Fifth

PROGRESS REPORT

(Project SR-110)

on

REPRODUCIBILITY OF KEYHOLE CHARPY AND TEAR TEST DATA ON LABORATORY HEATS OF SEMIKILLED STEEL

by

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Transmitted through

NATIONAL RESEARCH COUNCIL'S COMMITTEE ON SHIP STEEL

Advisory to

SHIP STRUCTURE COMMITTEE

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SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

February 7, 1955

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee is sponsoring an investigation of the influence of chemical composition and deoxidation on the notched bar properties of ship plate steels at Battelle Memorial Institute. A paper covering portions of this work was presented at the Symposium on Effect of Temperature on the Brittle Behavior of Metals with Particular Reference to Low Temperatures held at the annual meeting of the American Society for Testing Materials, Atlantic City, June 28--30, 1953. This paper, entitled "Reproducibility of Keyhole Charpy and Tear-Test Data on Laboratory Heats of Semikilled Steel" by R. H. Frazier, J. W. Spretnak and F. W. Boulger, constitutes Part I of the attached report, SSC-83, the progress report on the project. Part II of the report describes the results of later calculations.

The project is being conducted with the advisory assistance of the Committee on Ship Steel of the National Academy of Sciences-National Research Council.

Comments concerning this report are solicited and should be addressed to the Secretary, Ship Structure Committee.

This report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

K. K. Cowart

K. K. COWART
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

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Battelle Memorial Institute

under

Department of the Navy
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for

<u>SHIP STRUCTURE COMMITTEE</u>

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REPRODUCIBILITY OF KEYHOLE CHARPY AND TEAR-TEST DATA ON LABORATORY HEATS OF SEMIKILLED STEEL[1]

BY R. H. FRAZIER,[2] J. W. SPRETNAK,[2] AND F. W. BOULGER[2]

SYNOPSIS

Eighteen heats of semikilled steel were made, processed to $\frac{3}{4}$-in. plates, and tested in the laboratory. Analytical and mechanical test data showed that good reproducibility was obtained on replicate heats. Two types of semikilled steel were used for the investigation. Standard keyhole Charpy specimens and Navy tear-test specimens were tested to determine the transition temperature separating ductile and brittle fracture. The probability of brittle fracture was not the same for the two types of steel in tests at their transition temperatures, as customarily defined. The difference was small in Charpy tests but significant in tear tests. It is concluded that notched-bar transition temperatures should be defined on the basis of a fixed probability of brittle fracture. This practice uses the data more efficiently and is more discriminating.

The importance of brittle fracture of mild steel in the service performance of welded structures is well established. The threat of sudden brittle failures has become a reality in far too many ships, pipe lines, bridges, and storage tanks to be ignored. It is well known that the toughness of notched specimens in laboratory tests correlates with the behavior of the steel in welded construction (**1, 2, 3, 4**).[3] Notch toughness is a short term expressing the relative capacity of a steel for ductile fracture under adverse conditions of stress concentration, temperature, and rate of loading. Since notch ductility depends on many factors, it cannot be evaluated, except for arbitrary testing conditions.

Late in 1949, the Ship Structure Committee established a research project at Battelle Memorial Inst. to study the influence of deoxidation and chemical composition on the properties of ship steel. This investigation, under the guidance of the Committee on Ship Steel of the National Academy of Sciences, National Research Council, is being conducted for the Ship Structure Committee under Bureau of Ships Contract NObs-50020. During this work, "standard" steels were made, processed, and tested in the laboratory in order to check the constancy of experimental procedures. Ten heats of one nominal analysis and eight heats of another composition were produced at various times during the 3-yr period.

These steels provide information on the reproducibility of data for 200-lb heats of semikilled steel made and tested in the laboratory. Since the two types of steel differ in carbon and manganese

[1] The opinions expressed herein are those of the authors and do not necessarily represent those of the Ship Structure Committee, the Bureau of Ships, the Department of the Navy, or of the Advisory Committees of the National Academy of Sciences, National Research Council.

[2] Assistant Supervisor, Consultant, and Supervising Metallurgist, respectively, Battelle Memorial Inst., Columbus, Ohio.

