key attributes of the individual fatigue tests are listed in Tables 6 through 15 as:

- the stressed surface of the specimen (air or tin-side)
- the type of loading fixture (Type 1, 2 or 3)
- whether the specimen fractured during fatigue testing or survived
- the maximum load level that each specimen survived for 10 hours; in some cases if the specimen failed at a given load, this load value was assigned if the specimen survived more than 5 hours
- the load that failed the specimen during the static fatigue tests, given that the specimen did not survive the full sequence of loads
- for those specimens that survived the fatigue loads, the short-term load required to break the specimen
- the final column of the tables list the sequence of loads for each specimen; some loads have a time duration listed along with the load level; otherwise it can be assumed that the load duration was the scheduled 10 hour time period

Figures 11 through 14 present Weibull plots for the short-term failure loads for the static fatigue specimens. The objective of the plots was to show if exposure of the specimens to SCC (static fatigue)

reduced the subsequent short-term strengths of the specimens. Table 16 illustrates example statistical calculations for a set of data to establish Weibull parameters. Figure 12 addresses only data from tempered specimens and uses an expanded scale to more clearly separate the three individual curves for the tempered glass.

Figure 11 shows significantly higher short-term failure loads for tempered specimens relative to the failure loads for non-tempered specimens. Differences between the two sets of curves are consistent with the measured residual stress levels (on the order of 25,000 psi) as described in Appendix A.

Given the large scatter in the strength data, it is difficult to observe any reductions in short-term strengths of the SCC specimens relative to the set of baseline data from specimens not subjected to static fatigue. Depending on how the data were evaluated, the exposure to SCC can be interpreted to either increase or decrease the strength of the SCC specimens. One statistical evaluation excluded the specimens that had failed during the fatigue tests. This evaluation showed that the unfailed SCC specimens had somewhat higher strengths than the non-fatigued baseline specimens. Evidently the SCC tests eliminated the weakest specimens (those with large flaws at the edges of the drilled holes). The remaining unfailed SCC specimens were those that apparently had relatively small flaws which would have experienced essentially no SCC flaw growth. The second statistical evaluation considered all specimens. This included even those specimens that failed by SCC, which were treated as specimens that failed at zero load for evaluation of the short-term strength tests. Based on this evaluation the failure probabilities tend to be higher than for the baseline (no SCC) tests. Again it should be noted that the number of tested specimens was a relatively small and was perhaps inadequate for purposes of observing small effects of SCC on specimen strengths.

The test results should not be taken to imply that exposure to SCC can increase the subsequent short-term strength of an individual specimen. In this regard it is impossible for an individual specimen to perform a short-term fracture test both before and after exposure to SCC, as would be required to show the degrading effects of SCC on the specimen. The test data can only address the effect of SCC exposure based on the statisrical strengths of a population of exposed specimens, and the experimental results as presented above are seen to be inconclusive. Calculations were therefore performed using the crack growth model and crack growth rate curves of Figure 15 (from Reference 1) to predict the possible effects of SCC on short-strengths for the a set of 30 non-tempered specimens as listed in Table 3.

Short-term strengths of the unexposed specimens were used to estimate the size (depth) of the governing or largest flaw in each of 30 specimens as listed in Table 3. It was then assumed that each these specimens was subjected to a 155 pound load and calculations were performed to predict the increase in crack depth as a function of time. Figure shows 30 curves that begin at the initial crack depth (at time = 0.0) and then increase the crack depth as a function of time until the crack depth attains the depth needed for a sudden fracture governed by the fracture toughness of the glass. These critical crack depths occurred a times ranging from about 1 hour to 160 hours.

The SCC tests show substantial differences in the 10 hour breaking loads under SCC for the tempered versus non-tempered specimens. These loads are approximately 155 and 1,074 pounds respectively, or about a seven times increase in static fatigue strength as a result of tempering.

Figure 13 (air-side) and Figure 14 (tin-side) were prepared to show the possible effects of the different loading fixtures that were used for the static fatigue tests. One curve was plotted using only data from the final and most refined test method (Type 3). Another curve used data from both the Type 2 and 3 tests to obtain a larger and more statistically significant set of data. Type 3 specimens prevented contact at high loads along the edges of the glass specimens. The Type 3 specimens can therefore have higher stresses for the SCC loading and would be more likely to fail during the SCC tests. The surviving specimens would be expected to fail at higher loads in the subsequent short-term tests. Figure 13 shows the opposite of this expected trend. Figure 14 shows little difference between curves for the Type 3 tests versus the Type 2&3 tests. Evidently possible differences between the two sets of data are obscured by 1) little or

no contact actually occurred during the Type 2 tests, 2) scatter in the data and 3) the fact that the various SCC tests did not subject all specimens to the same sequence of loads and exposure times.

Predicted Reductions of Short-Term Breaking Loads

The test results do not imply that exposure to SCC increases subsequent short-term strengths of individual specimens, although average strengths of the surviving specimens may increase after exposure to SCC. It is inherently impossible to perform short-term fracture tests both before and after exposure to SCC for individual specimens, and thereby measure the degrading effects of SCC on specimens. The test data only address the effect of SCC exposure based on the statistical strengths of a population of exposed specimens. Calculations were therefore performed using the crack growth model and crack growth rate curves of Figure 15 (from Reference 1) to predict the possible effects of SCC on short-strengths for a set of 30 non-tempered specimens as listed in Table 3.

Short-term strengths of the unexposed specimens were used to estimate the initial size (depth) of the governing or largest flaw in each of 30 specimens as listed in Table 3. It was then assumed that each these specimens was subjected to a 155 pound load and calculations were performed to predict the increase in crack depth as a function of time. Figure 16 shows 30 curves that begin at the initial crack depths (at time = 0.0) and then increase the crack depths as a function of time until the crack depths attain the depth needed for a sudden fracture governed by the fracture toughness of the glass. These critical crack depths occurred a times ranging from about 1 hour to 160 hours.

From the results for crack depths versus time, it was possible to calculate the short-term breaking loads for each crack depth. Figure 17 show how SCC decreases the strengths of individual specimens. However, as time increases fewer unbroken specimens remain from the original population of specimens. Results from the calculations of Figure 17 were evaluated for an exposure time of 26 hours giving the following results:

	Before SCC Testing	After 26 Hours of SCC
Number of Unbroken Specimens	30	23
Average Short-Term Strength, lb	464	467
Standard Deviation in Strength, lb	56	37

Predicted results for the 30 specimens can also be compared with experimental results from Table 3 as follows:

	Before SCC Testing		After SCC Exposure	
	Calculations	Experiments	Calculations for 26 Hours	Experiments for 10 hours
Number of Unbroken Specimens	30	30	23	24
Average Short-Term Strength, lb	464	464	467	487
Standard Deviation in Strength, lb	56	56	37	46

In each case the time under the SCC loading is such that about 20 percent of the specimens fracture during the SCC test. Both the calculated and experimental results show a small increase in the average short-term breaking strength for the population of surviving SCC specimens along with a decrease in the standard deviation of the short-term strengths.

Summary and Conclusions

Tests were performed to establish the strength of tempered glass for which the strengths had been degraded by the presence of a drilled hole. The drilled hole introduced a stress concentration that elevated the local stress at the edge of the hole, and also introduced a distribution of small flaws around the edge of the hole. Results of the study showed that:

1. short-term strength tests for the tempered glass specimens were compared with strengths for non-tempered specimens and these tests showed that the tempered specimens had substantially greater short-term strengths (by a factor of about 3.5) than the non-tempered specimens; increases in strengths were consistent with measured levels of residual stresses in the tempered glass.
2. the effects of sustained loads (SCC or static fatigue) for tempered glass were similar to effects as observed previously for non-tempered glass.
3. the SCC tests show that the 10 hour breaking loads under SCC for the tempered versus non-tempered specimens increase by a factor of about seven as a result of tempering.
4. testing for SCC of tempered glass presented a number of experimental difficulties, due in part to the much greater loads needed to fail the tempered glass; measurements of failure loads also showed greater data scatter and the trends in the data were therefore somewhat more difficult to identify.
5. both the tempered and non-tempered glass specimens were exposed in water environments to high sustained levels of static stress that were sufficient to cause some of the specimens to fracture; as with non-tempered specimens, short-term tests of tempered specimens exposed to SCC (but non-fractured specimens) showed no clear decrease in the subsequent short-term breaking strengths; rather, the exposed but unbroken fatigue specimens appeared to have slightly higher strengths than specimens tested without exposure to static fatigue; evidently static fatigue serves as a proof test to screen out the weaker specimens that had larger fabrication flaws.
6. calculations using a crack growth model were performed and it was predicted that the short-term strengths of individual specimens should decrease as a result of SCC exposure; however, consistent with the experimental results, the calculations predicted that the average strengths of a surviving population of specimens should experience little change.

The method for the design of automotive glazing as proposed in Reference 1 for non-tempered glass should apply also to tempered glass. This method independently sets limits for sustained stresses and for short-term stresses, and assumes that interactions between the two failure mechanisms are small and can be neglected.

References

1. Simonen, F.A. and M.E. Dahl, *Strength of Glass with Holes Including* Stress Corrosion Cracking, prepared by Pacific Northwest National Laboratory, Richland, Washington 99352, for Visteon Automotive Systems Glass Division, January 2003.

Table 1 Data from Ring-on-Ring Tests (performed in 2003) of Tempered Square Specimens with Center Holes for Short-Term Strength

Sample Number	Sample Side (Tin/Air)	Load Type	Ultimate Load (lb)	Date
TB-T4	Small hole and Air-side in tension	Compression @ .1"/min	1284.2	11/24/2003
TB-T7	Small hole and Air-side in tension	Compression @ .1"/min	1183.4	11/24/2003
TB-T9	Small hole and Air-side in tension	Compression @ .1"/min	1331.8	11/24/2003
TB-T15	Small hole and Air-side in tension	Compression @ .1"/min	1317.3	11/24/2003
TB-T16	Small hole and Air-side in tension	Compression @ .1"/min	1389.4	11/24/2003
TB-T18	Small hole and Air-side in tension	Compression @ .1"/min	1388.5	11/24/2003
TB-T21	Small hole and Air-side in tension	Compression @ .1"/min	1171.4	11/24/2003
TB-T22	Small hole and Air-ide in tension	Compression @ .1"/min	1178.3	11/24/2003
TB-T24	Big hole and Tin-side in tension	Compression @ .1"/min	1462.2	11/24/2003
TB-T25	Big hole and Tin-side in tension	Compression @ .1"/min	1537.9	11/24/2003
TB-T26	Big hole and Tin-side in tension	Compression @ .1"/min	1384.5	11/24/2003
TB-T27	Big hole and Tin-side in tension	Compression @ .1"/min	1401.1	11/24/2003
TB-T30	Big hole and Tin-side in tension	Compression @ .1"/min	1311.4	11/24/2003
TB-T31	Big hole and Tin-side in tension	Compression @ .1"/min	1393.9	11/24/2003
TB-T32	Big hole and Tin-side in tension	Compression @ .1"/min	1441	11/24/2003
TB-A5	Small hole and Tin-side in tension	Compression @ .1"/min	1325	11/24/2003
TB-A6	Small hole and Tin-side in tension	Compression @ .1"/min	1543.5	11/24/2003
TB-A8	Small hole and Tin-side in tension	Compression @ .1"/min	1496	11/24/2003
TB-A10	Small hole and Tin-side in tension	Compression @ .1"/min	1473.4	11/24/2003
TB-A11	Small hole and Tin-side in tension	Compression @ .1"/min	1375.1	11/24/2003
TB-A12	Small hole and Tin-side in tension	Compression @ .1"/min	1243.6	11/24/2003
TB-A13	Small hole and Tin-side in tension	Compression @ .1"/min	1152	11/24/2003
TB-A14	Small hole and Tin-side in tension	Compression @ .1"/min	1452	11/24/2003
TB-A17	Big hole and Air-side in tension	Compression @ .1"/min	1251.9	11/26/2003
TB-A19	Big hole and Air-side in tension	Compression @ .1"/min	1282	11/26/2003
TB-A23	Big hole and Air-side in tension	Compression @ .1"/min	1256.7	11/26/2003
TB-A28	Big hole and Air-side in tension	Compression @ .1"/min	1252.2	11/26/2003
TB-A29	Big hole and Air-side in tension	Compression @ .1"/min	1241.6	11/26/2003
TB-A33	Big hole and Air-side in tension	Compression @ .1"/min	1069.5	11/26/2003
TB-A20	Big hole and Air-side in tension	Compression @ .1"/min	1458.1	11/26/2003

