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VALIDATION TESTING OF SHALLOW - NOTCHED ROUND-BAR SCREENING TEST SPECIMENS

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FOREWORD

This report summarizes the testing and analysis performed under contract NAS8-27980 to assess the capability of shallow-notched round-bar tensile specimens for screening critical environments as they affect the material fracture properties of the Space Shuttle Main Engine.

ABSTRACT

Round-bar tensile specimens containing a 0.050-inch-deep circumferential sharp notch were cyclically loaded in a 5000-psi hydrogen environment at temperatures of +70 and -15 F. Replication of test results and a marked change in cyclic life because of temperature variation demonstrated the validity of the specimen type to be utilized for screening tests.

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BACKGROUND

The Space Shuttle Main Engine (SSME) has many components that are subjected to high stresses in aggressive environments. To prevent premature failure of these components because of an undetected crack-like defect, a design criteria has been established utilizing the application of fracture mechanics. Life-prediction analyses must show that either the proof testing or the NDE (nondestructive evaluation) is adequate to detect and cause removal of any flaws that could cause premature failure.

Fracture mechanics calculations used to obtain life predictions require a knowledge of the crack growth rates for the material in the design environment. Several of the materials in critical regions of the SSME are subjected to widely varying environments of high-pressure hydrogen and hydrogen steam at various temperatures. It is impractical to perform fracture mechanics material testing to obtain crack growth rates for each of the design environments, not only because of the many variations in the environment, but also because the engine operating cycle of approximately 9 minutes makes crack growth testing a time-consuming and expensive procedure. Attempts to reduce the cycle-load time have not been successful because a significant change in crack growth rate characteristics resulted from the time change, and a quantitative time factor could not be established. Therefore, real-time growth rate testing appears to be necessary. As an alternative to reducing the time per specimen, an approach was developed that was based on the principle of "screening" the design environments. By determining which environment was more critical, and then obtaining the material crack growth rates only for the more critical environment, testing in the less-critical environments could be eliminated. If a relatively inexpensive screening test specimen could be found it would greatly reduce the total fracture mechanics material testing time and expense.

The most desirable test specimen, with respect to obtaining design-related data, is the part-through crack (PTC) specimen. Serious consideration was given to using the PTC specimen for screening test purposes. The principal advantage would be the close simulation of the crack-like defects of concern in the SSME. However, several disadvantages were associated with PTC specimens. First, PTC specimens are expensive. The cumulative expense of machining the overall specimen, creating a starter flaw, and precracking to the desired depth results in a significant cost before testing is started. Second, a large environmental chamber is necessary to surround the specimen. If only the media and pressure had to be created, a pressure cup could be used to cover the cracked region; but with broad temperature ranges an environmental chamber surrounding the specimen is necessary. Third, and perhaps most important, the actual crack size in the specimen is not always consistent or predictable. Therefore, if a series of screening tests were run to compare environments, the results might be negated because of variations between specimens. The cyclic life of screening test specimens should provide an index of the environments tested without requiring the data to be processed as a function of initial crack size or shape.

In the analytical work that preceded the fabrication and testing of specimens, it appeared that the shallow-notched round-bar (SNRB) test specimen provided the major advantage of the PTC specimen while reducing the magnitude of the disadvantages. The SNRB specimen is basically a round-bar tensile specimen with a central circumferential notch forming a part-through crack of near infinite aspect ratio (depth divided by surface length). Figure 1 shows the configuration used for the testing reported here, but the given notch geometry is not mandatory. Other notch configurations may adequately form the stress riser to simulate a crack. The notch geometry is limited only by the available machining techniques.

With respect to the disadvantages of the usual PTC specimen: (1) the SNRB specimen is relatively cheap to manufacture because of its shape; (2) the notch can be made very sharp because it is accessible (therefore, precracking may not be necessary); (3) the notch geometry can be measured prior to testing so replication is assured; and (4) the SNRB specimen requires only a small environmental chamber to be completely surrounded. Also, the SNRB specimen requires a relatively small amount of material, allowing a greater latitude in the material form that can be tested.

