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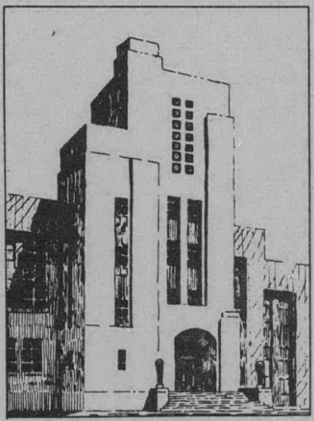
TRANSITION CHARACTERISTICS OF PRESTRAINED, NOTCHED STEEL SPECIMENS IN TENSION

by

Edward M. MacCutcheon and
Willard A. Wright



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by

E.M. MacCutcheon and W.A. Wright

ABSTRACT

The prestraining of notched steel plates or structures above the brittle-to-ductile transition temperature was suggested as a means of increasing toughness in performance at lower temperatures. An exploratory study was made with edge-notched bars cut from 3/4-inch-thick plates of four different steels. As a result of the prestrain procedure employed, three of the four steels exhibited somewhat greater toughness at a temperature just below the transition temperature.

An analysis of ship service data showed that small changes in toughness can influence the risk of fracture when marginal temperature conditions prevail. However, it was found that the lowering of the brittle-to-ductile transition temperature caused by the prestrain procedure was small, namely, about 5 degrees F.

INTRODUCTION

Current extensive studies of steel toughness have revealed that the scatter of results in the vicinity of the brittle-to-ductile transition temperature is a common phenomenon. Some tests have been observed which indicate that not all of the scatter is explainable by inhomogeneity of the steel. Of special importance to this study is a specimen tested at Swarthmore College. This specimen was partially strained at a temperature well above the transition temperature for the particular steel. The test was then continued at a temperature well below the transition temperature. During this second part of the test, the specimen absorbed more energy and went to a higher load than any specimen previously tested, including all those which were tested above the transition temperature.

Other parallel instances have come to the attention of the authors. For example, Mr. T.W. Green[1] presented tests showing that the so-called low-temperature stress-relieving process improved the low-temperature performance

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[1] References are listed on page 18.

of welded plates with built-in cracks. The process results in prestraining at 300° to 400° F., and it was believed by some that this had caused the increased toughness of the specimens.

More recent reports on a phenomenon which has been labeled "rheotropic embrittlement"[2] indicate that the prestraining of ordinary tensile bars alters the crystalline structure and promotes a favorable orientation of the fibers so that greater ductility occurs in tests at lower temperatures.

These findings have begun to form into a pattern. The authors suggest that this behavior may not be inherent in the material alone but may be associated also with the geometry of the specimen employed for the test. If it is associated with the geometry, then the performance can be studied with relation to the brittle-to-ductile transition temperature. It can be reasoned further that it might be possible to toughen the structure effectively by prestraining at a warm temperature. The practical possibilities of this technique called for an exploratory study.

This report presents the results of a preliminary investigation[3] conducted on samples of steel that were available at the David Taylor Model Basin. The objective was to determine the effect of prestraining at a temperature above the transition temperature on the brittle-to-ductile transition characteristics of ship plate steel. The tests described were exploratory in nature and the variety of pre-conditioning techniques was limited to those which could be employed easily in practice.

TEST SPECIMENS

Tests were made of two of the "S" series of plates, which conform to the new American Bureau of Shipping Class-B requirements, and of Dn and E steels which are "project" steels of the Ship Structure Committee. Plates $S2_E$ and $S3_E$ were from one heat, but they differed in grain size (austenitic grain size at 1700° F. as determined by the method of McQuaid and Ehn). Steel Dn is a fully-killed normalized steel and Steel E is a rimmed steel. Particulars of all the plates tested are given in Tables 1 and 2.

The test specimen used was a 1-inch-by-12-inch, full thickness, edge-notched bar of ship plate. This specimen was loaded by tension in the direction of the longest dimension, which was also the direction of rolling of the steel plates. The notch effect was introduced by hacksaw cuts in each side of the specimen leaving a 3/8-inch-wide test section (see Figure 1). Reference 4 indicates that the edge-notch test specimen 1 inch in width is a satisfactory indicator of the transition characteristics of larger specimens.

TABLE 1

Chemical Analysis of Mill Heats in Percent

Steel Code	C	Mn	Si	P	S	Cu	N	Type of Steel*	Grain Size**
$S2_E$	0.18	0.61	0.055	0.007	0.021	0.05	0.0052	S-K	1-4
$S3_E$	0.17	0.61	0.054	0.007	0.020	0.05	0.0046	S-K†	5-8
Dn	0.22	0.55	0.21	0.013	0.024	0.22	0.004	Si-K	-
E	0.20	0.33	0.01	0.013	0.020	0.18	0.002	Rim.	-

*Rimmed (Rim.), Semi-Killed (S-K), or Si-Killed (Si-K).

**McQuaid-Ehn.

†The steel for these plates was modified by the addition of aluminum in the ingot mold.

Data obtained from the Office of Inspector of Naval Material, Coatesville, Pa.

TABLE 2

Mechanical Properties of Steel from Mill Heats

Steel Code	Gage inches	Tensile Strength psi	Yield Point psi	Elongation in 8 Inches percent	Reduction in Area percent
$S2_E$	3/4	58,900	30,500	34.0	
$S3_E$	3/4	58,000	29,200	33.0	61.0
Dn	3/4	67,200	40,500	27.0	50.1
E	3/4	62,500	38,000	28.0	52.3

Data obtained from the Office of Inspector of Naval Material, Coatesville, Pa.

INSTRUMENTATION

The apparatus for measuring the thickness reduction to control the prestrain consisted of a leaf spring on which were mounted two SR-4 strain gages, one on each face of the spring. The strain gages were connected by a circuit that recorded the bending of the spring on a Baldwin strain indicator. This spring was held in a yoke which was fitted around the test specimen to hold the leaf spring perpendicular to the specimen at the center and midway between the notch roots. Figure 2 shows the leaf spring and yoke in position.

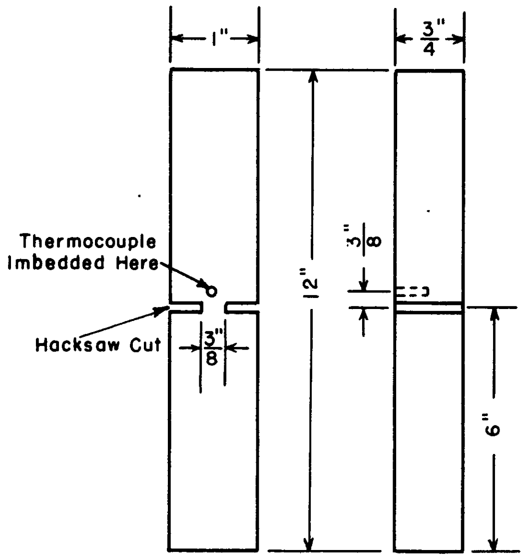

Figure 1 - Notch Tensile Specimen Showing Hacksaw Cut and Thermocouple Location

The spring gage was given a check calibration against two mechanical dial gages before each series of tests was begun. All other thickness measurements were made with a pointed micrometer, including checks on the prestrain thickness reduction.