[3] The boldface numbers in parentheses refer to the list of references appended to this paper, see p. 300.

contents, the laboratory heats illustrate the influence of manganese-carbon ratio on notched-bar toughness. Because the data are fairly numerous, they also permit some opinions on the choice of criteria for evaluating toughness in notched-bar tests.

COMPOSITION AND TENSILE PROPERTIES

The steels to be discussed were made in a laboratory induction furnace and rolled to $\frac{3}{4}$-in. plate, using a finishing temperature of 1850 F. Precautions taken in melting and processing to obtain uniform heats of each type are discussed elsewhere (10,11). All tests were made in the hot-rolled condition.

Table I lists the compositions and tensile properties of the eighteen laboratory steels. The type A steels have higher carbon and lower manganese contents than the type B steels. The compositions are balanced, however, so that the tensile properties are comparable for both grades.

Table I shows that all heats had compositions close to the intended analyses. In fact, the standard deviations of the values for the six elements reported approximate the limits of chemical analysis. The values for yield strength, tensile strength, and elongation also fall within narrow limits. The consistency of results may be surprising to some familiar with the difficulties of making semikilled steels. The analytical and tensile data indicate that laboratory heats can be made and processed to give uniform and reproducible results, even if produced at different times in a 3-yr period. Furthermore, the tensile data are equivalent to those for open-hearth steels of similar composition processed commercially.

TABLE I.—COMPOSITIONS AND PROPERTIES OF STEELS STUDIED.[a]

Heat	Composition, per cent						Yield Strength, psi		Tensile Strength, psi	Elongation in 8 in., per cent
	Carbon	Manganese	Silicon	Phosphorus	Sulfur	Nitrogen	Upper	Lower		
Type A Steels										
A6555	0.22	0.47	0.06	0.016	0.024	0.003	38 850	36 050	62 700	27.5
A6556	0.23	0.44	0.05	0.017	0.025	0.004	37 950	35 000	61 600	31.0
A6587	0.22	0.45	0.06	0.011	0.024	0.004	35 400	34 450	61 650	29.5
A6550	0.22	0.46	0.04	0.012	0.023	0.004	35 600	34 250	60 550	28.0
A6705	0.21	0.49	0.05	0.016	0.025	0.004	37 050	35 900	63 000	24.5
A7663	0.22	0.44	0.03	0.015	0.027	0.003	35 050	34 500	61 100	31.5
A7449	0.20	0.43	0.04	0.014	0.022	0.004	35 600	34 200	60 750	31.5
A8132	0.23	0.44	0.04	0.015	0.027	0.005	36 450	34 500	61 000	30.5
A6424	0.21	0.42	0.02	0.014	0.029	0.004	...	34 000	58 250	29.0
A8361	0.23	0.46	0.03	0.016	0.027	0.004	...	...	...	...
Average	0.22	0.45	0.04	0.015	0.025	0.004	36 490	34 760	61 180	29.2
Standard Deviation	0.01	0.02	0.01	0.002	0.002	0.0005	1 262	700	1 300	2.2
Type B Steels										
A6557	0.22	0.75	0.07	0.016	0.025	0.005	36 200	35 500	61 700	30.0
A6584	0.20	0.76	0.07	0.014	0.022	0.004	36 350	35 400	61 950	30.5
A6588	0.21	0.79	0.06	0.011	0.024	0.004	35 550	34 900	62 350	28.0
A6641	0.19	0.81	0.04	0.016	0.022	0.004	36 550	35 350	62 850	24.0
A6651	0.19	0.74	0.01	0.017	0.023	0.005	37 200	35 700	62 300	28.5
A7664	0.18	0.69	0.03	0.015	0.026	0.003	36 100	34 800	62 300	29.5
A7450	0.21	0.76	0.07	0.016	0.025	0.004	35 050	34 200	61 550	32.5
A8360	0.24	0.75	0.04	0.015	0.023	0.004	...	...	...	...
Average	0.20	0.76	0.05	0.015	0.024	0.004	36 100	35 120	62 140	29.0
Standard Deviation	0.02	0.03	0.02	0.002	0.001	0.0006	642	479	1 080	2.5

[a] Tension specimens were taken from ¾-in. plate and had 8-in. gage sections.