Table 2 Data from Ring-on-Ring Tests (performed in 2003) of Non-Tempered Square Specimens with Center Holes for Short-Term Strength

Sample Number	Sample Side (Tin/Air) in Tension	Load Type	Ultimate Load (lb)	Date
NTB-T2	Small hole and Air-side in tension	Compression @ .1"/min	399	11/24/2003
NTB-T4	Small hole and Air-side in tension	Compression @ .1"/min	308.5	11/24/2003
NTB-T7	Small hole and Air-side in tension	Compression @ .1"/min	354.8	11/24/2003
NTB-T9	Small hole and Air-side in tension	Compression @ .1"/min	325.4	11/24/2003
NTB-T10	Small hole and Air-side in tension	Compression @ .1"/min	391.4	11/24/2003
NTB-T11	Small hole and Air-side in tension	Compression @ .1"/min	364.9	11/24/2003
NTB-T12	Small hole and Air-side in tension	Compression @ .1"/min	344.4	11/24/2003
NTB-T14	Small hole and Air-side in tension	Compression @ .1"/min	293.9	11/24/2003
NTB-A5	Small hole and Tin-side in tension	Compression @ .1"/min	344.8	11/24/2003
NTB-A6	Small hole and Tin-side in tension	Compression @ .1"/min	466.7	11/24/2003
NTB-A8	Small hole and Tin-side in tension	Compression @ .1"/min	432.6	11/24/2003
NTB-A13	Small hole and Tin-side in tension	Compression @ .1"/min	435.2	11/24/2003
NTB-A19	Small hole and Tin-side in tension	Compression @ .1"/min	446.2	11/24/2003
NTB-A22	Small hole and Tin-side in tension	Compression @ .1"/min	326.2	11/24/2003
NTB-A3	Big hole and Air-side in tension	Compression @ .1"/min	270.8	11/24/2003
NTB-A23	Big hole and Air-side in tension	Compression @ .1"/min	393.7	11/24/2003
NTB-A24	Big hole and Air-side in tension	Compression @ .1"/min	355.8	11/24/2003
NTB-A27	Big hole and Air-side in tension	Compression @ .1"/min	407.1	11/24/2003
NTB-A29	Big hole and Air-ide in tension	Compression @ .1"/min	425.1	11/24/2003
NTB-A30	Big hole and Air-side in tension	Compression @ .1"/min	388.6	11/24/2003
NTB-T15	Big hole and Tin-side in tension	Compression @ .1"/min	430.2	11/24/2003
NTB-T16	Big hole and Tin-side in tension	Compression @ .1"/min	471.3	11/24/2003
NTB-T17	Big hole and Tin-side in tension	Compression @ .1"/min	424.2	11/24/2003
NTB-T18	Big hole and Tin-side in tension	Compression @ .1"/min	450.3	11/24/2003
NTB-T20	Big hole and Tin-side in tension	Compression @ .1"/min	431	11/24/2003
NTB-T21	Big hole and Tin-side in tension	Compression @ .1"/min	386.6	11/24/2003
NTB-T25	Big hole and Tin-side in tension	Compression @ .1"/min	416.9	11/24/2003
NTB-T26	Big hole and Tin-side in tension	Compression @ .1"/min	349	11/24/2003
NTB-T28	Big hole and Tin-ide in tension	Compression @ .1"/min	391.8	11/24/2003

Table 3 Data from Ring-on-Ring Tests (performed in 2002) 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 4 **Comparison Short Term Strengths of Tempered Specimens - Effects of 1) Tin-Side Versus Air-Side and 2) Big Versus Small Hole Side of Specimen**

	Air-Side	**Tin-Side**
Big Hole	1,258 lb.	1,418 lb.
Small Hole	1,280 lb.	1,382 lb.

Table 5 **Comparison Short-Term Strengths 1) Tempered Versus Non-Tempered Specimens and 2) Current Specimens Versus Past Specimens (Revised 2/17/04)**

		Breaking Load, lb.			
		Mean Load	**Maximum Load**	**Minimum Load**	**Min - Max**
2002 Tests Non-Tempered Specimens	All 30 Specimens (Tin and Air)	463	532	335	197
	15 Tin-Side Specimens	465	532	365	167
	15 Air-Side Specimens	462	518	335	183
2003 Tests Non-Tempered Specimens	All 29 Specimens (Tin and Air)	387	471	271	200
	15 Tin-Side Specimens	414	471	326	145
	15 Air-Side Specimens	359	425	271	154
2003 Tests Tempered Specimens	All 30 Specimens (Tin and Air)	1335	1543	1069	474
	15 Tin-Side Specimens	1399	1543	1152	391
	15 Air-Side Specimens	1270	1458	1069	389

Table 6 Results of 2003 Water Emersion Fatigue Tests - Air-Side Data - Loading Fixture Types 1, 2 and 3

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-A49	Tempered	Big	Air	1	No	12/11/2003	1115		1216		1040,1055,1070,1085,1100,1115/5.6hr
TB-A50	Tempered	Big	Air	2	No	12/18/2003	1010		1224		995/8.54hr,980,995,1010,1025/95min
TB-T65	Tempered	Small	Air	2	No	01/22/2004	1115		1229		1040,1055,1070,1085,1100,1115
TB-A43	Tempered	Big	Air	1	No	12/11/2003	1115		1231		1040,1055,1070,1085,1100,1115/5.6hr
TB-A77	Tempered	Big	Air	3	No	04/05/2004	1070		1248		1010,1025,1040,1055,1070,1085/1hr, 1010,1025,1040,1055/3hr
TB-T85	Tempered	Small	Air	3	No	04/05/2004	1070		1255		1115/2.5hr,1085/4min,1055/2min,1055/7.2hr,10 10,1025,1040, 1055,1070,1085/1hr
TB-A48	Tempered	Big	Air	1	No	12/11/2003	1115		1256		1040,1055,1070,1085,1100,1115/5.6hr
TB-T67	Tempered	Small	Air	2	No	01/22/2004	1115		1266		1010,1025,1040,1055,1070,1085, 1100,1115
TB-T66	Tempered	Small	Air	2	No	01/16/2004	1115		1287		1040,1055,1070,1085,1100,1115
TB-T59	Tempered	Small	Air	2	No	01/16/2004	1115		1291		1040,1055,1070,1085,1100,1115
TB-T68	Tempered	Small	Air	2	No	02/04/2004	1130		1296		1025/3min,1025,1040,1055,1070,1085, 1100,1115,1130
TB-T35	Tempered	Small	Air	1	No	12/03/2003	1065		1298		940,955,970,985,1005,1025,1045, 1065,1090/9min
TB-A41	Tempered	Big	Air	2	No	12/10/2003	1025		1307		980,995,1010,1025,1015/12min,995, 1010,1025/9.5min
TB-T83	Tempered	Small	Air	3	No	04/05/2004	1070		1322		1115/2.4hr,1085/4min,1085/2min,1055/7.2hr,10 10,1025, 1040,1055,1070,1085/1hr
TB-T80	Tempered	Small	Air	2	No	02/12/2004	1130		1342		1025,1040,1055,1070,1085,1100, 1115,1130
TB-T70	Tempered	Small	Air	2	No	02/12/2004	1030		1369		1025,1040,1055,1070,1085,1100, 1115,1130
TB-T58	Tempered	Small	Air	2	No	01/16/2004	1115		1385		1040,1055,1070,1085,1100,1115
TB-A36	Tempered	Small	Air	1	No	12/03/2003	1065		1399		940,955,970,985,1005,1025,1045, 1065,1090/9min
TB-T79	Tempered	Small	Air	2	No	02/12/2004	1130		1416		1025,1040,1055,1070,1085,1100,1115,1130
TB-T84	Tempered	Small	Air	3	No	04/05/2004	1070		1457		1070,1115/2.5hr,1085/4min,1085/2min,1055/7.2 hr,1010,1025, 1040,1055,1070,1085/1hr
TB-A42	Tempered	Big	Air	1	Yes	12/10/2003	995	995		Broke 8.54hr @ 995 lb	1015/12min,995/8.54hr
TB-A51	Tempered	Big	Air	2	Yes	12/18/2003	1010	1025		Broke 95min @ 1025 lb	980,995,1010,1025/95min
TB-A76	Tempered	Big	Air	3	Yes	03/31/2004	1055	1055		Broke 7.2 hr @ 1055 lb	995,1010,1025,1040,1055/7.2hr
TB-A78	Tempered	Big	Air	3	Yes	04/09/2004	1055	1055		Broke 3.16 hr @ 1055 lb	1040,1055/3.16hr
TB-T69	Tempered	Small	Air	2	Yes	02/03/2004	1010	1025		Broke 3 min @ 1025 lb	1025/3min
TB-T82	Tempered	Small	Air	3	Yes	03/19/2004	1100	1115		Broke 2.5 hr @ 1115 lb	1085,1100,1115/2.5hr
TB-T86	Tempered	Small	Air	3	Yes	03/23/2004	1070	1085		Broke 4.5 min @ 1085 lb	1115/2.5hr,1085/4min,1085/2min, 1085/4.5min
TB-T87	Tempered	Small	Air	3	Yes	03/22/2004	1070	1085		Broke 4 min @ 1085 lb	1085/4min
TB-T88	Tempered	Small	Air	3	Yes	03/23/2004	1070	1085		Broke 2 min @ 1085 lb	1085/2min
TB-T89	Tempered	Small	Air	3	Yes	03/26/2004	1070	1085		Broke during initial loading <1 min @ 1088 lb after surviving 1085 lb for 2 min	1085/4.5min,1085/2min,1088/<1min
TB-T90	Tempered	Small	Air	3	Yes	03/29/2004	1010	1025		Broke 2.3 min @ 1025 lb	1025/2.3min
TB-T92	Tempered	Small	Air	3	Yes	03/27/2004	1010	1025		Broke 1.6 min @ 1025 lb	1025/1.6min
TB-T97	Tempered	Small	Air	3	Yes	03/31/2004	995	1010		Broke 3 min @ 1010 lb	1025/2.3min,1010/3min
TB-T98	Tempered	Small	Air	3	Yes	04/05/2004	1070	1085		Broke 1 hr @ 1085 lb	1010,1025,1040,1055,1070,1085/1hr

Table 7 Results of 2003 Water Emersion Fatigue Tests - Air-Side Data - Loading Fixture Types 2 and 3