The temperature-control equipment consisted of a set of radiant resistance heaters and a powerstat (variable transformer). The electric-resistance heaters were mounted parallel to each other on a frame and far enough apart to permit a test specimen and fittings between them (see Figure 3). Two curved mirror surfaces were located outside of the heaters and helped to direct heat energy onto the specimen. The heaters were controlled manually through the powerstat.

The exact temperature of the specimen was indicated by a thermocouple imbedded in the specimen in the vicinity of the notch root (see Figure 1). Temperature was accurately controlled throughout each test.

The tests were performed in a 30,000-pound universal testing machine at the Taylor Model Basin.

TEST PROCEDURE

PRESTRAINING OF SPECIMENS

The specimens were prestrained at a temperature 50 to 60 degrees above the transition temperature for the different steels as indicated in Reference 4 and Table 3. A series of exploratory tests was performed on Dn steel with a variety of prestrains. The remainder of the specimens of all steels were then prestrained to 0.005-inch thickness reduction. The rate of application of prestrain load was 15,000 pounds per minute from zero up to the yield load for all specimens. Above the yield load, the strain rate varied somewhat from specimen to specimen. When the strain indicator showed that the specimen had been prestrained the desired amount, the load was released. The thickness reduction was checked with a dial micrometer by measuring through the neck before and after prestrain.

TABLE 3

Temperatures During Prestraining and Tests

Steel	Brittle-to-Ductile Transition Temperature, Degrees, F. From Reference 4	Prestraining Temperature Degrees, F.	Rupture Test Temperature Degrees, F.
Dn	87	140	75
E	180	240	170
$S2_E$	130	180	120
$S3_E$	90	140	80

RUPTURE TESTS

The testing temperature for Dn steel was 12 degrees below and for the remaining steel samples 10 degrees below the transition temperature of Reference 4 (see Table 3). In addition tests were made on specimens of Dn steel, prestrained 0.005-inch thickness reduction, at several other temperatures.*

The load was increased from zero to rupture at a rate of 15,000 pounds per minute. The criterion for ductility was the maximum contraction in thickness between the two faces of the specimen in the area between the notch roots.

The surfaces of the fractures of all specimens were examined, and the character of the fracture was recorded as fibrous or granular.

RESULTS

The hypothesis is advanced that the total strain, i.e., the prestrain plus the strain during test, will be equal to a constant amount regardless of the portion consumed in the prestrain. In Figure 4 the ordinate is the strain recorded during the test and the abscissa is the prestrain. To conform to the hypothesis, the prestrain consumes a portion of the ductility so that the reserve is decreased by the amount of the prestrain. Thus the line M indicates the location of test results if brittle specimens perform exactly in conformance with the hypothesis. Any departure from the line M presumably indicates the presence of a physical phenomenon. Thus points below the line might result from strain aging whereas points above the line might occur for

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*Some specimens of Dn steel had to be cooled below room temperature and then transferred to the testing position in the machine and allowed to reach the testing temperature. In this case, the reported temperature is that at 15,000 pounds load and the rupture temperature was 2° to 5° F. higher.

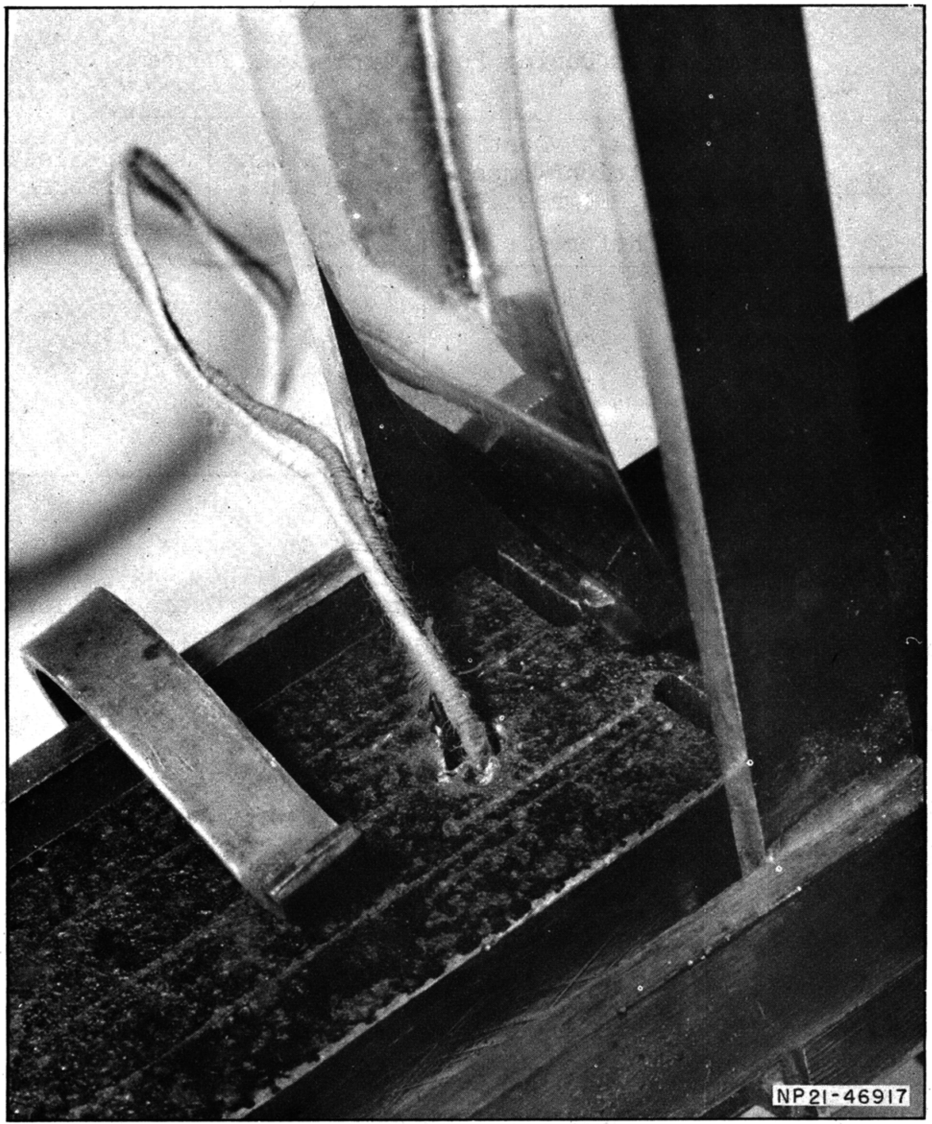

Figure 2a - Closeup Showing Leaf Spring and Thermocouple Location

some other reason. For instance, if the test results occur at Point a, then the vertical distance A is indicative of the presence of a physical phenomenon. In like manner, Line N represents the hypothetical behavior of ductile specimens.