NOTCHED-BAR PROPERTIES

Standard longitudinal keyhole Charpy specimens, notched normal to plate surface, and tear-test specimens of the type described by Kahn and Imbembo (5) were used to evaluate toughness. Transition temperatures in these notched-bar tests were determined for all the steels listed in Table I. The transition temperature is the temperature at which the mode of rupture changes from ductile or shear fracture to the brittle or cleavage fracture. The temperature at which this change in mode of fracture occurs is a function of both testing method and steel quality. In the Navy tear test, a change from totally fibrous to a predominantly granular texture of the fracture surface occurs as the testing temperature is decreased. According to the terms used by Vanderbeck and Gensamer (13), the tear test measures a "fracture" transition, and the Charpy test measures a "ductility" transition.

TABLE II.—TRANSITION TEMPERATURES OF LABORATORY STEELS IN NOTCHED-BAR TESTS.[a]

Heat	Transition Temperature, deg Fahr	
	Keyhole Charpy	Tear Test
TYPE A STEELS		
A6555	+12	+80, +70
A6556	+4	+70, +70
A6587	+12	+100, +70
A6650	+25	+70, +80
A6705	+5	+60, +90
A7663	+23	+90
A7449	+16	+70
A8132	+33	+100
A6424	+52	+95
A8361	+25	+90
Average	+21	+80
Standard Deviation	13.6	13.7
TYPE B STEELS		
A6557	−13	+70
A6584	−6	+70
A6588	−20	+70
A6641	−25	+80
A6651	−24	+70
A7664	−7	+80
A7450	−13	+60
A8360	−11	+60
Average	−15	+70
Standard Deviation	8.0	7.1

[a] The Charpy and tear-test data for the first six heats of type A steel and for the first seven heats of type B steel were used for the probability studies. Based on only those heats, the Charpy transition temperatures are:
Type A steels.. +13.5 F; standard deviation, 8.05 F
Type B steels.. −15.4 F; standard deviation, 7.21 F

There are many ways of defining brittle fracture in Charpy tests in order to determine transition temperatures. At the start of this investigation, the transition temperature was defined as the temperature at which the average Charpy value was 20 ft-lb. Four specimens of each steel were tested at each selected temperature. Table II shows that the type B steels had an average transition temperature 36 F lower than the average for the type A steels. Since the Charpy test is a sensitive one, the transition temperatures have standard deviations of 13.6 and 8 F for grade A and grade B steels, respectively. This scatter is of the order expected for similar steels, according to other investigators (6, 7). The difference in Charpy transition temperatures between the two grades is large enough to be convincing. The Charpy test indicates that increasing the manganese-carbon ratio from 2.0 to 3.8 in these steels lowered the transition temperature from +21 F to −15 F. Using the *t* test for significance (8, 9) of these data, it was found that this difference in average transition temperatures would occur by chance less than one time in a hundred. There is little doubt that the averages for these Charpy tests discriminate between type A and type B steels.

The Navy tear test developed by Kahn and Imbembo (5) used a specimen of the type shown in Fig. 1. The specimen is loaded in tension with pin-and-shackle fixtures through the large holes while submerged in a liquid bath for temperature control. The tear-test transition temperature was defined by Kahn and Imbembo as the highest temperature at which one or more specimens develop a fracture area with less than 50 per cent of the ductile or shear type. Tests are made at intervals of 10 F, and as many as four specimens are tested at appropriate temperatures.

Table II lists the tear-test transition temperatures for the experimental steels. Two determinations were made for five of the type A steels; intervals of several months elapsed before the second tests were made on these steels. The average transition temperature, in tear tests, was +80 F for the type A steels and +70 F for the type B steels. The difference between grades is in the order suggested by the Charpy tests, but it is small, considering the scatter in duplicate determinations and between heats of the same type. The *t* test for significance indicates that the differences in transition temperatures found could occur by chance alone in seven cases out of a hundred.