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-A50	Tempered	Big	Air	2	No	12/18/2003	1010		1224		995/8.54hr,980,995,1010,1025/95min
TB-T65	Tempered	Small	Air	2	No	01/22/2004	1115		1229		1040,1055,1070,1085,1100,1115
TB-A77	Tempered	Big	Air	3	No	04/05/2004	1070		1248		1010,1025,1040,1055,1070,1085/1hr, 1010,1025,1040,1055/3hr
TB-T85	Tempered	Small	Air	3	No	04/05/2004	1070		1255		1115/2.5hr,1085/4min,1055/2min,1055/7.2hr,1010,1025,1040, 1055,1070,1085/1hr
TB-T67	Tempered	Small	Air	2	No	01/22/2004	1115		1266		1010,1025,1040,1055,1070,1085, 1100,1115
TB-T66	Tempered	Small	Air	2	No	01/16/2004	1115		1287		1040,1055,1070,1085,1100,1115
TB-T59	Tempered	Small	Air	2	No	01/16/2004	1115		1291		1040,1055,1070,1085,1100,1115
TB-T68	Tempered	Small	Air	2	No	02/04/2004	1130		1296		1025/3min,1025,1040,1055,1070,1085, 1100,1115,1130
TB-A41	Tempered	Big	Air	2	No	12/10/2003	1025		1307		980,995,1010,1025,1015/12min,995, 1010,1025/9.5min
TB-T83	Tempered	Small	Air	3	No	04/05/2004	1070		1322		1115/2.4hr,1085/4min,1085/2min,1055/7.2hr,1010,1025, 1040,1055,1070,1085/1hr
TB-T80	Tempered	Small	Air	2	No	02/12/2004	1130		1342		1025,1040,1055,1070,1085,1100, 1115,1130
TB-T70	Tempered	Small	Air	2	No	02/12/2004	1030		1369		1025,1040,1055,1070,1085,1100, 1115,1130
TB-T58	Tempered	Small	Air	2	No	01/16/2004	1115		1385		1040,1055,1070,1085,1100,1115
TB-T79	Tempered	Small	Air	2	No	02/12/2004	1130		1416		1025,1040,1055,1070,1085,1100,1115,1130
TB-T84	Tempered	Small	Air	3	No	04/05/2004	1070		1457		1070,1115/2.5hr,1085/4min,1085/2min,1055/7.2hr,1010,1025, 1040,1055,1070,1085/1hr
TB-A51	Tempered	Big	Air	2	Yes	12/18/2003	1010			Broke 95min @ 1025 lb	980,995,1010,1025/95min
TB-T69	Tempered	Small	Air	2	Yes	02/03/2004	1010	1025		Broke 3 min @ 1025 lb	1025/3min
TB-A76	Tempered	Big	Air	3	Yes	03/31/2004	1055	1055		Broke 7.2 hr @ 1055 lb	995,1010,1025,1040,1055/7.2hr
TB-A78	Tempered	Big	Air	3	Yes	04/09/2004	1055	1055		Broke 3.16 hr @ 1055 lb	1040,1055/3.16hr
TB-T82	Tempered	Small	Air	3	Yes	03/19/2004	1100	1115		Broke 2.5 hr @ 1115 lb	1085,1100,1115/2.5hr
TB-T86	Tempered	Small	Air	3	Yes	03/23/2004	1070	1085		Broke 4.5 min @ 1085 lb	1115/2.5hr,1085/4min,1085/2min, 1085/4.5min
TB-T87	Tempered	Small	Air	3	Yes	03/22/2004	1070	1085		Broke 4 min @ 1085 lb	1085/4min
TB-T88	Tempered	Small	Air	3	Yes	03/23/2004	1070	1085		Broke 2 min @ 1085 lb	1085/2min
TB-T89	Tempered	Small	Air	3	Yes	03/26/2004	1070	1085		Broke during initial loading <1 min @ 1088 lb after surviving 1085 lb for 2 min	1085/4.5min,1085/2min,1088/<1min
TB-T90	Tempered	Small	Air	3	Yes	03/29/2004	1010	1025		Broke 2.3 min @ 1025 lb	1025/2.3min
TB-T92	Tempered	Small	Air	3	Yes	03/27/2004	1010	1025		Broke 1.6 min @ 1025 lb	1025/1.6min
TB-T97	Tempered	Small	Air	3	Yes	03/31/2004	995	1010		Broke 3 min @ 1010 lb	1025/2.3min,1010/3min
TB-T98	Tempered	Small	Air	3	Yes	04/05/2004	1070	1085		Broke 1 hr @ 1085 lb	1010,1025,1040,1055,1070,1085/1hr

Table 8 Results of 2003 Water Emersion Fatigue Tests - Air-Side Data - Loading Fixture Type 1

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-A49	Tempered	Big	Air	1	No	12/11/2003	1115		1216		1040,1055,1070,1085,1100,1115/5.6hr
TB-A43	Tempered	Big	Air	1	No	12/11/2003	1115		1231		1040,1055,1070,1085,1100,1115/5.6hr
TB-A48	Tempered	Big	Air	1	No	12/11/2003	1115		1256		1040,1055,1070,1085,1100,1115/5.6hr
TB-T35	Tempered	Small	Air	1	No	12/03/2003	1065		1298		940,955,970,985,1005,1025,1045, 1065,1090/9min
TB-A36	Tempered	Small	Air	1	No	12/03/2003	1065		1399		940,955,970,985,1005,1025,1045, 1065,1090/9min
TB-A42	Tempered	Big	Air	1	Yes	12/10/2003	995	995		Broke 8.54hr @ 995 lb	1015/12min,995/8.54hr

Table 9 Results of 2003 Water Emersion Fatigue Tests - Air-Side Data - Loading Fixture Type 2

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-A50	Tempered	Big	Air	2	No	12/18/2003	1010		1224		995/8.54hr,980,995,1010,1025/95min
TB-T65	Tempered	Small	Air	2	No	01/22/2004	1115		1229		1040,1055,1070,1085,1100,1115
TB-T67	Tempered	Small	Air	2	No	01/22/2004	1115		1266		1010,1025,1040,1055,1070,1085, 1100,1115
TB-T66	Tempered	Small	Air	2	No	01/16/2004	1115		1287		1040,1055,1070,1085,1100,1115
TB-T59	Tempered	Small	Air	2	No	01/16/2004	1115		1291		1040,1055,1070,1085,1100,1115
TB-T68	Tempered	Small	Air	2	No	02/04/2004	1130		1296		1025/3min,1025,1040,1055,1070,1085, 1100,1115,1130
TB-A41	Tempered	Big	Air	2	No	12/10/2003	1025		1307		980,995,1010,1025,1015/12min,995, 1010,1025/9.5min
TB-T80	Tempered	Small	Air	2	No	02/12/2004	1130		1342		1025,1040,1055,1070,1085,1100, 1115,1130
TB-T70	Tempered	Small	Air	2	No	02/12/2004	1030		1369		1025,1040,1055,1070,1085,1100, 1115,1130
TB-T58	Tempered	Small	Air	2	No	01/16/2004	1115		1385		980,995,1010,1025,1040,1055,1070, 1085,1100,1115
TB-T79	Tempered	Small	Air	2	No	02/12/2004	1130		1416		
TB-T58	Tempered	Small	Air	2	No	01/16/2004	1115		1385		1040,1055,1070,1085,1100,1115
TB-A51	Tempered	Big	Air	2	Yes	12/18/2003	1010	1005		Broke 95min @ 1025 lb	980,995,1010,1025/95min
TB-T69	Tempered	Small	Air	2	Yes	02/03/2004	1010	1005		Broke 3 min @ 1025 lb	1025/3min

Table 10 Results of 2003 Water Emersion Fatigue Tests - Air-Side Data - Loading Fixture Type 3

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-A77	Tempered	Big	Air	3	No	04/05/2004	1070		1248		1010,1025,1040,1055,1070,1085/1hr, 1010,1025,1040,1055/3hr
TB-T85	Tempered	Small	Air	3	No	04/05/2004	1070		1255		1115/2.5hr,1085/4min,1055/2min,1055/7.2hr,1010,1025,1040, 1055,1070,1085/1hr
TB-T83	Tempered	Small	Air	3	No	04/05/2004	1070		1322		1115/2.4hr,1085/4min,1085/2min,1055/7.2hr,1010,1025, 1040,1055,1070,1085/1hr
TB-T84	Tempered	Small	Air	3	No	04/05/2004	1070		1457		1070,1115/2.5hr,1085/4min,1085/2min,1055/7.2hr,1010,1025, 1040,1055,1070,1085/1hr
TB-A76	Tempered	Big	Air	3	Yes	03/31/2004	1055	1055		Broke 7.2 hr @ 1055 lb	995,1010,1025,1040,1055/7.2hr
TB-A78	Tempered	Big	Air	3	Yes	04/09/2004	1055	1055		Broke 3.16 hr @ 1055 lb	1040,1055/3.16hr
TB-T82	Tempered	Small	Air	3	Yes	03/19/2004	1100	1115		Broke 2.5 hr @ 1115 lb	1085,1100,1115/2.5hr
TB-T86	Tempered	Small	Air	3	Yes	03/23/2004	1070	1085		Broke 4.5 min @ 1085 lb	1115/2.5hr,1085/4min,1085/2min, 1085/4.5min
TB-T87	Tempered	Small	Air	3	Yes	03/22/2004	1070	1085		Broke 4 min @ 1085 lb	1085/4min
TB-T88	Tempered	Small	Air	3	Yes	03/23/2004	1070	1085		Broke 2 min @ 1085 lb	1085/2min
TB-T89	Tempered	Small	Air	3	Yes	03/26/2004	1070	1085		Broke during initial loading <1 min @ 1088 lb after surviving 1085 lb for 2 min	1085/4.5min,1085/2min,1088/<1min
TB-T90	Tempered	Small	Air	3	Yes	03/29/2004	1010	1025		Broke 2.3 min @ 1025 lb	1025/2.3min
TB-T92	Tempered	Small	Air	3	Yes	03/27/2004	1010	1025		Broke 1.6 min @ 1025 lb	1025/1.6min
TB-T97	Tempered	Small	Air	3	Yes	03/31/2004	995	1010		Broke 3 min @ 1010 lb	1025/2.3min,1010/3min
TB-T98	Tempered	Small	Air	3	Yes	04/05/2004	1070	1085		Broke 1 hr @ 1085 lb	1010,1025,1040,1055,1070,1085/1hr

Table 11 Results of 2003 Water Emersion Fatigue Tests - Tin-Side Data - Loading Fixture Types 1, 2 and 3