Data from the tests are presented graphically in Figures 5 through 8. The thickness reduction during the rupture test is plotted against the prestrain. The points represent the numerical average of several test results. The number of test results is indicated by the numeral beside the plotted point. The vertical bracket designates the range or scatter of results encountered under identical prestrain and temperature conditions.

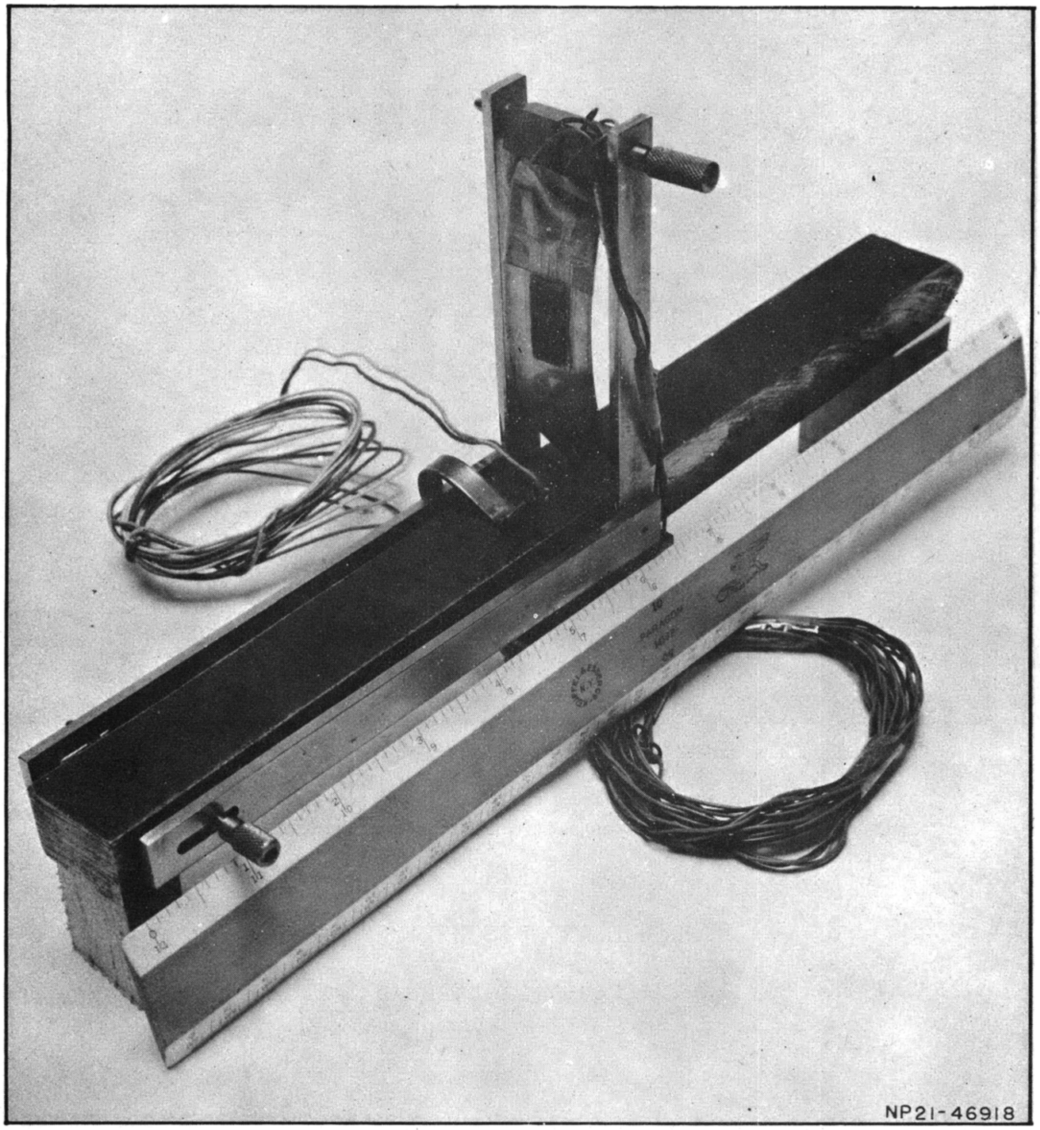

Figure 2b

Figure 2 - Thickness Gage Mounted on Specimen

Table 4 gives the results of Dn steel specimens tested at 75° F. but prestrained more or less than 0.005-inch thickness reduction. Table 5 is a tabulation of the results of tests of specimens of all four steels prestrained to a thickness reduction of 0.005 inch and of control specimens that had not been prestrained. All rupture tests in Table 5 were made at temperatures immediately below the transition temperature. Table 6 presents results of tests on Dn specimens tested at temperatures other than 75° F.