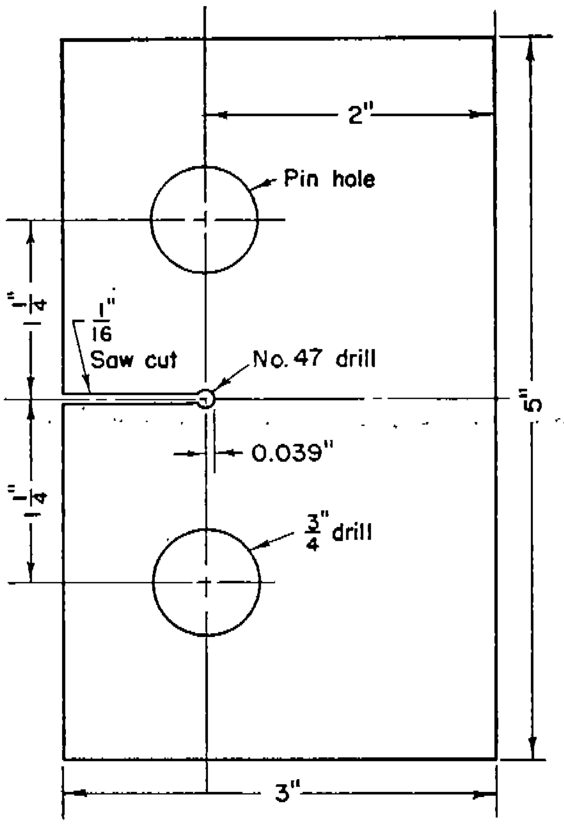

FIG. 1.—Navy Tear-Test Specimen Utilizing Full Plate Thickness.

It seems safe to conclude, therefore, that the tear test did not discriminate as well as the Charpy test between the two types of steel. Assuming that the steels of the same grade did not differ in some obscure way not reflected by tension, Charpy, or analytical data, there are two possible explanations for the poorer discrimination of the tear test. These possibilities are:

1. That the tear test is inherently less sensitive to the effect of manganese on toughness than the Charpy test.

2. That the method of defining the transition temperature does not use the tear-test data efficiently.

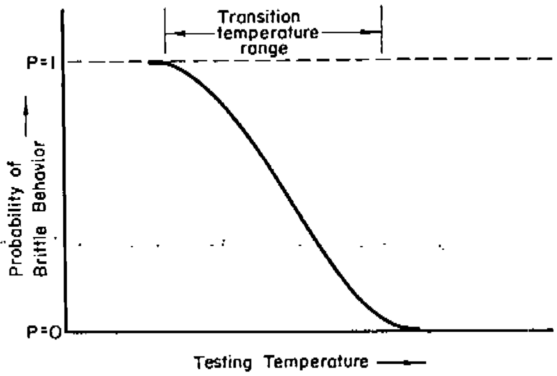

FIG. 2.—Schematic Diagram Illustrating the Probability Nature of the Transition from Ductile to Brittle Behavior in Steels.

Both possibilities were investigated by analyzing the behavior of Charpy and tear-test specimens from the standpoint of probability. Consideration in this fashion permits a logical judgment on the question of whether all heats of the same type behaved essentially alike in the tests.

PROBABILITY ANALYSIS OF FRACTURE BEHAVIOR

In analyzing the present data, the transition from ductile to brittle behavior was considered to be described by a curve relating the probability of brittle behavior to the testing temperature. This behavior is illustrated by the rectilinear plot in Fig. 2. According to this concept, each particular specimen exhibits either ductile or brittle behavior. The effect of lowering the testing temperature is to increase the frequency and probability of brittle fractures.

Figure 3 shows the frequency distribution of Charpy values for 40 specimens of type A steel tested at 0 F. It is apparent that the specimens can be classified in two groups. The energy-absorption values for the tougher bars range from 13 to 27 ft-lb, and those for brittle samples vary from 1 to 12 ft-lb.

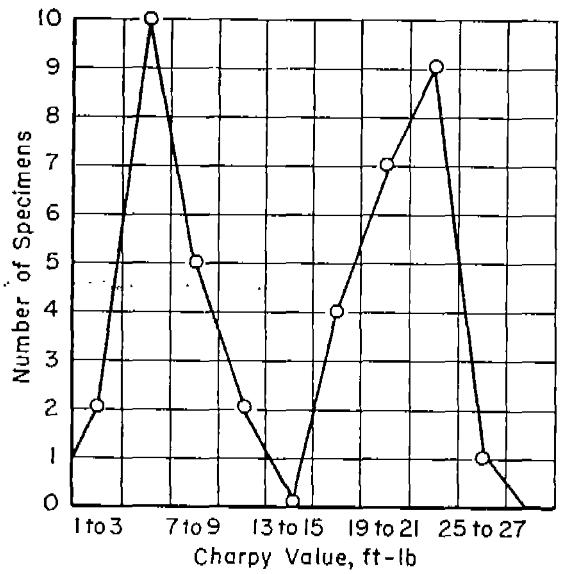

FIG. 3.—Frequency of Energy Values for a Group of Forty Specimens of Type A Steel Tested at 0 F.