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-T46	Tempered	Big	Tin	1	No	12/11/2003	1115		1132		980,995,1015,1030,1045,1060,1075, 1090,1100,1115/5.6hr
TB-T38	Tempered	Big	Tin	2	No	12/18/2003	1010		1219		1015/12min,995/8.54hr,980,995, 1010,1025/95min
TB-T44	Tempered	Big	Tin	2	No	12/18/2003	1010		1223		1015/12min,995/8.54hr,980,995, 1010,1025/95min
TB-A64	Tempered	Small	Tin	2	No	02/12/2004	1130		1292		1025,1040,1055,1070,1085,1100, 1115,1130
TB-A81	Tempered	Small	Tin	3	No	04/16/2004	1145		1299		1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A81	Tempered	Small	Tin	3	No	04/16/2004	1145		1299		1010,1025,1040,1055,1070,1085,1100, 1115,1030,1045,1060/1.6hr
TB-A52	Tempered	Small	Tin	2	No	01/16/2004	1115		1306		980,995,1010,1025,1040,1055,1070, 085,1100,1115
TB-A75	Tempered	Small	Tin	2	No	02/25/2004	1130		1325		1085,1100,1115,1130
TB-A57	Tempered	Small	Tin	2	No	02/04/2004	1130		1336		1025/3min,1055,1070,1085,1100, 1115,1130
TB-A53	Tempered	Small	Tin	2	No	01/16/2004	1115		1345		980,995,1010,1025,1040,1055,1070, 085,1100,1115
TB-A60	Tempered	Small	Tin	2	No	02/03/2004	1130		1351		1025/3min,1025,1040,1055,1070,1085, 1100,1115,1130
TB-A63	Tempered	Small	Tin	2	No	02/12/2004	1130		1377		1025,1040,1055,1070,1085,1100, 1115,1130
TB-A39	Tempered	Small	Tin	1	No	12/03/2003	1065		1379		940,955,970,985/9min,1005,1025, 1045,1065,1090
TB-A72	Tempered	Small	Tin	2	No	02/25/2004	1130		1382		1085,1100,1115,1130
TB-A73	Tempered	Small	Tin	2	No	02/25/2004	1130		1383		1085,1100,1115,1130
TB-A91	Tempered	Small	Tin	3	No	04/16/2004	1145		1384		1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A101	Tempered	Small	Tin	3	No	04/30/2004	1055		1393		1055/6.83hr
TB-A40	Tempered	Small	Tin	1	No	12/03/2003	1065		1396		40,955,970,985/9min,1005,1025, 1045,1065,1090
TB-A56	Tempered	Small	Tin	2	No	01/22/2004	1115		1398		1040,1055,1070,1085,1100,1115
TB-A93	Tempered	Small	Tin	3	No	04/16/2004	1145		1398		1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A55	Tempered	Small	Tin	2	No	01/22/2004	1115		1414		1040,1055,1070,1085,1100,1115
TB-A62	Tempered	Small	Tin	2	No	02/04/2004	1130		1424		1025,1040,1055,1070,1085,1100,,115,1130
TB-A74	Tempered	Small	Tin	2	No	02/25/2004	1130		1430		1085,1100,1115,1130
TB-A99	Tempered	Small	Tin	3	No	04/30/2004	1055		1433		1055/6.83hr
TB-A71	Tempered	Small	Tin	3	No	04/30/2004	1055		1439		1085,1100,1115,1130,1055/6.83hr
TB-A61	Tempered	Small	Tin	2	No	02/03/2004	1130		1440		1025/3min,1025,1040,1055,1070,1085, 1100,1115,1130
TB-A104	Tempered	Small	Tin	3	No	04/30/2004	1055		1441		1055/6.83hr
TB-A54	Tempered	Small	Tin	2	No	01/22/2004	1115		1501		1040,1055,1070,1085,1100,1115
TB-A95	Tempered	Small	Tin	3	No	04/16/2004	1145		1525		1010,1025,1040,1055,1070,1085,1100,1115,1130,1145,1160/1.6min
TB-A34	Tempered	Small	Tin	1	Yes	12/03/2003	1065	1090		Broke 9 min @ 1090 lb	940,955,970,985/9min,1005,1025, 1045,1065,1090/9min
TB-A94	Tempered	Small	Tin	3	Yes	04/16/2004	1145	1160		Broke 1.6 hr @ 1160 lb	1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-T37	Tempered	Big	Tin	1	Yes	12/03/2003	1000	1015		Broke 12 min @ 1015 lb	1015/12min
TB-T45	Tempered	Big	Tin	1	Yes	12/11/2003	1115	1115		Broke 5.6 hr @ 1115 lb	980,995,1015,1030,1045,1060,105,1090, 1100,1115/5.6hr
TB-T47	Tempered	Big	Tin	1	Yes	12/17/2003	980	995		Broke 1 min @ 995 lb	995/1min
TB-T103	Tempered	Big	Tin	3	Yes	04/26/2004	1055	1070		Broke 56 min @ 1070 lb	1070/56min
TB-T105	Tempered	Big	Tin	3	Yes	04/30/2004	1040	1055		Broke 15 min @ 1055 lb	1055/15min
TB-A100	Tempered	Small	Tin	3	Yes	04/30/2004	1055	1055		Broke 6.83 hr @ 1055 lb	1055/6.83hr
TB-A102	Tempered	Small	Tin	3	Yes	04/21/2004	1085	1085		Broke 5.97 hr @ 1085 lb	1085/5.97hr
TB-A96	Tempered	Small	Tin	3	Yes	04/21/2004	1100	1115		Broke 7min @ 1115 lb	

Table 12 Results of 2003 Water Emersion Fatigue Tests - Tin-Side Data - Loading Fixture Types 2 and 3

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-A52	Tempered	Big	Tin	2	No	12/18/2003	1010		1219		1015/12min,995/8.54hr,980,995, 1010,1025/95min
TB-A53	Tempered	Big	Tin	2	No	12/18/2003	1010		1223		1015/12min,995/8.54hr,980,995, 1010,1025/95min
TB-A54	Tempered	Small	Tin	2	No	02/12/2004	1130		1292		1025,1040,1055,1070,1085,1100, 115,1130
TB-A55	Tempered	Small	Tin	3	No	04/16/2004	1145		1299		1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A56	Tempered	Small	Tin	3	No	04/16/2004	1145		1299		1010,1025,1040,1055,1070,1085,1100,1115,1030,1045,1060/1.6hr
TB-A57	Tempered	Small	Tin	2	No	01/16/2004	1115		1306		980,995,1010,1025,1040,1055,1070, 085,1100,1115
TB-T38	Tempered	Small	Tin	2	No	02/25/2004	1130		1325		1085,1100,1115,1130
TB-T44	Tempered	Small	Tin	2	No	02/04/2004	1130		1336		1025/3min,1055,1070,1085,1100, 1115,1130
TB-A60	Tempered	Small	Tin	2	No	01/16/2004	1115		1345		980,995,1010,1025,1040,1055,1070,1085,1100,1115
TB-A61	Tempered	Small	Tin	2	No	02/03/2004	1130		1351		1025/3min,1025,1040,1055,1070,1085, 1100,1115,1130
TB-A62	Tempered	Small	Tin	2	No	02/12/2004	1130		1377		1025,1040,1055,1070,1085,1100,1115,1130
TB-A63	Tempered	Small	Tin	2	No	02/25/2004	1130		1382		1085,1100,1115,1130
TB-A64	Tempered	Small	Tin	2	No	02/25/2004	1130		1383		1085,1100,1115,1130
TB-A72	Tempered	Small	Tin	3	No	04/16/2004	1145		1384		1010,1025,1040,1055,1070,1085,1100,1115,1130,1145,1160/1.6min
TB-A73	Tempered	Small	Tin	3	No	04/30/2004	1055		1393		1055/6.83hr
TB-A74	Tempered	Small	Tin	2	No	01/22/2004	1115		1398		1040,1055,1070,1085,1100,1115
TB-A75	Tempered	Small	Tin	3	No	04/16/2004	1145		1398		1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A81	Tempered	Small	Tin	2	No	01/22/2004	1115		1414		1040,1055,1070,1085,1100,1115
TB-A91	Tempered	Small	Tin	2	No	02/04/2004	1130		1424		1025,1040,1055,1070,1085,1100, 1115,1130
TB-A93	Tempered	Small	Tin	2	No	02/25/2004	1130		1430		1085,1100,1115,1130
TB-A94	Tempered	Small	Tin	3	No	04/30/2004	1055		1433		1055/6.83hr
TB-A95	Tempered	Small	Tin	3	No	04/30/2004	1055		1439		1085,1100,1115,1130,1055/6.83hr
TB-T103	Tempered	Small	Tin	2	No	02/03/2004	1130		1440		1025/3min,1025,1040,1055,1070,1085,1100,1115,1130
TB-T105	Tempered	Small	Tin	3	No	04/30/2004	1055		1441		1055/6.83hr
TB-A81	Tempered	Small	Tin	2	No	01/22/2004	1115		1501		1040,1055,1070,1085,1100,1115
TB-A71	Tempered	Small	Tin	3	No	04/16/2004	1145		1525		1010,1025,1040,1055,1070,1085,1100, 115,1130,1145,1160/1.6min
TB-A99	Tempered	Small	Tin	3	Yes	04/16/2004	1145	1160		Broke 1.6 hr @ 1160 lb	1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A101	Tempered	Big	Tin	3	Yes	04/26/2004	1055	1070		Broke 56 min @ 1070 lb	1070/56min
TB-A104	Tempered	Big	Tin	3	Yes	04/30/2004	1040	1055		Broke 15 min @ 1055 lb	1055/15min
TB-A100	Tempered	Small	Tin	3	Yes	04/30/2004	1055	1055		Broke 6.83 hr @ 1055 lb	1055/6.83hr
TB-A102	Tempered	Small	Tin	3	Yes	04/21/2004	1085	1085		Broke 5.97 hr @ 1085 lb	1085/5.97hr
TB-A96	Tempered	Small	Tin	3	Yes	04/21/2004	1100	1115		Broke 7min @ 1115 lb	

Table 13 Results of 2003 Water Emersion Fatigue Tests - Tin-Side Data - Loading Fixture Type 1

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-T46	Tempered	Big	Tin	1	No	12/11/2003	1115		1132		980,995,1015,1030,1045,1060,1075, 1090,1100,1115/5.6hr
TB-A39	Tempered	Small	Tin	1	No	12/03/2003	1065		1379		940,955,970,985/9min,1005,1025, 1045,1065,1090
TB-A40	Tempered	Small	Tin	1	No	12/03/2003	1065		1396		40,955,970,985/9min,1005,1025, 1045,1065,1090
TB-A34	Tempered	Small	Tin	1	Yes	12/03/2003	1065	1090		Broke 9 min @ 1090 lb	940,955,970,985/9min,1005,1025, 1045,1065,1090/9min
TB-T37	Tempered	Big	Tin	1	Yes	12/03/2003	1000	1015		Broke 12 min @ 1015 lb	1015/12min
TB-T45	Tempered	Big	Tin	1	Yes	12/11/2003	1115	1115		Broke 5.6 hr @ 1115 lb	980,995,1015,1030,1045,1060,105,1090, 1100,1115/5.6hr
TB-T47	Tempered	Big	Tin	1	Yes	12/17/2003	980	995		Broke 1 min @ 995 lb	995/1min

Table 14 Results of 2003 Water Emersion Fatigue Tests - Tin-Side Data - Loading Fixture Type 2

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-T38	Tempered	Big	Tin	2	No	12/18/2003	1010		1219		1015/12min,995/8.54hr,980,995, 1010,1025/95min
TB-T44	Tempered	Big	Tin	2	No	12/18/2003	1010		1223		1015/12min,995/8.54hr,980,995, 1010,1025/95min
TB-A64	Tempered	Small	Tin	2	No	02/12/2004	1130		1292		1025,1040,1055,1070,1085,1100, 1115,1130
TB-A52	Tempered	Small	Tin	2	No	01/16/2004	1115		1306		980,995,1010,1025,1040,1055,1070, 1085,1100,1115
TB-A75	Tempered	Small	Tin	2	No	02/25/2004	1130		1325		1085,1100,1115,1130
TB-A57	Tempered	Small	Tin	2	No	02/04/2004	1130		1336		1025/3min,1055,1070,1085,1100, 1115,1130
TB-A53	Tempered	Small	Tin	2	No	01/16/2004	1115		1345		980,995,1010,1025,1040,1055,1070, 1085,1100,1115
TB-A60	Tempered	Small	Tin	2	No	02/03/2004	1130		1351		1025/3min,1025,1040,1055,1070,1085, 1100,1115,1130
TB-A63	Tempered	Small	Tin	2	No	02/12/2004	1130		1377		1025,1040,1055,1070,1085,1100, 1115,1130
TB-A72	Tempered	Small	Tin	2	No	02/25/2004	1130		1382		1085,1100,1115,1130
TB-A73	Tempered	Small	Tin	2	No	02/25/2004	1130		1383		1085,1100,1115,1130
TB-A56	Tempered	Small	Tin	2	No	01/22/2004	1115		1398		1040,1055,1070,1085,1100,1115
TB-A55	Tempered	Small	Tin	2	No	01/22/2004	1115		1414		1040,1055,1070,1085,1100,1115
TB-A62	Tempered	Small	Tin	2	No	02/04/2004	1130		1424		1025,1040,1055,1070,1085,1100, 1115,1130
TB-A74	Tempered	Small	Tin	2	No	02/25/2004	1130		1430		1085,1100,1115,1130
TB-A61	Tempered	Small	Tin	2	No	02/03/2004	1130		1440		1025/3min,1025,1040,1055,1070,1085, 1100,1115,1130
TB-A54	Tempered	Small	Tin	2	No	01/22/2004	1115		1501		1040,1055,1070,1085,1100,1115