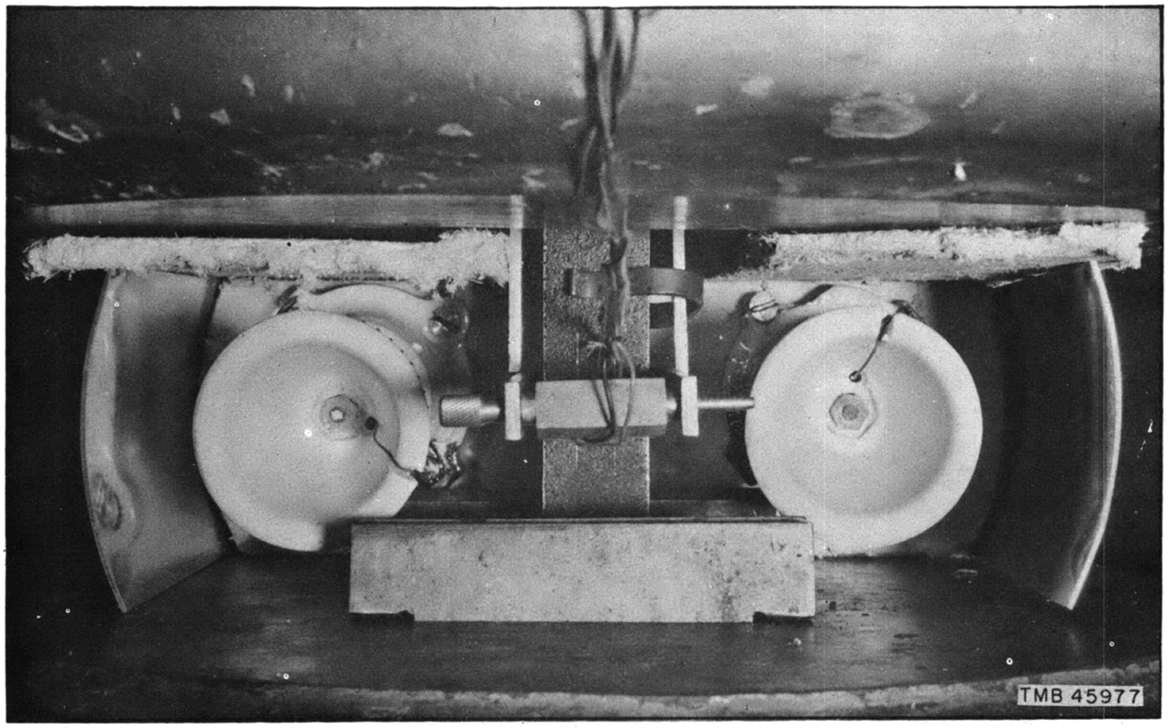

Figure 3 - Test Specimen in Position for Testing

Two electric resistors form the heating unit. The curved metal mirrors can be seen at each side of the heater unit.

FINDINGS AND DISCUSSION

Not all the physical effect (Distance A in Figure 4) is useful for practical purposes. If the prestrain method is to be beneficial, the service strain must actually exceed the strain that would occur in a structure which had not been prestrained. Thus the absolute amount of strain during the test must exceed the strain observed in tests of specimens with no prestrain. This performance is indicated by Distance B on Figure 4.

The exploratory study described in this report involves an attempt to answer two related questions:

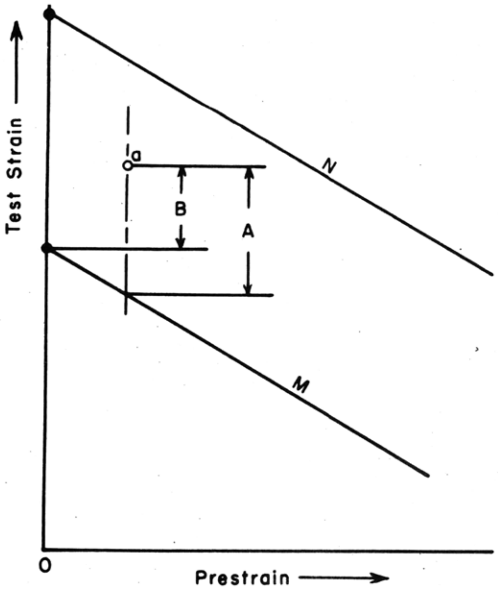

Figure 4 - Diagram of Method of Data Presentation

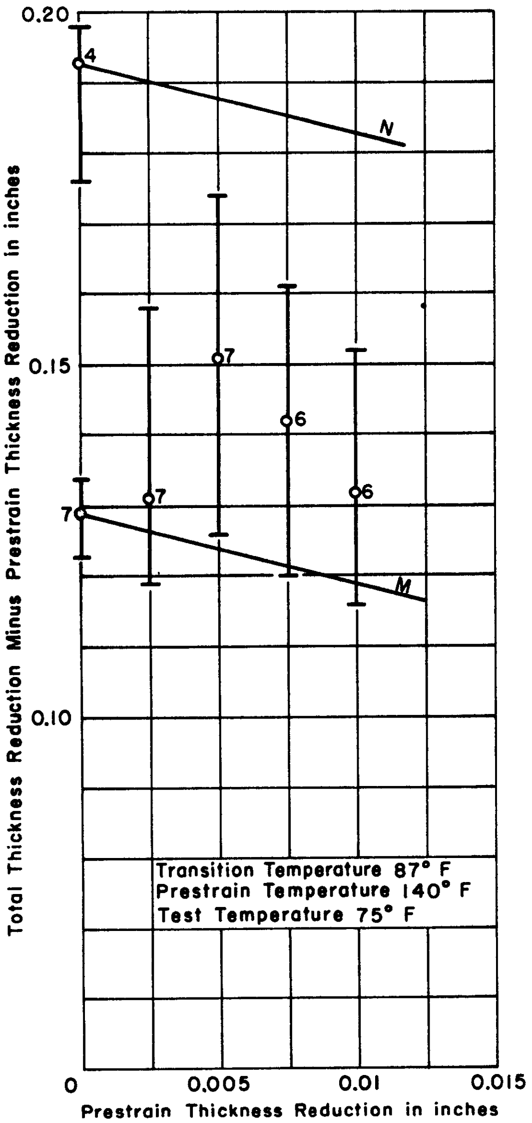

Figure 5 - Data from Rupture Tests of Dn Steel Specimens

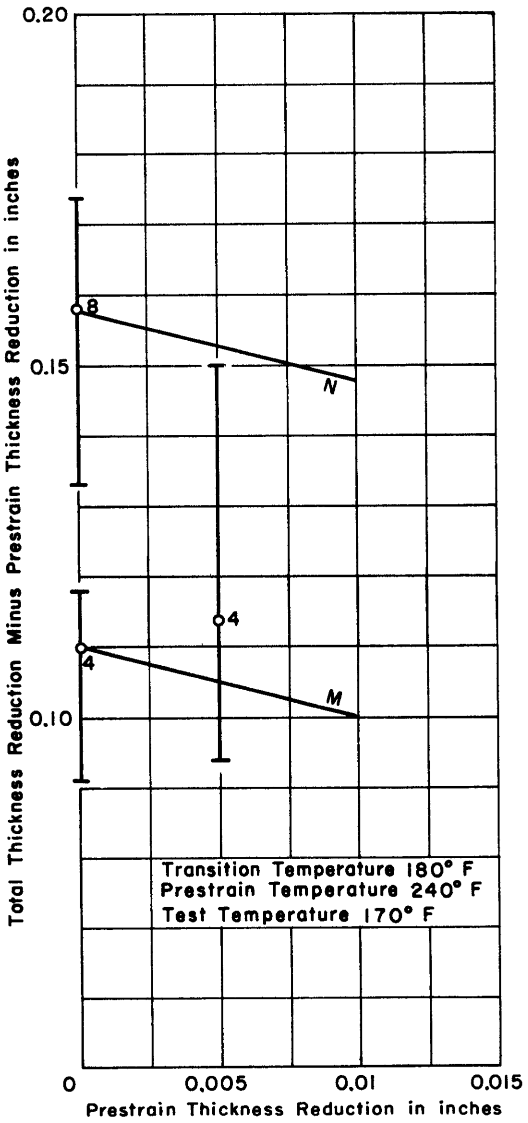

Figure 6 - Data from Rupture Tests of E Steel Specimens

1. Is there a physical phenomenon present? (Distance A in Figure 4.)
2. If so, can it be put to practical use? (Distance B in Figure 4.)