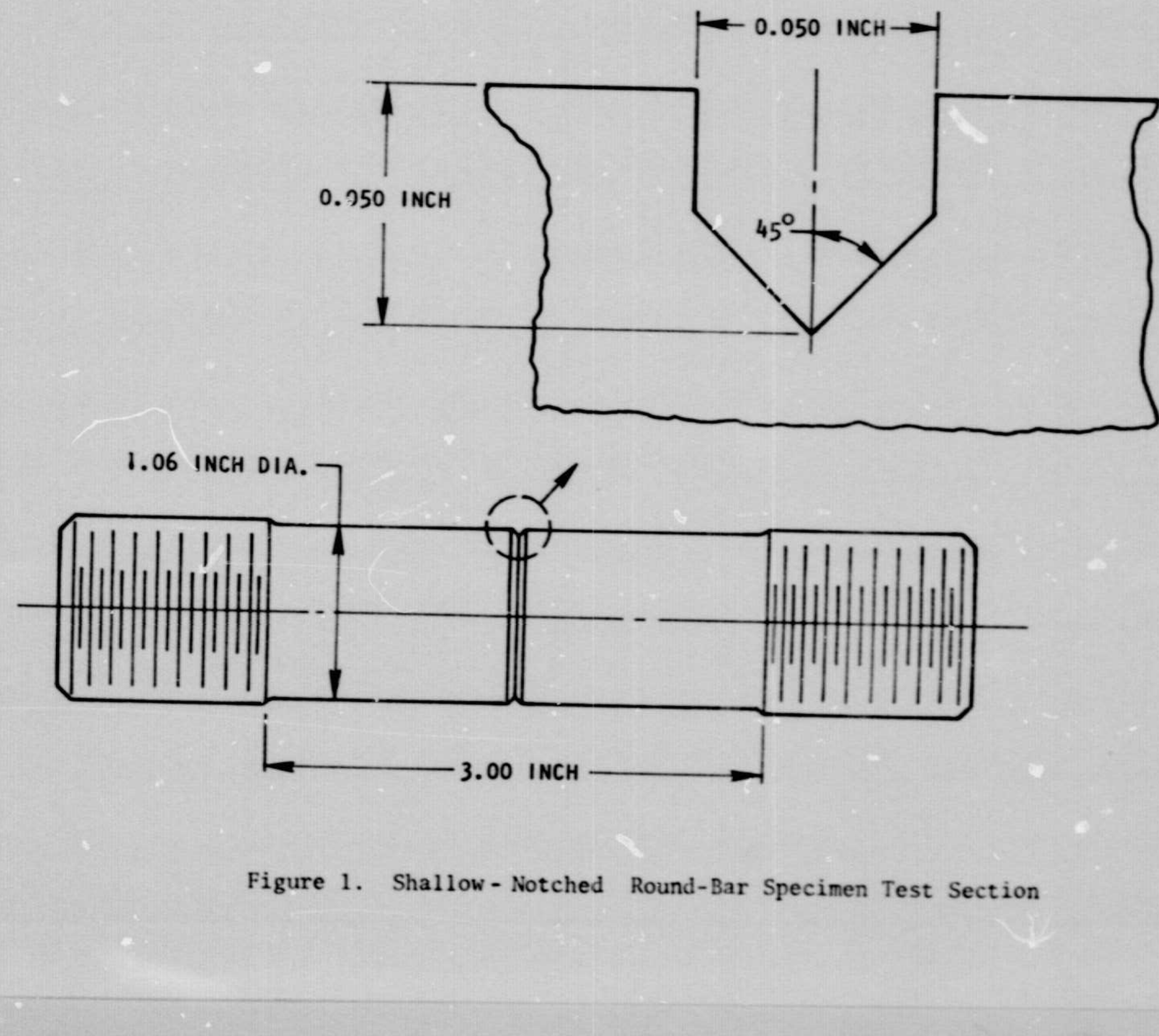

Figure 1. Shallow-Notched Round-Bar Specimen Test Section

Although several important questions remained unanswered, the possibility of achieving considerable savings in compact specimen testing made the performance of validation testing seem worthwhile to assess the characteristics of SNRB specimens as a vehicle for screening SSME environmental effects on material crack growth rates.

PRETEST ANALYSIS OF THE SNRB

For small crack depths relative to the gross section, the stress intensity at the crack front can be approximated by the following relationship:

$$K = \sigma \sqrt{\pi a}$$

where

σ = gross stress near the notch

a = notch depth

Because Inconel 718 material is of primary interest in the SSME, the first specimens used were comprised of this material. Operating stresses in the SSME approach the yield stress so a stress of 160 ksi (room temperature yield strength) was chosen as a maximum sustained stress for cyclic loading. An initial notch depth of 0.050 inch (nominal) was selected to cause an initial stress intensity somewhat greater than 60 ksi $\sqrt{\text{in.}}$, thereby causing failure to be assured within a relatively few cycles if the specimen performed in a predictable manner.