Table 15 Results of 2003 Water Emersion Fatigue Tests - Tin-Side Data - Loading Fixture Type 3

Test ID	Tempered	Hole Size	Stressed Surface	Loading Fixtures	Broken by Fatigue	Date	Maximum 10 hr Surviving Fatigue Load, lb	10 hr Failing Fatigue Load lb	Short Term Post Fatigue Breaking Load, lb	Notes	Load Sequence
TB-A81	Tempered	Small	Tin	3	No	04/16/2004	1145		1299		1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A81	Tempered	Small	Tin	3	No	04/16/2004	1145		1299		1010,1025,1040,1055,1070,1085,1100, 1115,1030,1045,1060/1.6hr
TB-A91	Tempered	Small	Tin	3	No	04/16/2004	1145		1384		1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A101	Tempered	Small	Tin	3	No	04/30/2004	1055		1393		1055/6.83hr
TB-A93	Tempered	Small	Tin	3	No	04/16/2004	1145		1398		1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A99	Tempered	Small	Tin	3	No	04/30/2004	1055		1433		1055/6.83hr
TB-A71	Tempered	Small	Tin	3	No	04/30/2004	1055		1439		1085,1100,1115,1130,1055/6.83hr
TB-A104	Tempered	Small	Tin	3	No	04/30/2004	1055		1441		1055/6.83hr
TB-A95	Tempered	Small	Tin	3	No	04/16/2004	1145		1525		1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-A94	Tempered	Small	Tin	3	Yes	04/16/2004	1145	1160		Broke 1.6 hr @ 1160 lb	1010,1025,1040,1055,1070,1085,1100, 1115,1130,1145,1160/1.6min
TB-T103	Tempered	Big	Tin	3	Yes	04/26/2004	1055	1070		Broke 56 min @ 1070 lb	1070/56min
TB-T105	Tempered	Big	Tin	3	Yes	04/30/2004	1040	1055		Broke 15 min @ 1055 lb	1055/15min
TB-A100	Tempered	Small	Tin	3	Yes	04/30/2004	1055	1055		Broke 6.83 hr @ 1055 lb	1055/6.83hr
TB-A102	Tempered	Small	Tin	3	Yes	04/21/2004	1085	1085		Broke 5.97 hr @ 1085 lb	1085/5.97hr
TB-A96	Tempered	Small	Tin	3	Yes	04/21/2004	1100	1115		Broke 7min @ 1115 lb	

Table 16 Example of Weibull Statistical Analysis of 2003 Specimen Strength Data

Water Emersion Fatigue - Air-Side - With Failed Specimens – Tempered – Loading Fixture Type 2									
	Sample Number	Load		Sorted Sample Number	Sorted Load	F	ln(ln(1/1-F))	ln(load)	Load (kip)
1	TB-A50	1224		TB-A51	1	0.04861	-2.99909	-6.90776	0.001
2	TB-T65	1229		TB-T69	1	0.11806	-2.07444	-6.90776	0.001
3	TB-T67	1266		TB-A50	1224	0.18750	-1.57195	0.20212	1.224
4	TB-T66	1287		TB-T65	1229	0.25694	-1.21408	0.20620	1.229
5	TB-T59	1291		TB-T67	1266	0.32639	-0.92861	0.23586	1.266
6	TB-T68	1296		TB-T66	1287	0.39583	-0.68537	0.25231	1.287
7	TB-A41	1307		TB-T59	1291	0.46528	-0.46839	0.25542	1.291
8	TB-T80	1342		TB-T68	1296	0.53472	-0.26772	0.25928	1.296
9	TB-T70	1369		TB-A41	1307	0.60417	-0.07606	0.26773	1.307
10	TB-T58	1385		TB-T80	1342	0.67361	0.11303	0.29416	1.342
11	TB-T79	1416		TB-T70	1369	0.74306	0.30667	0.31408	1.369
12	TB-T58	1385		TB-T58	1385	0.81250	0.51520	0.32570	1.385
13	TB-A51	1		TB-T58	1385	0.88194	0.75922	0.32570	1.385
14	TB-T69	1		TB-T79	1416	0.95139	1.10655	0.34784	1.416
F = (i – 0.3)/(N + 0.4) i = ranking of specimen N = total number of specimens									

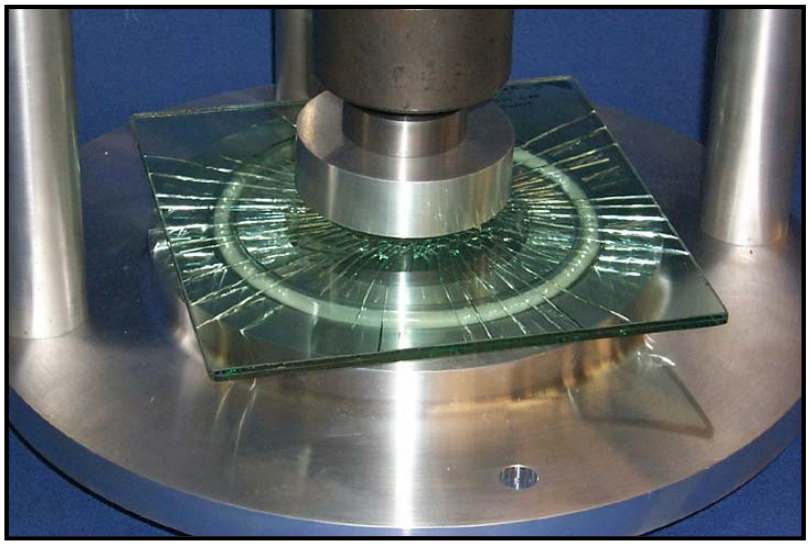


Figure 1 Ring-on-Ring Test for Short-Term Loading

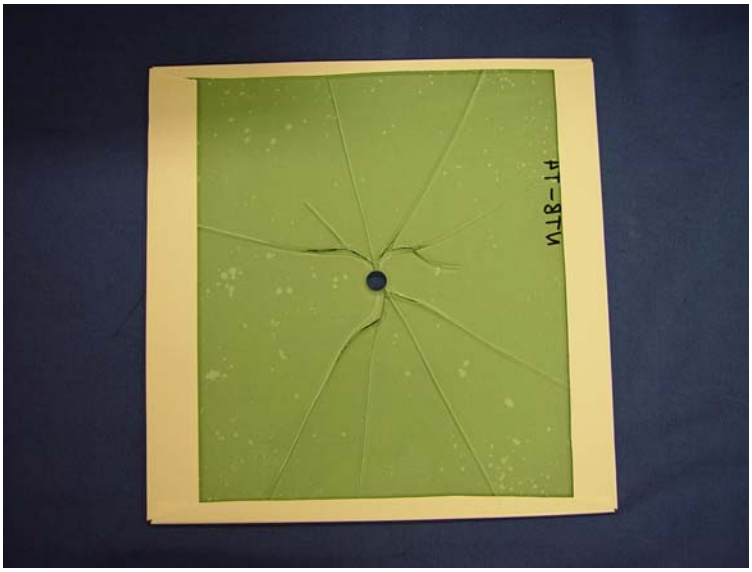


Figure 2 Fracture Pattern for Non-Tempered Specimens

Figure 3 Loading Fixtures for Stack of Five Fatigue Specimens Including Water Emersion

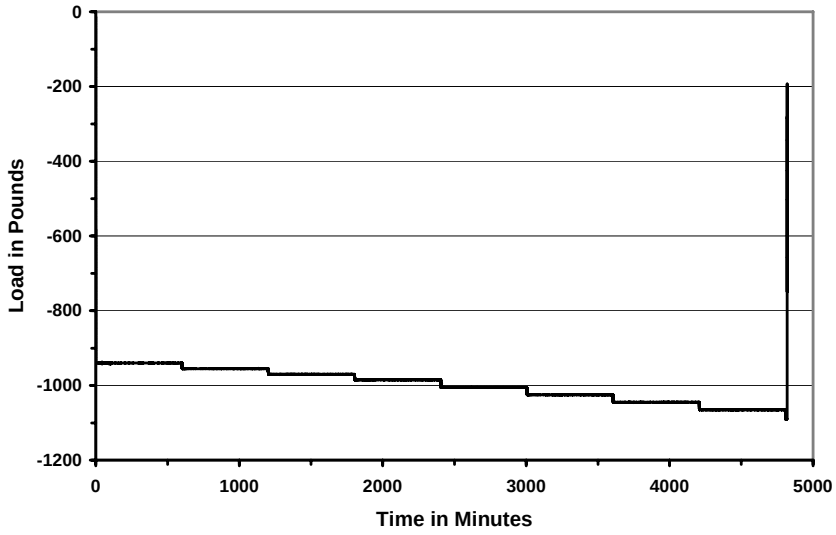


Figure 4 Loading Sequence for Stack of Five Specimens Tested Under Sustained Load in Water (Specimen TB-A34 – Tin/Small Hole – Failed After 9 Minutes at 1090 lb)

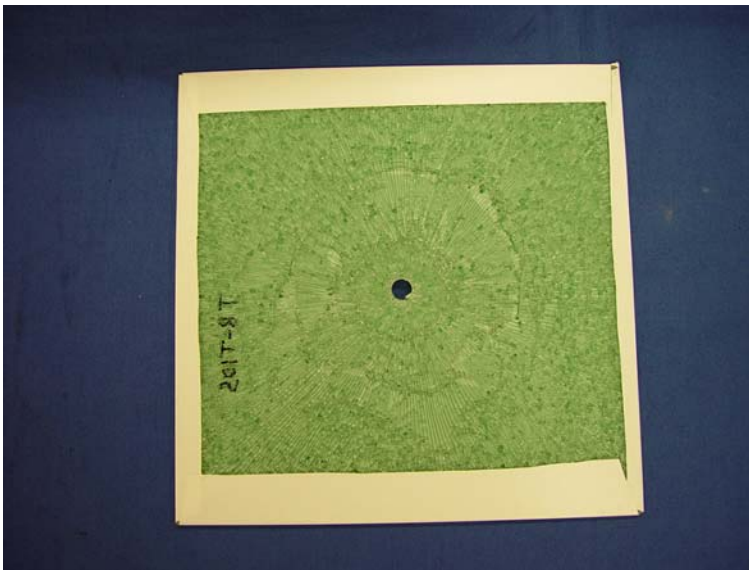


Figure 5 Fracture Pattern for Tempered Specimens

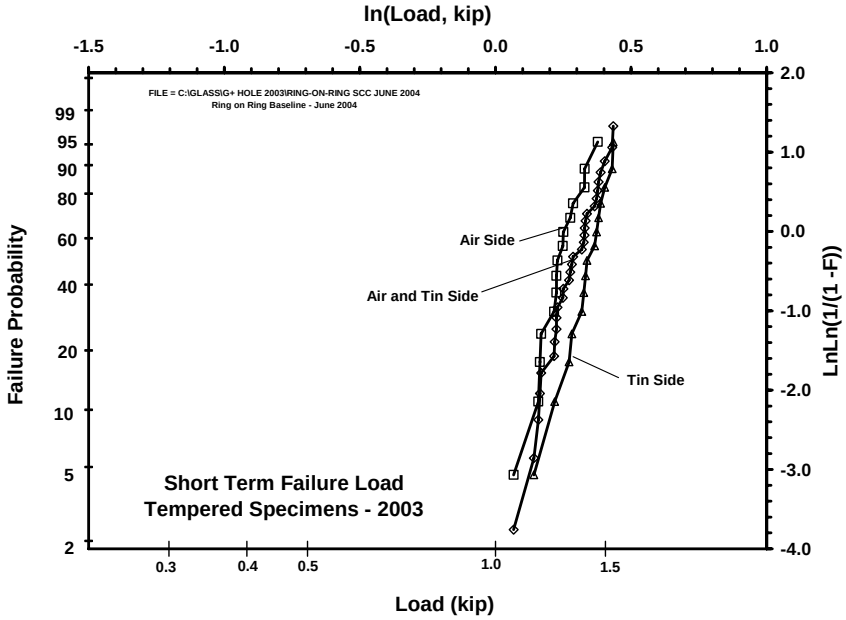


Figure 6 Short Term Failure Loads (no fatigue exposure) for 2003 Tempered Specimens