Preliminary investigations to determine the optimum amount of prestrain were made using Dn steel. The results of these tests (Figure 5 and Table 4) indicate that a prestrain thickness reduction of 0.005 inch gave optimum results. This amount was used in succeeding tests on other types of steel for want of sufficient specimens to determine the most effective prestrain for each steel.

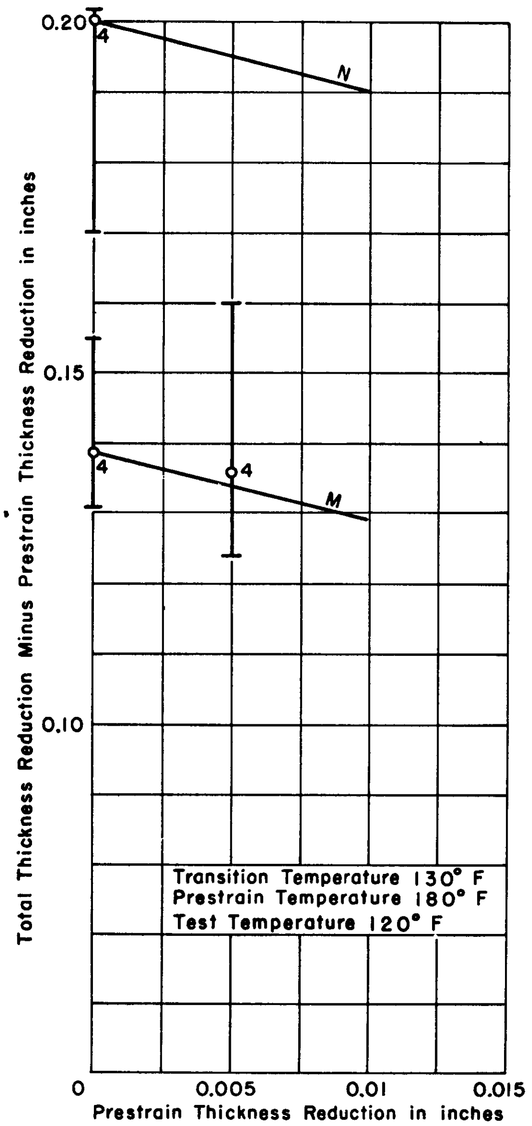

Figure 7 - Data from Rupture Tests of $S2_E$ Steel Specimens

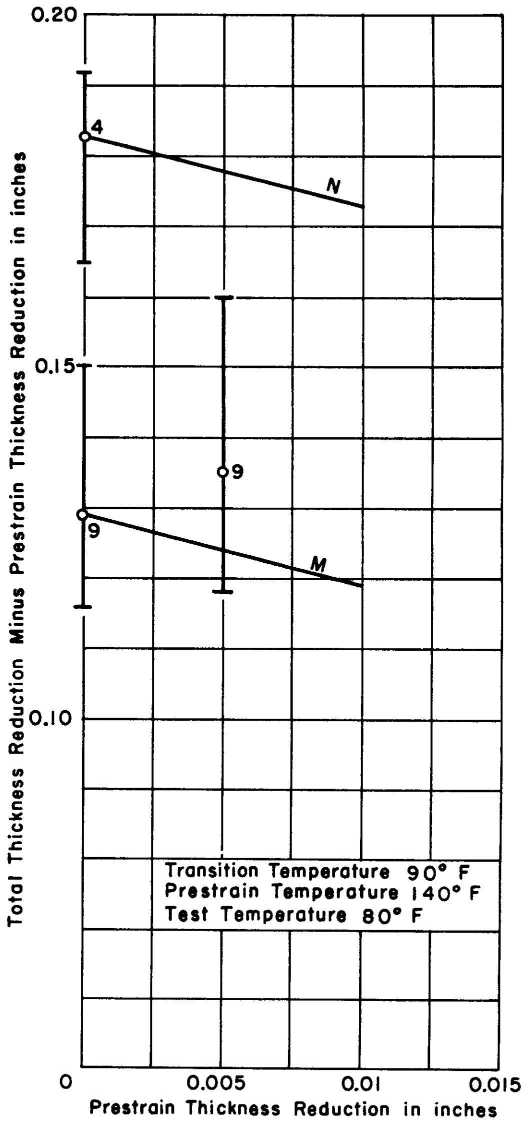

Figure 8 - Data from Rupture Tests of $S3_E$ Steel Specimens

The results of the tests at a temperature about 10 degrees below transition temperature appear to indicate improved ductility with prestrain because the average thickness reduction for the prestrained specimens is greater than that for the specimens without prestrain for three of the four steels; see Figures 5 through 8 and Table 5.

A statistical appraisal of the data in Table 5 revealed that the average difference in the thickness reduction between prestrained and unstrained specimens of all four steels was 0.0142 inch. This is the distance A which is indicative of the existence of a physical phenomenon. Statistically there is

TABLE 4

Data from Specimens of Dn Steel Prestrained Various Amounts and Tested at 75° F

Specimen	Prestrain Thickness Reduction inches	Fracture Test Thickness Reduction inches	Type of Failure*	Prestraining Temperature °F.
C-9	0.0025	0.158	S	140
C-13	.0025	.119	S-C	140
C-15	.0025	.122	S-C	140
F-3	.0025	.136	S-C	140
F-4	.0025	.131	S-C	140
F-13	.0025	.128	S-C	140
F-14	.0025	.125	S-C	140
H-3	.0075	.124	S-C	140
H-4	.0075	.161	S	140
H-5	.0075	.129	S-C	140
H-6	.0075	.159	S	140
H-7	.0075	.163	S	140
H-9	.0075	.120	S-C	140
A-17	.010	.139	S	140
H-8	.010	.152	S	140
C-10	.010	.136	S	140
C-7	.010	.121	S-C	140
C-20	.010	.128	S-C	140
G-4	0.010	0.123	S-C	140

*Fibrous (S), Granular (C), or Mixed (S-C).

only 1 chance in 150 that this difference is the result of scatter of test data. The distance B, which indicates the practical usefulness, averages 0.0092 inch, and the chance that this is explainable by test scatter is 1 in 12.

Dn steel by itself made a much better showing; the distance A is 0.0286 inch. Statistical evaluation indicates practical certainty that there is a physical phenomenon present and that the difference is not the result of test scatter. For steel Dn the distance B was 0.0236 inch, and there is only 1 chance in 5000 that this is explainable by test scatter.