Data from compact specimens in room temperature 5000-psi hydrogen showed a threshold for environmental effects to be at about 40 ksi $\sqrt{\text{in.}}$ Therefore, rapid growth was to be expected at the initial specimen stress intensity of 60 ksi $\sqrt{\text{in.}}$ The plain strain plastic zone size predicted for the specimen was 0.022 inch so the machined notch sharpness of less than 0.001 inch radius was believed to be adequate without precracking. However, the large size of the plastic zone relative to the notch depth (0.022 versus 0.050 inch) raised the question of a stress concentration reduction. Considerable information was available concerning plastic zone effects on true cracks, but this information did not necessarily apply to the notch of the SNRB specimens. A judgment estimate was made that the reduction in stress concentration (due to plasticity) would be offset by the effective crack deepening usually associated with a plastic zone correction.

VALIDATION TESTS PLANNING

The importance of screening test specimens to the SSME materials fracture testing program demanded that empirical validation of the specimen type be obtained before the program could be committed to this technical approach. Although the available information provided a certain degree of confidence that SNRB specimens would perform adequately, some doubts still existed that could be removed only through actual testing. For this reason a series of tests was planned that would assess the validity of SNRB specimens as a vehicle for screening tests.

The primary requisite for a crack growth rate screening test specimen is to provide an index of the relative growth rates as a function of small environmental changes. SNRB specimens were predicted to provide such an index by counting the number of load-time cycles that replicate specimens survived in differing environments. Obviously the data scatter for those specimens must be small if the same specimens are to reflect subtle changes in environmental effects. To assess the ability of SNRB specimens to provide a valid index of environmental effects, the following plan was initiated:

1. Manufacture four nominally identical SNRB test specimens as defined in Fig. 1.

2. Test two specimens to failure in the environment of 70 F, 5000-psi hydrogen, using the load-time cycle of Fig. 2 .

3. Test two specimens to failure in the environment of -80 F, 5000-psi hydrogen, using the load-time cycle of Fig. 2 .

The data expected to result from the above testing was planned to provide a measure of the specimen-to-specimen data scatter relative to the mean shift of specimen life (attributable to the environmental change). Test data from Inconel 718 compact specimens obtained in these environments showed a significant decrease in