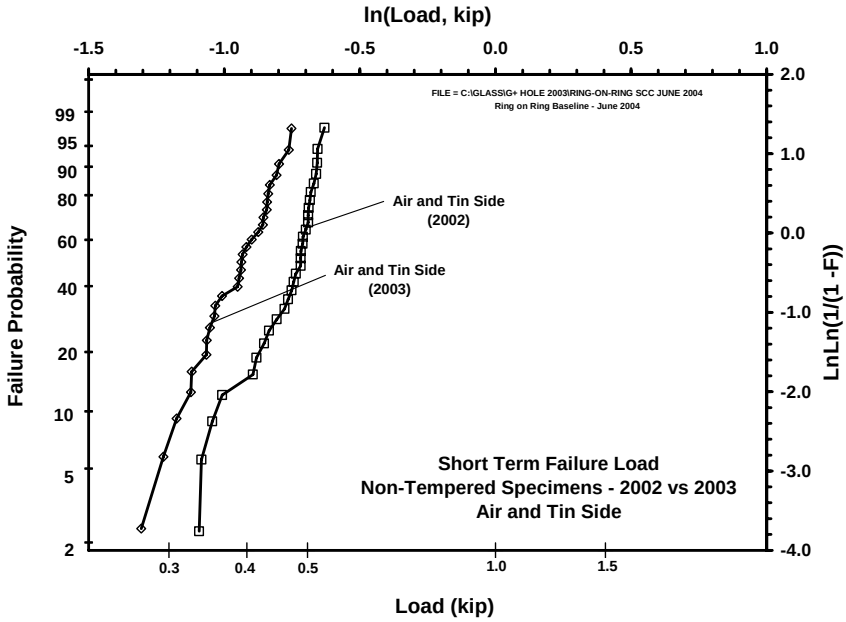


Figure 7 Short Term Failure Loads (no fatigue exposure) – Non-tempered 2002 Versus 2003 Specimens

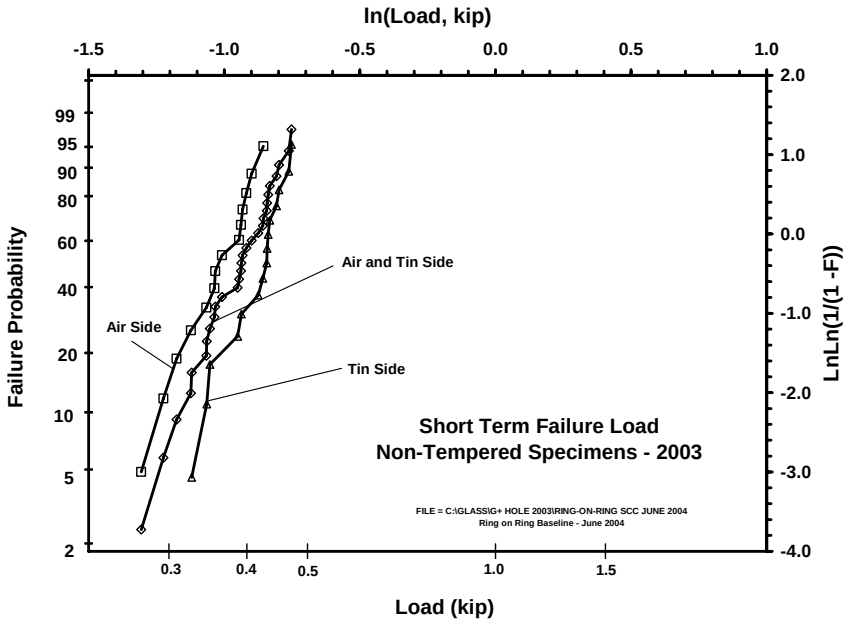


Figure 8 Short Term Failure Loads (no fatigue exposure) for 2003 Batch of Non-Tempered Specimens

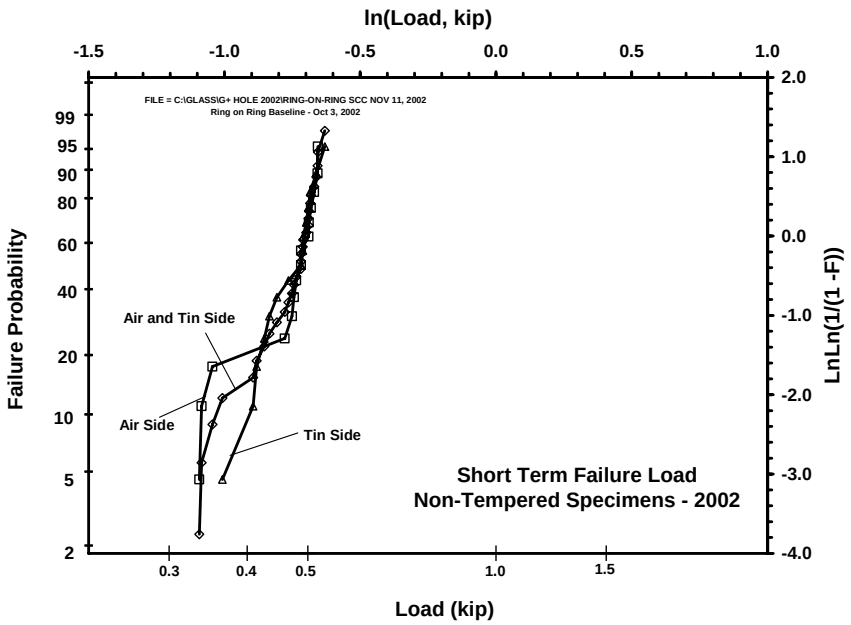


Figure 9 Short Term Failure Loads (no fatigue exposure) for 2002 Batch of Non-Tempered Specimens

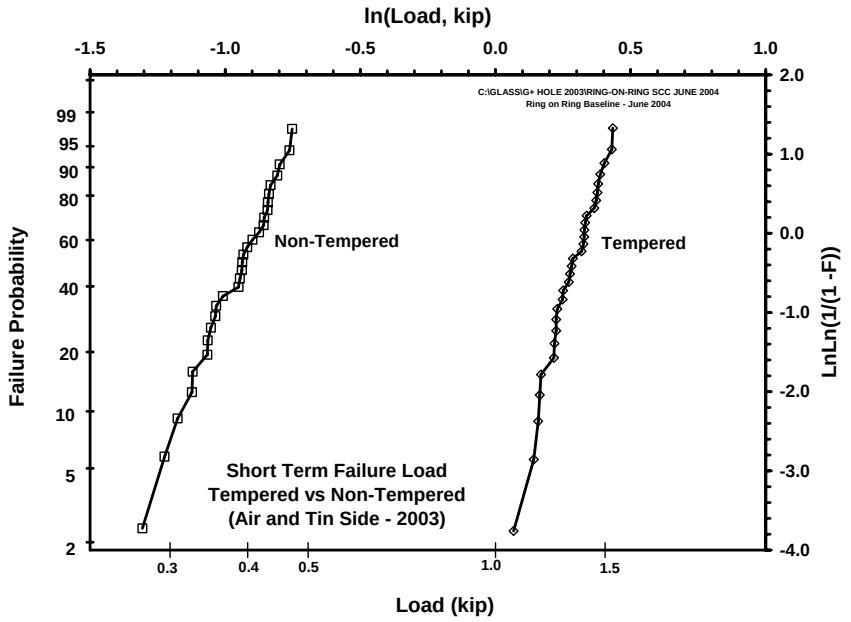


Figure 10 Short Term Failure Loads (no fatigue exposure) – Tempered Versus Non-Tempered for 2003 Batch of Specimens

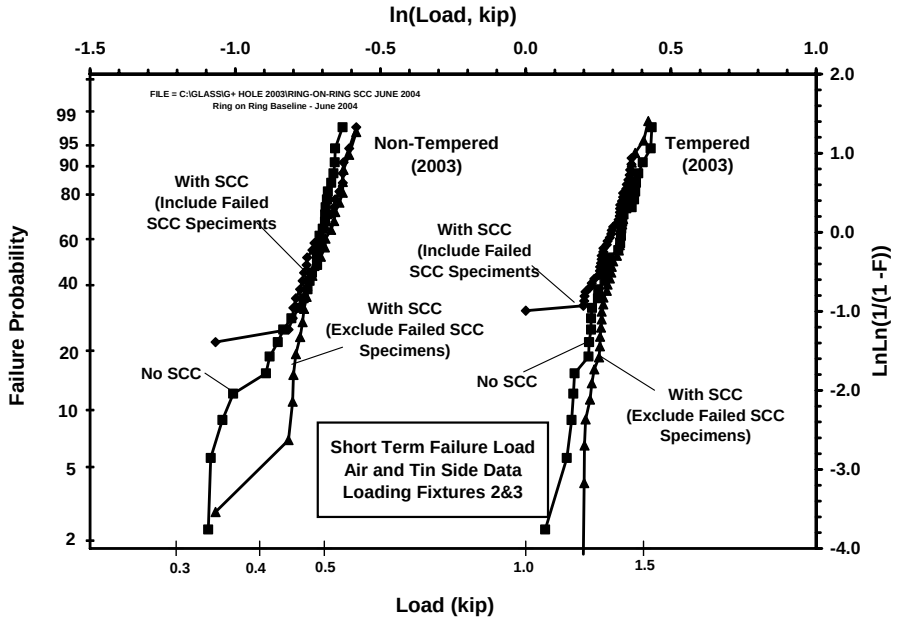


Figure 11 Short Term Failure Loads (Air and Tin with and without Fatigue Exposure) – Tempered Versus Non-Tempered for 2003 Batch of Specimens