TABLE 5

Data from Specimens Prestrained to a Thickness Reduction of 0.005 Inch and From Unprestrained Specimens Tested at a Fixed Temperature Below the Transition Temperature

Steel Code	Specimen	Prestrain Thickness Reduction inches	Rupture Test Thickness Reduction inches	Type of Failure*	Test Temperature °F	Prestraining Temperature °F
Dn	F-15	0	0.129	S-C	75	-
Dn	F-16	0	.132	S-C	75	-
Dn	F-17	0	.134	S-C	75	-
Dn	F-18	0	.126	S-C	75	-
Dn	F-20	0	.130	S-C	75	-
Dn	H-1	0	.125	S-C	75	-
Dn	H-2	0	.123	S-C	75	-
Dn	F-5	0.005	.157	S	75	140
Dn	F-6	.005	.126	S-C	75	140
Dn	F-8	.005	.143	S	75	140
Dn	F-9	.005	.154	S	75	140
Dn	F-10	.005	.172	S	75	140
Dn	F-11	.005	.174	S	75	140
Dn	F-12	.005	.138	S-C	75	140
E	6E49	0	.116	S-C	170	-
E	6E61	0	.091	S-C	170	-
E	6E67	0	.115	S-C	170	-
E	6E77	0	.118	S-C	170	-
E	6E16	.005	.111	S-C	170	240
E	6E22	.005	.094	S-C	170	240
E	6E31	.005	.100	S-C	170	240
E	6E43	.005	.150	S	170	240
$S2_E$	S2-22	0	.155	S	120	-
$S2_E$	S2-28	0	.134	S-C	120	-
$S2_E$	S2-30	0	.137	S-C	120	-
$S2_E$	S2-36	0	.131	S-C	120	-
$S2_E$	S2-8	.005	.133	S-C	120	180
$S2_E$	S2-12	.005	.129	S-C	120	180
$S2_E$	S2-14	.005	.124	S-C	120	180
$S2_E$	S2-16	.005	.160	S	120	180
$S3_E$	S3-20	0	.166	S	80	-
$S3_E$	S3-24	0	.115	S-C	80	-
$S3_E$	S3-26	0	.121	S-C	80	-
$S3_E$	S3-28	0	.120	S-C	80	-
$S3_E$	S3-30	0	.121	S-C	80	-
$S3_E$	S3-32	0	.116	S-C	80	-
$S3_E$	S3-34	0	.128	S-C	80	-
$S3_E$	S3-36	0	.150	S	80	-
$S3_E$	S3-38	0	.123	S-C	80	-
$S3_E$	S3-2	.005	.157	S	80	140
$S3_E$	S3-4	.005	.140	S	80	140
$S3_E$	S3-6	.005	.147	S	80	140
$S3_E$	S3-8	.005	.160	S	80	140
$S3_E$	S3-10	.005	.118	S-C	80	140
$S3_E$	S3-12	.005	.124	S-C	80	140
$S3_E$	S3-14	.005	.119	S-C	80	140
$S3_E$	S3-16	.005	.128	S-C	80	140
$S3_E$	S3-18	0.005	0.119	S-C	80	140

*Fibrous (S), Granular (C), Mixed (S-C),

TABLE 6

Data from Specimens of Dn Steel Prestrained to a Thickness Reduction of 0.005 Inch and from Unprestrained Specimens Tested at Various Temperatures

Specimen	Prestrain Thickness Reduction inches	Rupture Test Thickness Reduction inches	Type of Failure*	Test Temperature °F	Prestraining Temperature °F
H-12	0.005	0.143	S-C	100	140
H-14	.005	.140	S-C	90	140
H-15	.005	.139	S-C	80	140
H-16	.005	.121	S-C	60	140
H-17	.005	.120	S-C	60	140
H-18	.005	.138	S-C	80	140
H-19	.005	.131	S-C	90	140
H-20	.005	.150	S-C	100	140
K-1	.005	.180	S	110	140
K-2	.005	.175	S	100	140
K-3	.005	.184	S	110	140
K-4	.005	.180	S	100	140
K-5	.005	.173	S	90	140
K-6	.005	.172	S	90	140
K-8	0	.188	S	110	-
K-9	.005	.185	S	80	140
K-10	.005	.161	S	80	140
K-11	.005	.120	S-C	80	140
K-12	.005	.176	S	90	140
K-13	0	.182	S	100	-
K-14	0	.180	S	100	-
K-15	0	.166	S	90	-
K-16	0	.175	S	90	-
K-17	0	.170	S	80	-
K-18	0	.177	S	80	-
K-19	0	.145	S-C	60	-
K-20	0	.128	S-C	60	-
C-4	.005	.117	S-C	65	140
C-17	0.005	0.109	S-C	65	140

*Fibrous (S), Granular (C), or Mixed (S-C).

Two related subsidiary questions arise with respect to the problem of practical utility of the phenomenon which appears to exist:

1. How much tougher does the structure become?
2. How much is the risk of fracture reduced by the increased toughness?

An attempt was made to answer the first question by means of additional tests on prestrain specimens of Dn steel at various temperatures to try to establish a brittle-to-ductile transition-temperature curve. A rather unsatisfying scatter of data resulted. Figure 9 shows the results of testing prestrained specimens over a range of temperatures and includes the results of control tests on specimens with no prestrain. Table 6 contains the new test data supporting Figure 9.* Again, the numerals in Figure 9 indicate the number of tests averaged at each point. No benefit from prestrain is evident from the present tests alone. Figure 9 also contains the results of earlier tests on specimens which had no prestrain. On the basis of all these data it appears that the beneficial influence amounts to not much more than 5° F.

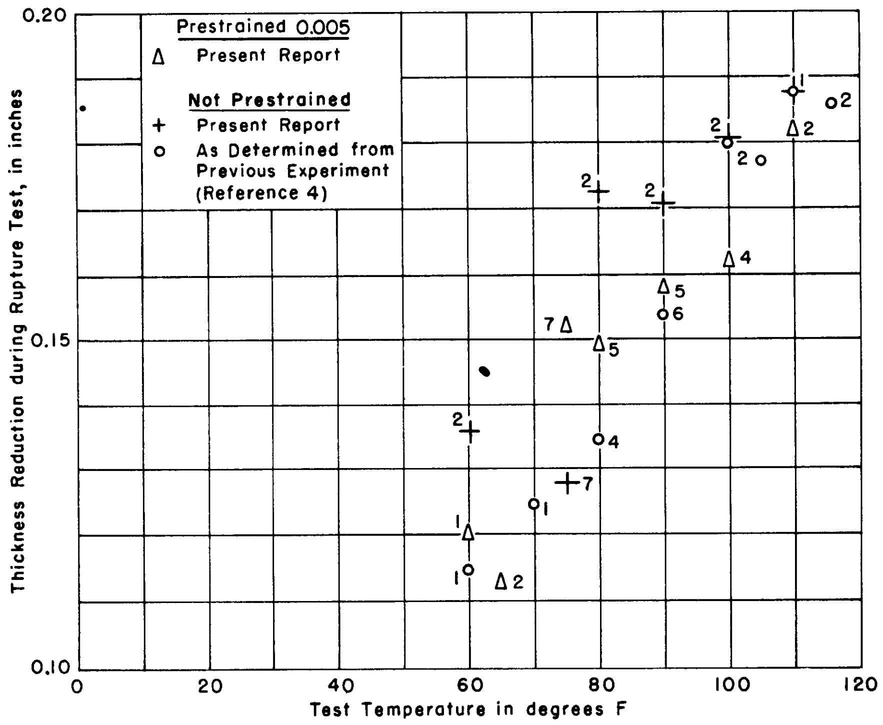

Figure 9 - Thickness Reduction versus Test Temperature for Dn Steel

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*The new control specimens of Dn steel without prestrain were from plate locations intermingled with the prestrained specimens. The test bars of Reference 4 were from the same plate but 1 foot to 2 feet distant in the direction of rolling. All specimens were from the center portion of the same plate of Dn steel.