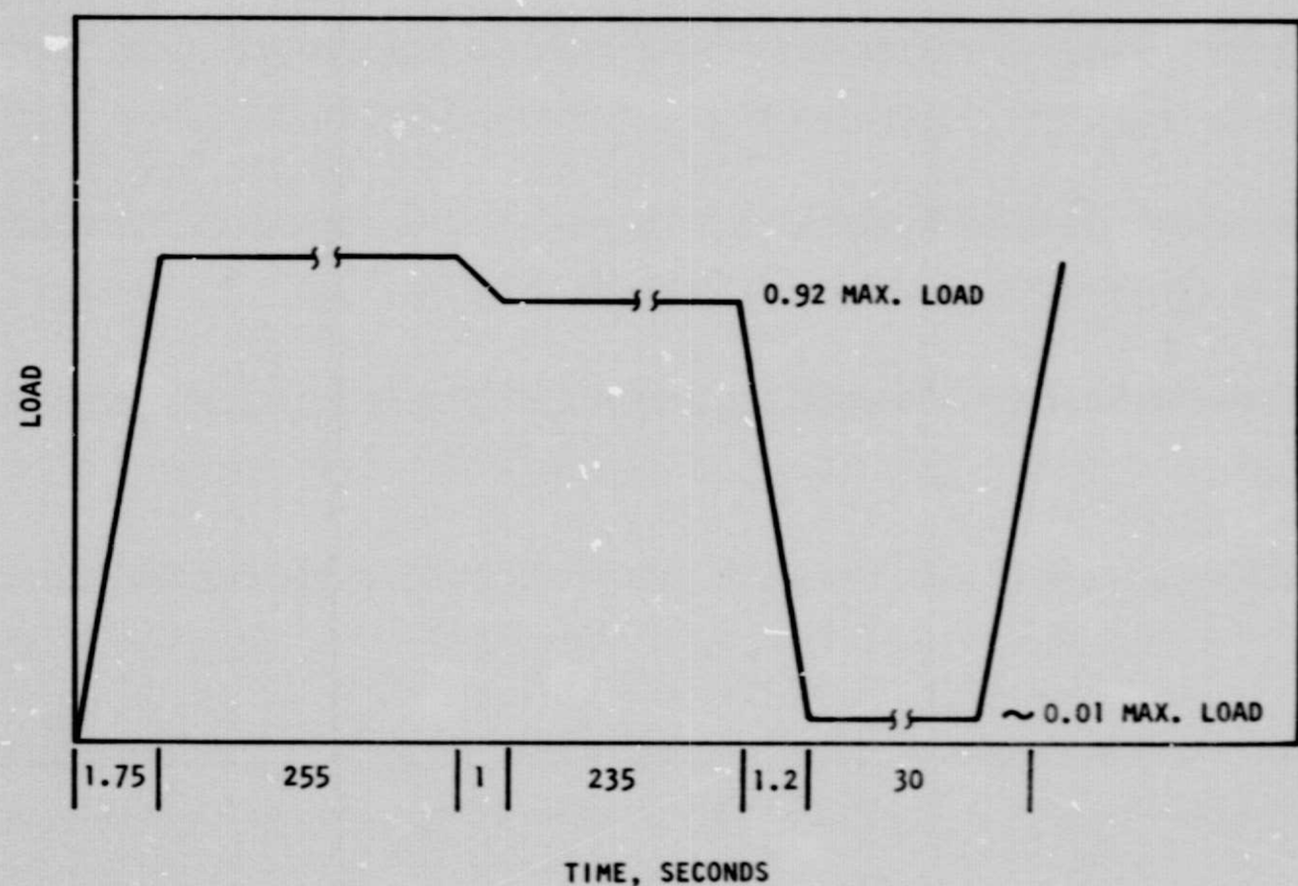

Figure 2. Simulated SSME Load-Time Cycle

growth rate at the lower temperature (-80 F) so the SNRB specimen results could be compared with known data.

Several other items of interest were not primary test objectives, although they affected the confidence that could be placed in the test results. The specimen fracture faces were hoped to exhibit the markings of subcritical crack growth, not only to determine the average growth rate, but also to determine the uniformity of crack growth. Confidence in the test results would be affected if crack growth were not found to occur along the full length of the notch circumference. This would suggest that the notch was not sufficiently uniform and/or sharp, leading to the possibility that data scatter would be large. Precracking could be used to sharpen the notch, if necessary, but the additional time and expense of precracking hopefully could be avoided.

Another item of interest relating to fracture face markings was the effect on specimen behavior caused by misalignment of the loading fixture. The SNRB specimens are nominally loaded in pure tension, but fixture misalignment introduces bending, thereby causing uneven loading of the notch circumference. When the bending stress is significantly large relative to the direct tension stress, the crack growth will be correspondingly affected. Bending causes the fracture face markings to exhibit a crack front ring that is eccentric to the original notch (crack) front. Hopefully, each SNRB specimen would show uniform crack growth, but the real question of interest was the data scatter (specimen-to-specimen) of the cyclic life.

TEST RESULTS

Testing of the first two replicate specimens in 70 F, 5000-psi hydrogen went as planned. Specimen I-18 survived four cycles before failure and Specimen I-19 survived three cycles before failure. Test result replication was even better than indicated by the cycle count because I-19 failed near the end of the 9-minute hold time of the fourth cycle and I-18 failed as the load was increasing to begin the fifth cycle. With this evidence that the SNRB specimen would provide replicate test results, the decision was made to proceed with testing in the lower temperature environment.

Specimen I-17 was tested in -80 F, 5000-psi hydrogen until a total of 55 cycles of loading had been accumulated without failure. At this point it was decided that the change in crack growth rates relative to the 70 F environment was too large to properly assess the validity of the specimen for screening tests, so the environmental chamber (dewar) was allowed to warm up while the cyclic loading continued. After 71 additional cycles (126 total), the specimen failed. The dewar temperature was approximately -15 F when failure occurred. This temperature was believed to be sufficiently high to expect failure in a reasonable number of cycles and still accomplish the objectives of validity testing. On this basis the test plans were redirected to test replicate specimens at -15 F.

Specimens I-20 and I-21 were tested in -15 F, 5000-psi hydrogen until failure occurred. Specimen I-20 survived 22 cycles and I-21 survived 15 cycles.

Figure 3 shows the temperature effect indicated by the subject screening test specimens. Each specimen provides one data point on the plot. Note that the specimen tested at -80 F is plotted as having survived 126 SSME cycles. Actually, the specimen only survived 55 cycles at the lower temperature, but little doubt exists that 126 cycles would have been survived if the temperature had not been increased.

The plot of Fig. 3 demonstrates that the scatter between replicate test results is acceptably small relative to the average effect of changing the environment.