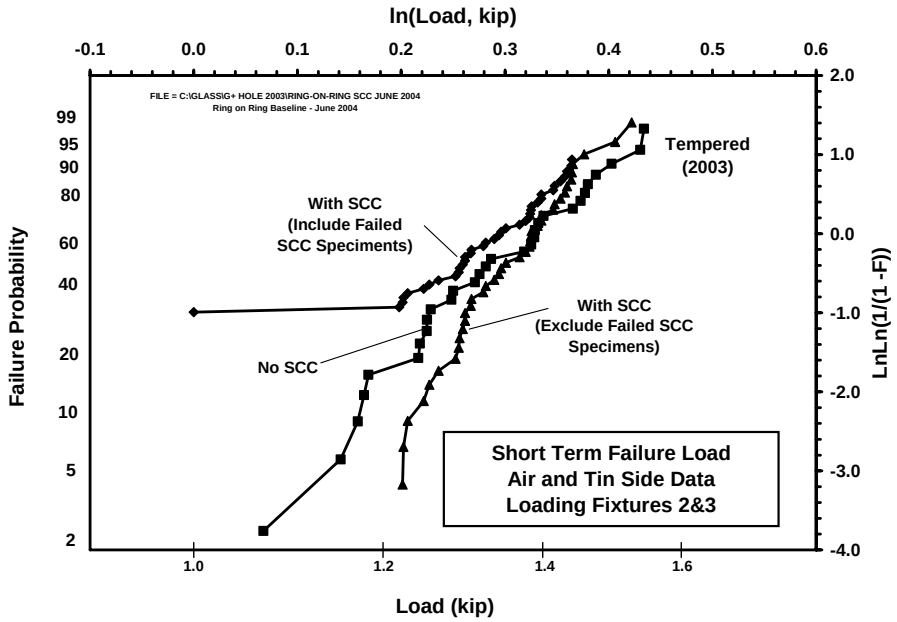


Figure 12 Short Term Failure Loads (Both Air and Tin Side) With and Without Fatigue Exposure – Tempered 2003 Specimens

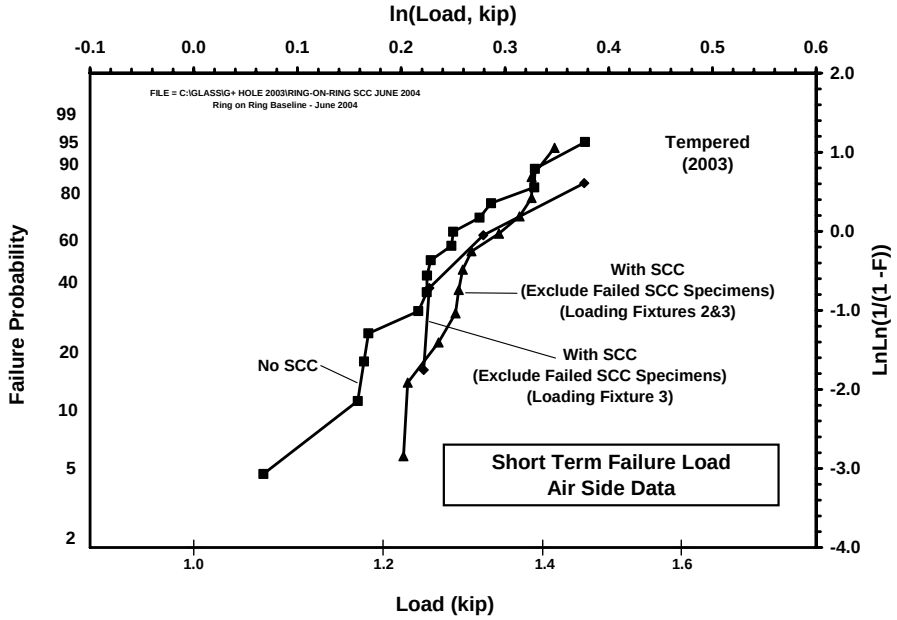


Figure 13 Short Term Failure Loads (Air-Side) With and Without Fatigue Exposure – Tempered 2003 Specimens

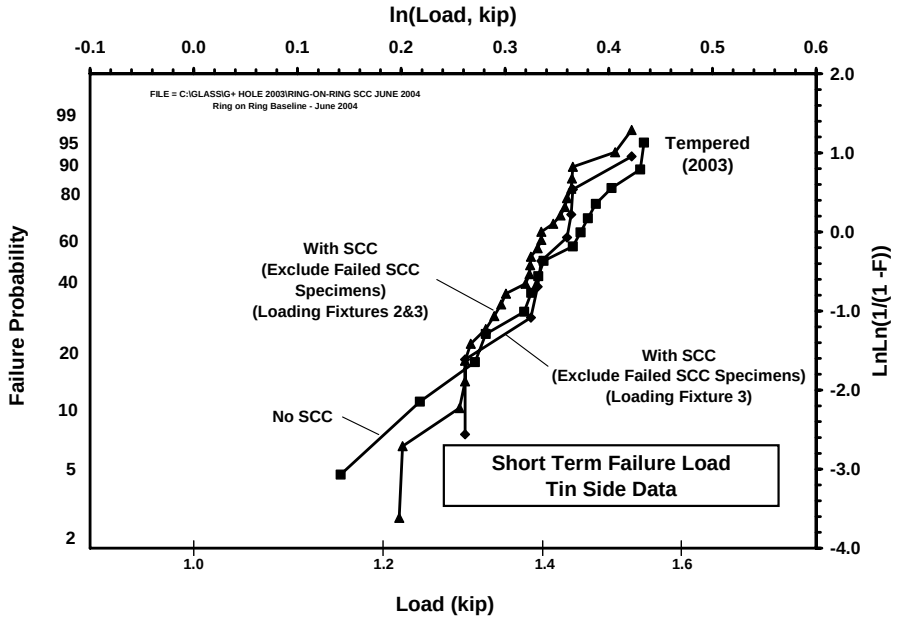


Figure 14 Short Term Failure Loads (Tin-Side) With and Without Fatigue Exposure – Tempered 2003 Batch of Specimens

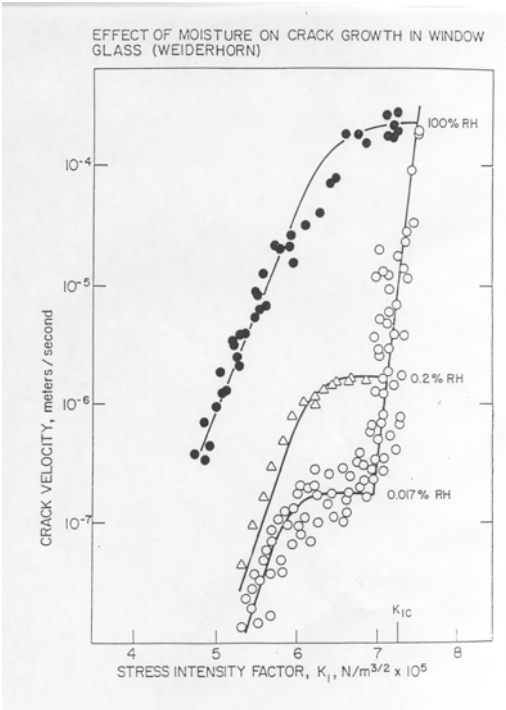


Figure 15 The Growth Rates (100% RH) for Stress Corrosion Cracks in Glass Used in PNNL's Fracture Mechanics Calculations for Water Immersion Tests

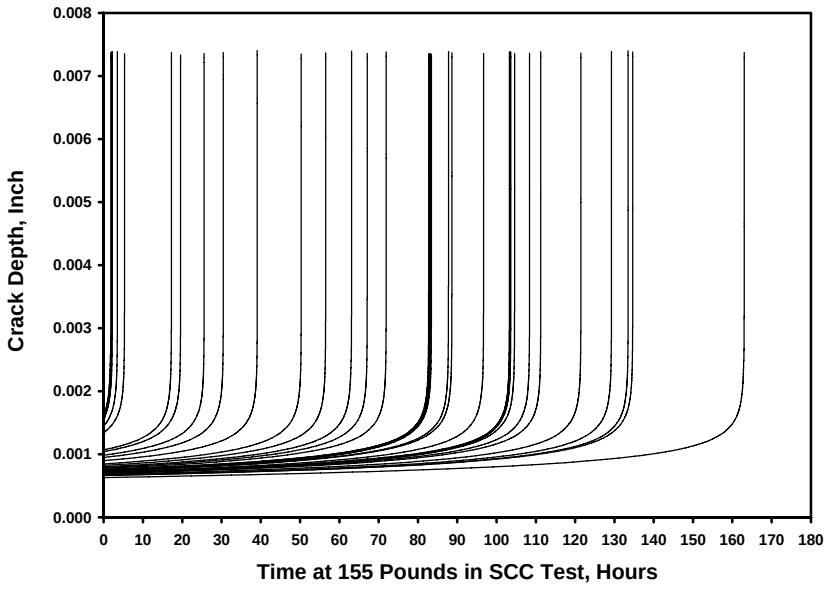


Figure 16 Predicted Crack Growth for the Collection of 30 Non-Tempered 2002 Specimens Tested for Short-Term Strength

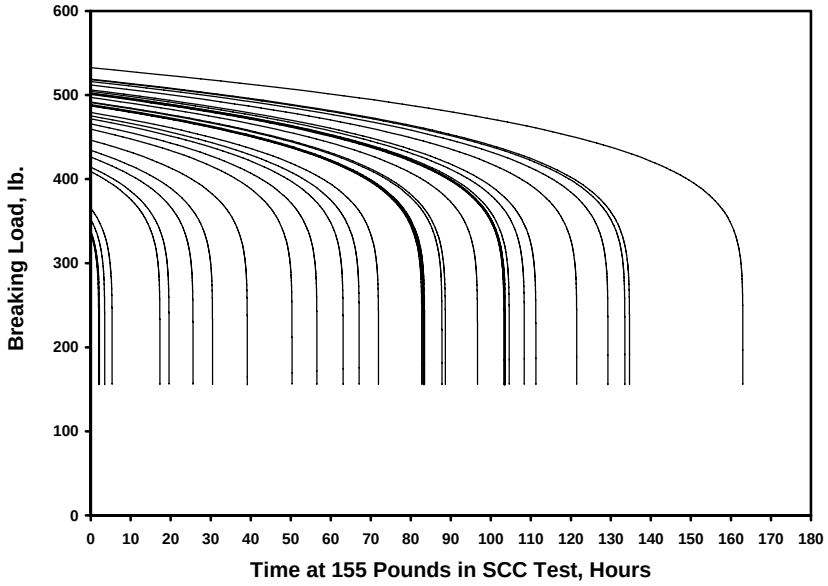


Figure 17 Predicted Short-Term Strengths for the Collection of 30 Non-Tempered 2002 Specimens as Function of Time at Stress in SCC Water Environment

Appendix A

Residual Stress Measurements

PNNL performed residual stress measurements using a grazing angle surface polarimeter (GASP) device. Figure 1 shows the locations for stress measurements. The initial measurements (as expected) showed essentially zero stress for the non-tempered specimens. Results of stress measurements for three tempered specimens are presented in Table 1.

Three tempered samples and one non-tempered sample were measured. It was possible to measure stresses only for the tin sides of samples. Measurements for the tin side of tempered specimens showed stresses between 100 to 240 MPa (14,000 to 35,000 psi).