This possible toughness increase in Dn steel emphasizes the importance of determining the change in risk of fracture which can be expected to result from a small increase in toughness. A complete generalization of this question would be confusing so a specific example has been selected from well-substantiated data in Reference 5. There the service history of 667 selected Liberty ships was observed, and their service frequency versus air temperature was recorded as well as the history of above-waterline fractures (Figure 26 of Reference 5). In the present report the service frequency and fracture frequency data of Reference 5 were approximated by mathematical expressions (Figures 10 and 11) and the fracture frequency was divided by the service frequency to obtain an expression for the fracture rate (Figure 12). The mathematical expressions are indicated on the figures.

Moving the fracture rate curve to a lower temperature is analogous to increasing the toughness of the structure. The effect of such additional toughness is indicated by the reduction in the total number of fractures occurring in the service temperature range. The dotted lines in Figure 12 indicate fracture rate curves 30 degrees below and 30 degrees above that for the actual ships. Figure 13 gives the total number of fractures which would result

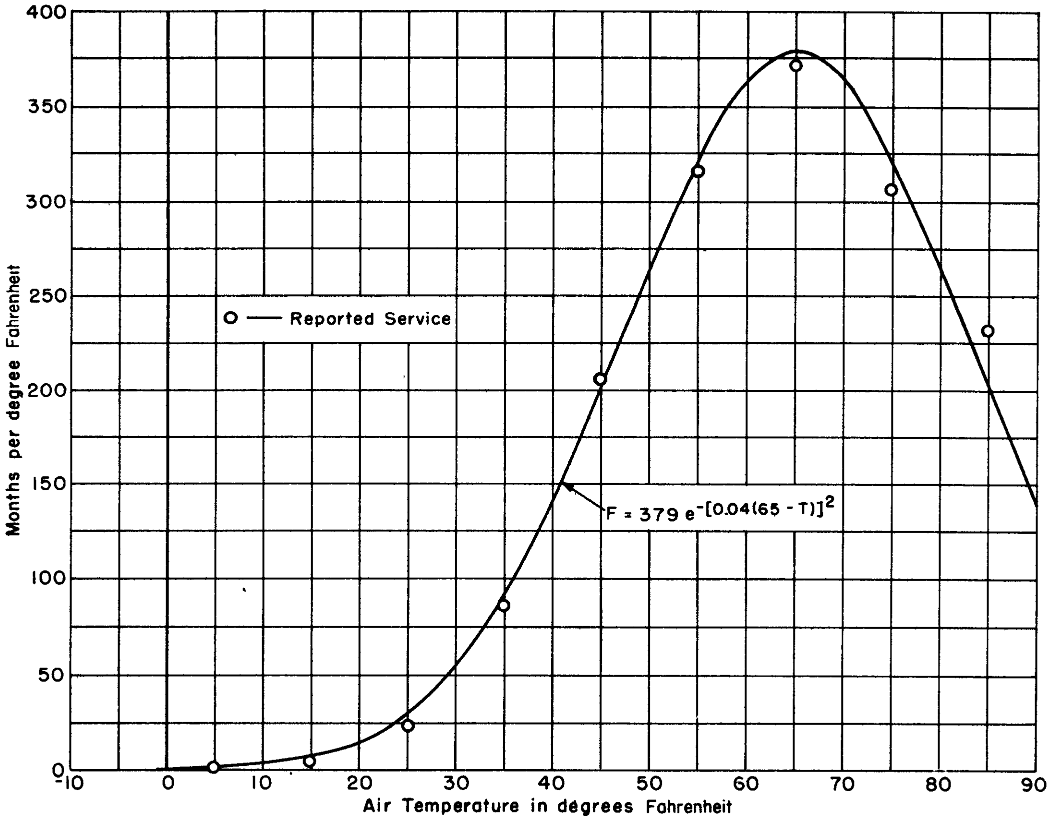

Figure 10 - Frequency of Ship Service, F

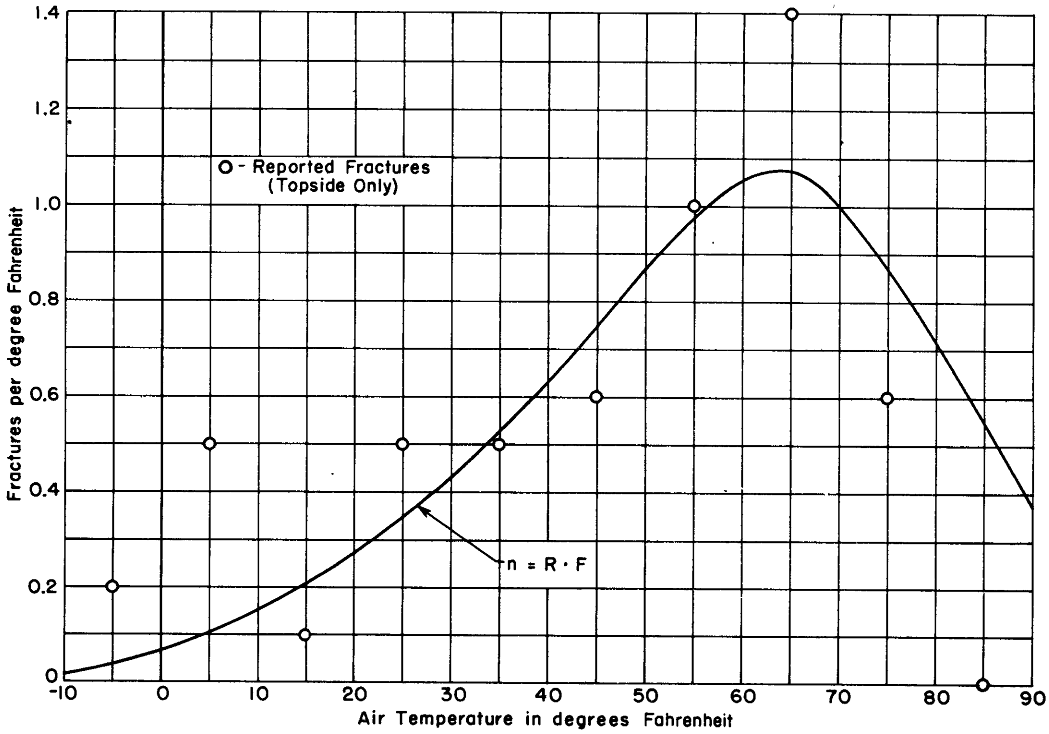

Figure 11 - Frequency of Fracture, n

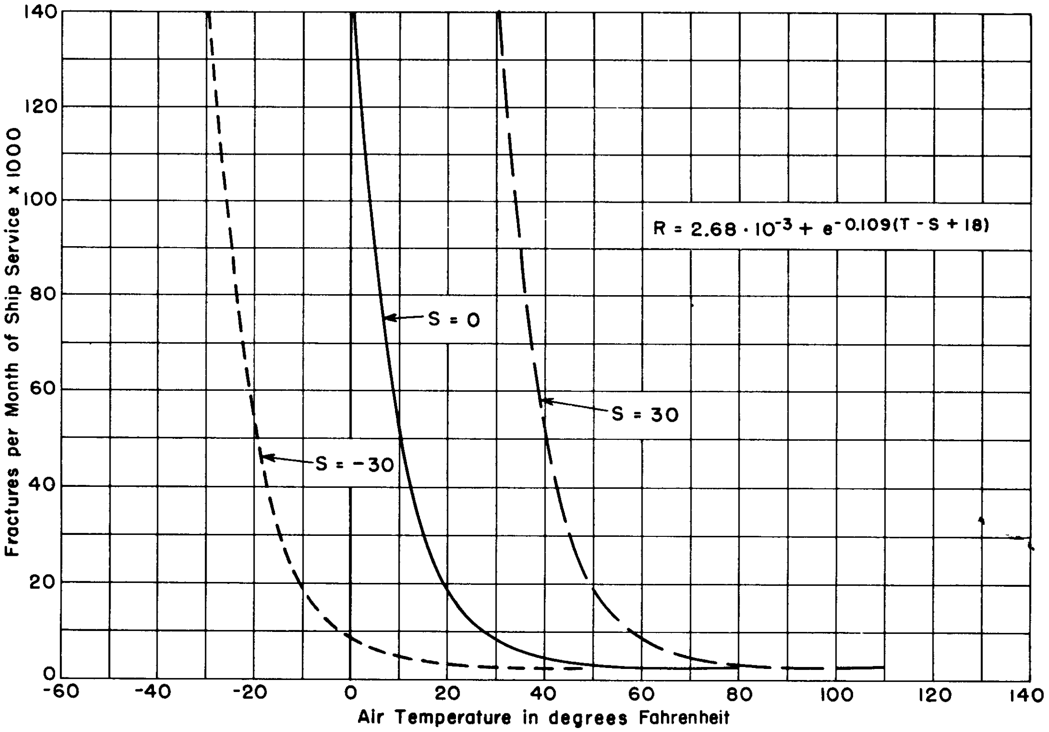

Figure 12 - Rate of Fracture, R

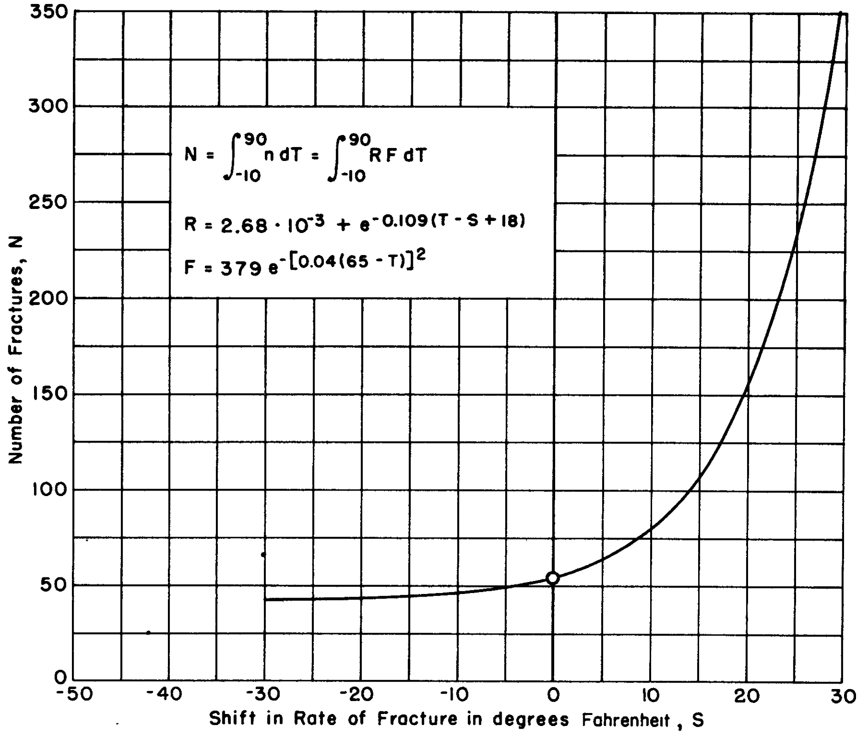

Figure 13 - Total Number of Fractures, N

for various fracture rate curves within this range. When the shift in toughness, S, equals 0, and the total number of fractures is 54, 10° improvement would be shown as S equals -10. Here the total number of fractures has been reduced, from 54 to 45.6, i.e., a 17-percent improvement. For S = -30°, a further 10° improvement would result in practically no benefit. On the other hand, for S = +30°, 371 fractures are predicted (this is outside of the border of Figure 13). A 10° improvement would bring the curve to S = +20° where 153 fractures are predicted. Thus a 59-percent improvement results from a 10° F. shift in transition temperature.

This study reveals that the beneficial effects of an increase in toughness depend entirely upon the particular circumstances prevailing. In marginal cases a substantial reduction in the risk of fractures results from small increases in toughness, say 10° F. On the other hand, almost no benefit occurs in cases where the risk of fracture is already low.

In spite of the scatter of results and the uncertainty of the interpretation of some of the tests it appears that a physical phenomenon is present. Further study might reveal ways to improve the control, reduce the scatter, and add to the increase in toughness. The practical possibilities of this technique as a structural conditioner warrant additional investigations in this field.

CONCLUSIONS

These preliminary tests permit the following conclusions:

1. The prestraining of notched steel specimens at temperatures above the brittle-to-ductile transition temperature increases the toughness of the specimens when tested at certain temperatures immediately below the transition temperature.

2. The increase in toughness resulting from prestraining notched steel specimens at temperatures above the brittle-to-ductile transition temperature is small.

3. A procedure to obtain benefits consistently from the prestrain method was not devised.

4. Minor increases in toughness can reduce the risk of fracture substantially if other prevailing conditions dictate a high rate of fracture. The benefit may be small under other circumstances.

5. Further study of this subject is warranted.

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