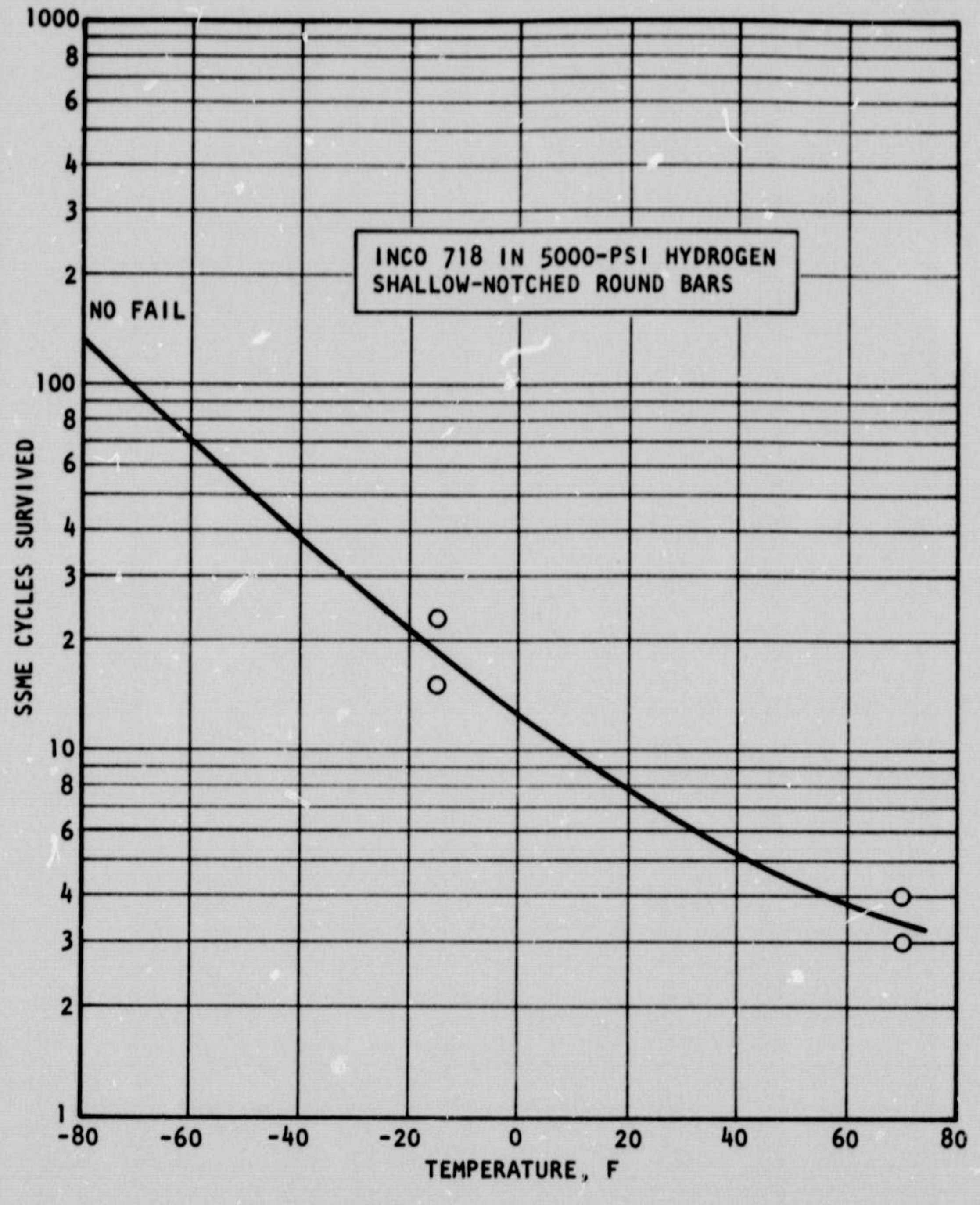

Figure 3. Temperature Effect Indicated by Screening Test Specimens

Although four specimens are not a statistically large number on which to generalize conclusions, the SNRB specimens apparently provide a strong index by which to measure the relative effect of differing environments.

All four specimens had fracture face markings to indicate subcritical crack growth prior to failure. Figure 4 shows sketches of the fracture faces enlarged 2.75X scale with the solid outer lines indicating the original notch root location and the dashed lines indicating the extent of the apparent subcritical growth.

The general smoothness of the crack front contour supports the position that the machined notch sharpness is adequate without the necessity of precracking. A lack of sharpness is characteristically indicated by nonuniform crack growth. Dull notches usually evidence cusps or bulges in the crack front because the dullness accentuates the normal material variation in transforming from a notch to a true crack during the initial cycling. Local increases in crack size then increase the local stress intensity, which, in turn, increases the crack growth and forms a bulge.