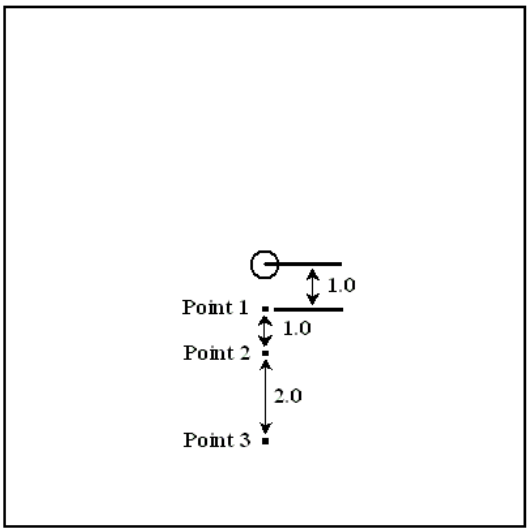


Figure 1. Measurement Setup for 12x12 inch Single-Ply Test Sample

Table 1 Results of Residual Stress Measurements for Tempered Specimens

ID: TB-T1

Point Number	0 degrees	-45 degrees	+45 degrees	Max Principle Stress, MPa	Max Principle Stress, ksi	Min Principle Stress, MPa	Min Principle Stress, ksi
1	78	74	79	219	18.7	143	20.7
2	75	73	76	169	24.5	137	19.9
3	74	74	79	230	33.3	132	19.1

ID: TB-T2

Point Number	0 degrees	-45 degrees	+45 degrees	Max Principle Stress, MPa	Max Principle Stress, ksi	Min Principle Stress, MPa	Min Principle Stress, ksi
1	75	71	77	182	26.4	121	17.5
2	76	75	77	182	26.4	156	22.6
3	75	75	76	171	24.8	154	22.3

ID: TB-T3

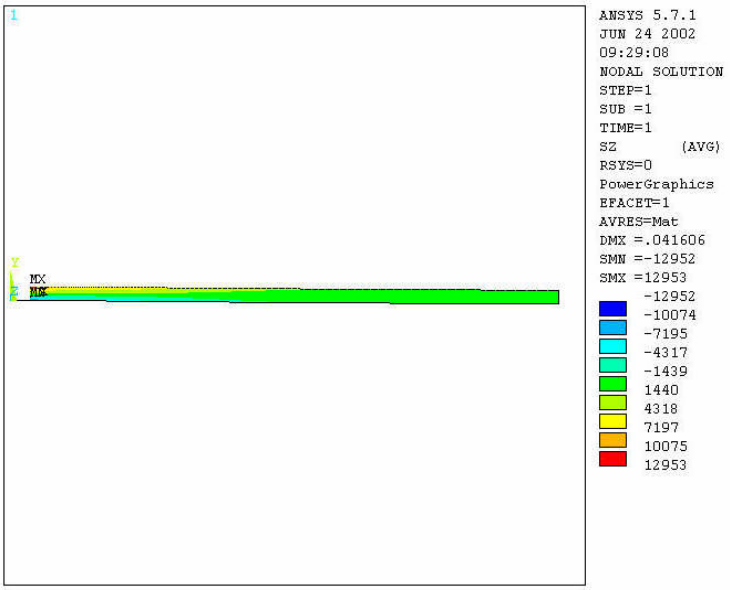
Point Number	0 degrees	-45 degrees	+45 degrees	Max Principle Stress, MPa	Max Principle Stress, ksi	Min Principle Stress, MPa	Min Principle Stress, ksi
1	75	45	73	160	23.2	133	19.3
2	80	75	77	239	34.6	100	14.5
3	76	76	73	175	25.3	131	19.0

Appendix B
Finite Element Stress Calculations of Glass Test Specimens With and Without Holes

Stress calculations were performed with the ANSYS finite element code. The results related local stresses to the loads applied to the ring-on-ring specimens. Figure B-1 shows example stress contours for a specimen (12-inch by 12-inch square with a thickness of 0.1875 inch) with a center hole that increased the local stress at the edge of the hole by a factor of about two relative to the stress without a hole. The geometry of the finite element model did not include the presence of a chamfer at the corners of the hole. The peak stress as indicated in the lower plot of Figure B-1 had a value of 12,953 psi for the 400-pound load. This was the loading at the inner ring (2.5 inch diameter) and outer ring (6.0 inch diameter).

Figure B-2 shows the variation in stress along the tensile surface of the specimen spanning the distance from the edge of the 2.5-inch diameter hole to the outer edge of the finite element model at a diameter of 14.486 inch. The finite element model approximated the geometry of the square plate with a circular plate. The outer diameter of 14.486 corresponded to the average of the 12x12-inch dimension of the square plate and the diagonal dimension of the plate. Figure B-3 shows the effect of the assumed outer diameter assumed for the circular plate. If the plate diameter is terminated at the diameter of the outer loading ring (6 inches) the maximum hoop stress at the edge of the center hole is significantly higher (16,115 psi) than the predicted stress (12,953 psi) for a plate with an overhang beyond the 6.0 inch loading diameter.

Figure B-4 shows results of calculations for the 12x12 inch plate specimen that did include the center hole, but did account for the effects of large bending displacement at high load levels. It is seen that nonlinear effects come into play only at loads of about 1500 pounds or greater. The breaking loads of the tests perform for Visteon were all less than 1500 pounds. It was concluded that nonlinear effects from large transverse bending displacements did not need to be considered in calibrating the ring-on-ring tests.



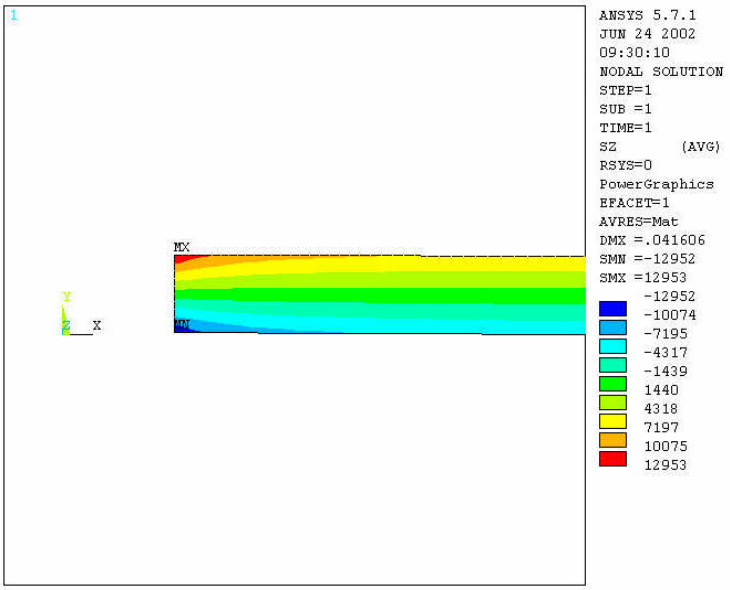


Figure B-1 Stress Distribution for Ring-on-Ring Specimen with Hole Peak Hoop Stress = 12,953 psi (400 lb. Load)

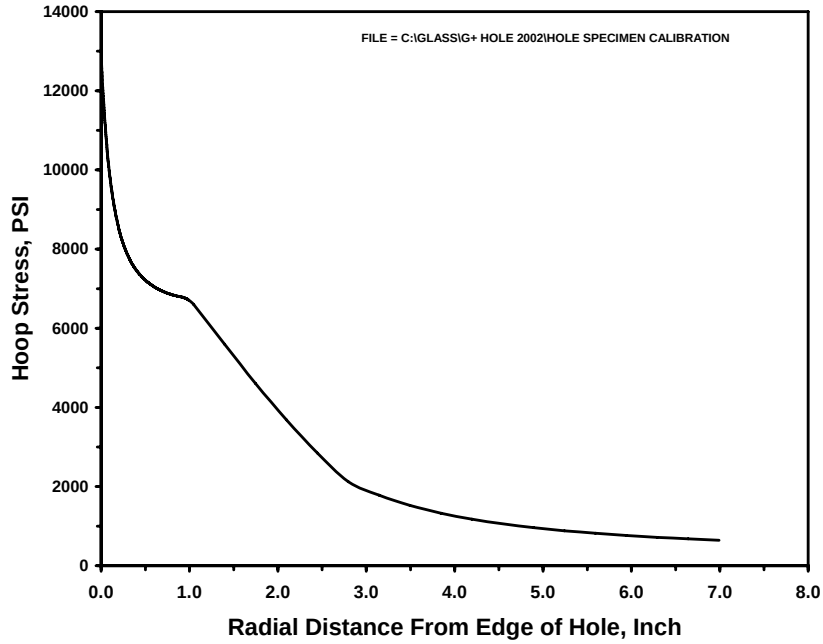


Figure B-2 Stress Concentration at Hole

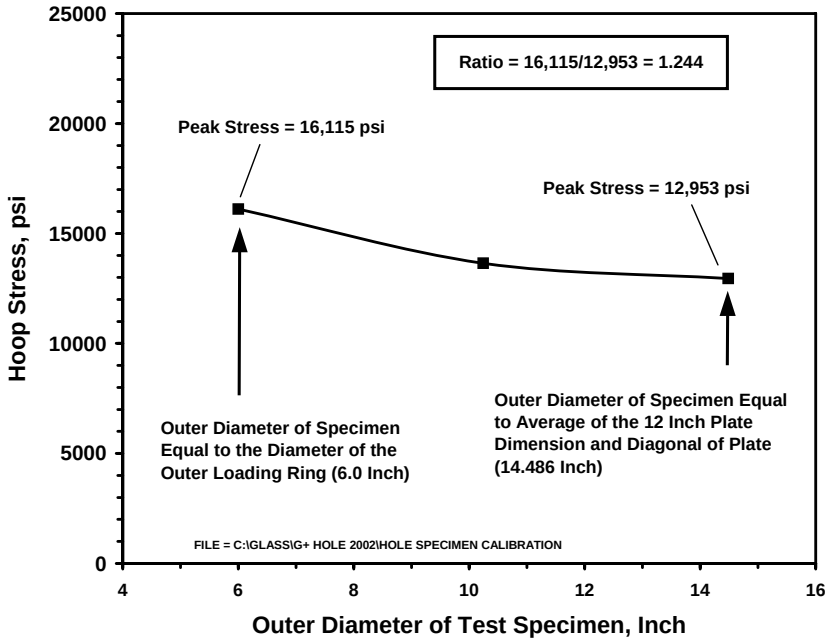


Figure B-3 Effect of Outer Dimension of Test Specimen

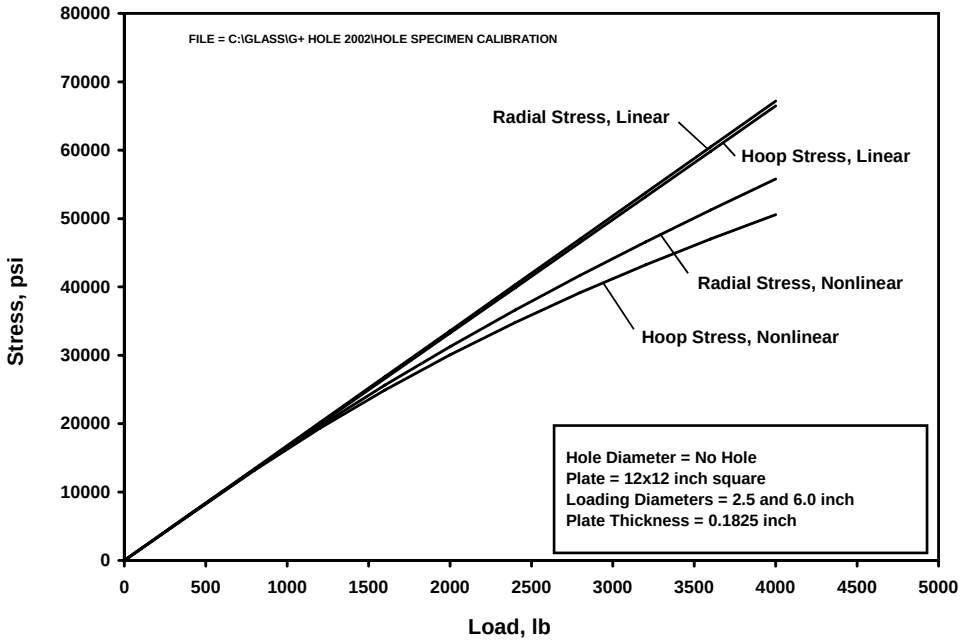


Figure B-4 Effect of Large Deflection on Calculated Stress