It is common experience that two such frequency distributions usually are obtained when a large number of similar specimens are broken at a particular temperature in the transition range. This justifies considering tough and brittle specimens as coming from different statistical populations.

The ductile and brittle specimens were easy to classify for the probability analysis. In the Charpy tests, brittle bars gave values ranging from 2 to 12 ft-lb. Brittle tear-test specimens ordinarily had fracture areas exhibiting only 0 to 15 per cent of shear texture. The percentage of shear texture in the fracture areas of ductile bars usually ranged from 85 to 100.

All of the raw Charpy data for six type A heats were combined in order to calculate frequencies for a probability plot. This was also done for seven type B heats. These data are summarized in Table III.

The frequencies of brittle fractures are plotted as a function of temperature on probability paper in Fig. 4. They give a straight line, as would be expected from the hypothesis that brittle fracture is a probability phenomenon. The line of best fit in Fig. 4 was obtained by the "least-squares" method. This was done by transferring the points to a rectilinear coordinate plot, calculating the line, and transferring the line to the probability plot. If one selects the probability of brittle fracture $p = 0.5$ as the criterion, then the transition temperature is −2 F for the type A heats. Samples of this steel are equally likely to give tough or brittle fractures if tested at this temperature.

The data in Fig. 4 permit testing the homogeneity of the Charpy data obtained on the type A steels. This was done by the chi square test widely used in statistical analyses. For this case, the chi square value corresponding to a fiducial limit of $p = 0.05$ is 3.84. That is, if the chi square value were equal to

TABLE III.—SUMMARY OF CHARPY KEYHOLE IMPACT DATA ON TYPE A AND TYPE B HEATS.

TYPE A HEATS

Temperature, deg Fahr.	−40	0	20	40	60	60	75
Number of tests	20	24	20	24	8	8	20
Number brittle	20	12	3	1	0	0	0
Fraction brittle	1.00	0.50	0.15	0.04	0.00	0.00	0.00

TYPE B HEATS

Temperature, deg Fahr.	−80	−40	−20	0	20	40	75
Number of tests	20	22	10	20	10	22	20
Number brittle	20	17	4	1	0	0	0
Fraction brittle	1.00	0.77	0.40	0.05	0.00	0.00	0.00

3.84, and if the data were heterogeneous, there would be five chances in one hundred of obtaining a second array of data with as little dispersion around the trend line. The chi square value calculated for the data plotted in Fig. 4 is 0.204; consequently, the Charpy data for the type A heats give no evidence of heterogeneity. Impact data for a group of heats which differed enough in compositions or processing to give a chi square value of above 3.84 would be judged statistically heterogeneous by the same criterion.

Figure 4 also shows the frequencies of brittle fracture for specimens of type B steel plotted, as a function of temperature, on probability paper. The trend line was selected by the "least-squares" method. The chi square value indicating heterogeneity in this case is also 3.84 for $p = 0.05$. The chi square value calculated from the plotted data is 0.195, which indicates that the type B steels do not evidence significant heterogeneity.