Eccentric loading because of fixture misalignment probably caused the eccentricity of the crack growth marking ring most evident on the fracture faces of Specimens I-18 and I-19. There is no reason to believe that the fixture misalignment during these tests was any different than the usual tests so the effect on test results must be assessed. A strong coincidence is noted in the fact that the two specimens tested at 70 F exhibited the most eccentricity in the growth ring, whereas the specimens tested at -15 F had some growth at all points along the notch circumference. This coincidence suggests that the differences in growth markings are more a function of the material characteristics (as affected by the environment) than a consequence of fixture alignment variations. The best evidence that normal fixture misalignments are acceptable can be drawn from the fact that the two specimens with the closest replication in cyclic life (Specimens I-18 and I-19) showed the greatest eccentricity in growth ring markings. Apparently the normal variation in fixture misalignment does not greatly affect the cyclic life of the SNRB specimen in low cycle fatigue.

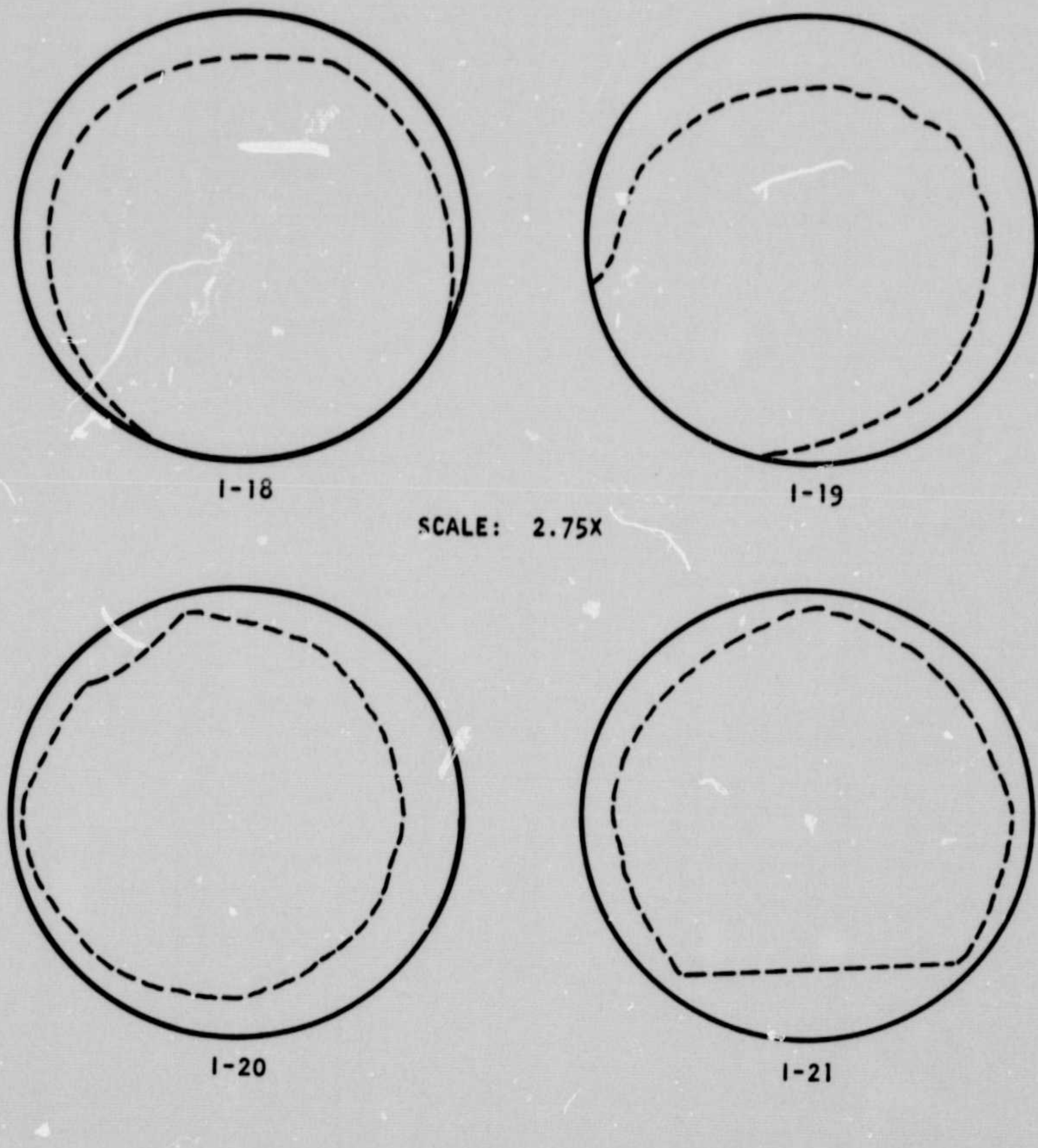

Figure 4. Subcritical Crack Growth Fracture Face Markings

CRACK GROWTH RATE CALCULATIONS

Although the SNRB screening test specimens were not intended to provide any data other than "cycles-to-failure," a posttest decision was made to assess the correlation between previously obtained compact specimen data and crack growth rates calculated from SNRB fracture face measurements. A simple approach was used, basically similar to the procedure associated with PTC specimens.

1. Using the pretest specimen dimensions, calculate the initial notch (crack) depth:

$$a_i = \frac{\text{Gross Diameter - Notch Diameter}}{2}$$

2. Assume the crack growth measured on the fracture face is the change in crack depth:

$$\Delta a = \text{crack growth at given location}$$

3. Calculate the average crack size over the measured length of growth:

$$a \text{ average} = a_i + \frac{\Delta a}{2}$$

4. Calculate the average stress intensity over the measured length of growth, neglecting crack front curvature and plasticity corrections:

$$K = \sigma \sqrt{\pi a}$$

where

σ - gross section stress

a = a average

5. Calculate the crack growth rate:

$$da/dN = \Delta a \div \text{(number of cycles)}$$

6. Plot da/dN versus K (equals ΔK for $R=0$)

In Step 5 of the procedure the failure cycle is assumed to leave no crack growth marks, so only the number of cycles survived without failure are used in the calculation.

Summary pages of the crack growth calculations are presented in the Appendix. Figure 5 shows the calculated data plotted along with the previously obtained compact specimen data.

The SNRB specimen data obtained from 70 F testing can be seen to fall in with the compact specimen data obtained at the same temperature. The -15 F SNRB data appear to be appropriately separated from the 70 F and -80 F compact specimen data. Only three data points were calculated for each specimen because any additional points would fall on the same line. A locus of all points for each specimen is uniquely determined by the initial notch depth, the gross stress, and the number of cycles survived. Only the portion of the locus line associated with measured crack growths is shown in Fig. 5.

A measure of scatter in the crack growth rate data can be obtained by comparing the specimen-to-specimen variation with the effect of changing temperature. Both replicate pairs showed a growth rate factor of approximately 1.3 between the higher and lower values at each temperature. In contrast, the average indicated growth rate at 70 F shows a factor of approximately 5.0 over the corresponding value at -15 F. The SNRB specimen data provides an excellent measure of the temperature effect on environmental crack growth for Inconel 718 material in 5000-psi hydrogen.

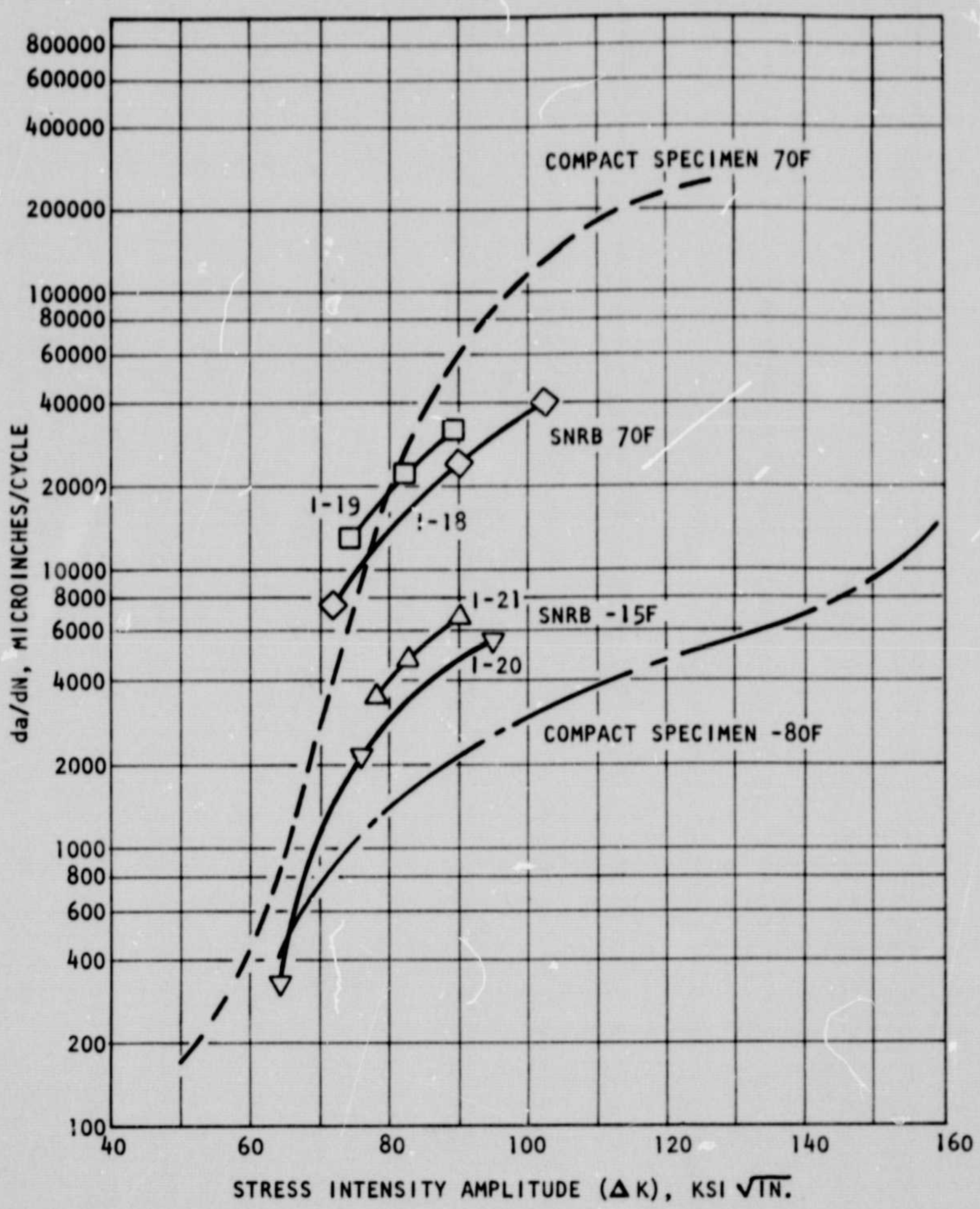

Figure 5. Inconel 718 Growth Rate in 5000-psi Hydrogen

CONCLUSIONS

The following conclusions were reached as a result of the subject testing and analysis:

1. Shallow-notched round-bar specimens provide a valid indication of relative environmental effects.
2. Inconel 718 specimens intended for testing in high-pressure hydrogen do not require precracking if the machined notch is adequately sharp.
3. Specimen notch depths of 0.050 inch are adequate to precipitate failure in a reasonable number of cycles, when environmental crack growth effects are large.
4. Normal fixture misalignment does not greatly influence the cyclic life of the shallow-notched round-bar specimens.

APPENDIX

SHALLOW - NOTCHED ROUND-BAR SPECIMEN TEST RESULTS

The following pages present the test data obtained for the wrought Inconel 718 specimens used during this test series. Four specimens were tested overall.

SHALLOW - NOTCHED ROUND-BAR
SCREENING TEST SPECIMEN I-18

Material: Inconel 718 Wrought

Test Temperature: 70 F

Test Media: 5000-psi hydrogen

Gross Stress: 160 ksi

Cycle Life: 4

Measurement Location	Initial Depth, inch	Delta Depth, inch	Average Depth, inch	Average K	da/dN
1	0.050	0.030	0.065	72.3	7,500
3	0.050	0.100	0.100	89.7	25,000
5	0.050	0.160	0.130	102.3	40,000

SHALLOW - NOTCHED ROUND-BAR

SCREENING TEST SPECIMEN I-19

Material: Inconel 718 Wrought

Test Temperature: 70 F

Test Media: 5000-psi hydrogen

Gross Stress: 160 ksi

Cycle Life: 3

Measurement Location	Initial Depth, inch	Delta Depth, inch	Average Depth, inch	Average K	da/dN
2	0.049	0.040	0.069	74.5	13,300
4	0.049	0.070	0.084	82.2	23,000
6	0.049	0.100	0.099	89.2	33,000

SHALLOW-NOTCHED ROUND-BAR

SCREENING TEST SPECIMEN I-20

Material: Inconel 718 Wrought

Test Temperature: -15 F

Test Media: 5000-psi hydrogen

Gross Stress: 160 ksi

Cycle Life: 22

Measurement Location	Initial Depth, inch	Delta Depth, inch	Average Depth, inch	Average K	da/dN
1	0.048	0.007	0.0515	64.4	318
3	0.048	0.047	0.072	75.8	2,140
6	0.048	0.124	0.110	94.1	5,600

SHALLOW-NOTCHED ROUND-BAR

SCREENING TEST SPECIMEN I-21

Material: Inconel 718 Wrought

Test Temperature: -15 F

Test Media: 5000-psi hydrogen

Gross Stress: 160 ksi

Cycle Life: 15

Measurement Location	Initial Depth, inch	Delta Depth, inch	Average Depth, inch	Average K	da/dN
1	0.049	0.053	0.076	77.9	3,530
2	0.049	0.071	0.085	82.4	4,730
3	0.049	0.104	0.101	90.1	6,930