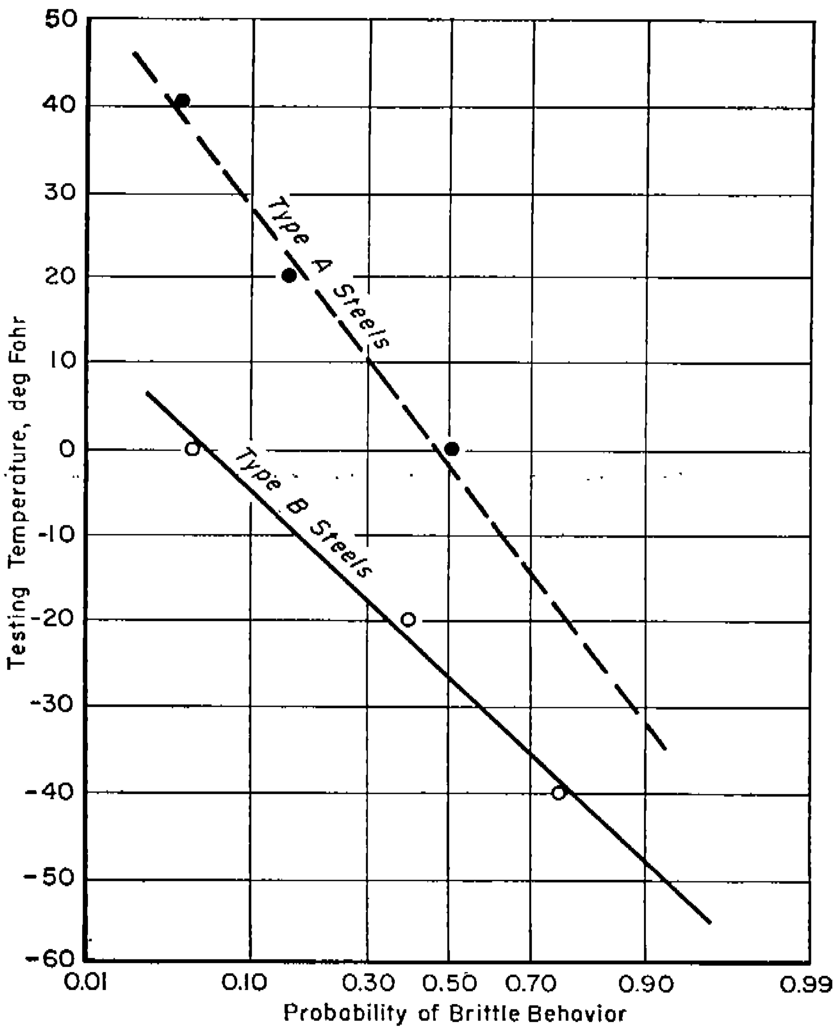

FIG. 4.—Frequencies of Brittle Charpy Specimens at Various Testing Temperatures.

The slope of the trend line in the probability plot for the type B steels is somewhat greater than for the type A steels. This means that the B steels are more sensitive to changes in temperature. If the probability of brittle fracture $p = 0.5$ is chosen as the criterion, the transi-

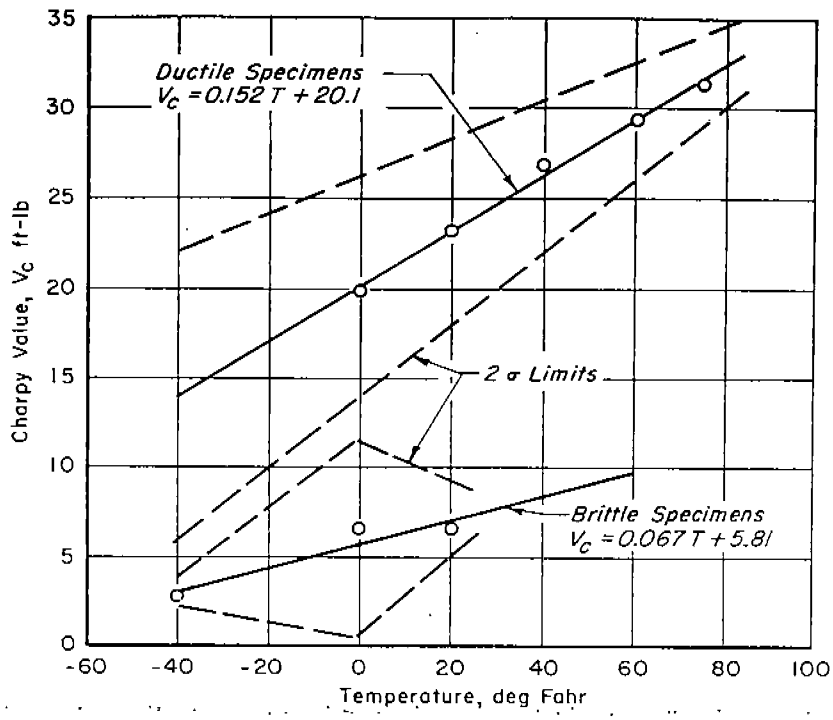

FIG. 5.—Keyhole Charpy Test Characteristics of Type A Steels.

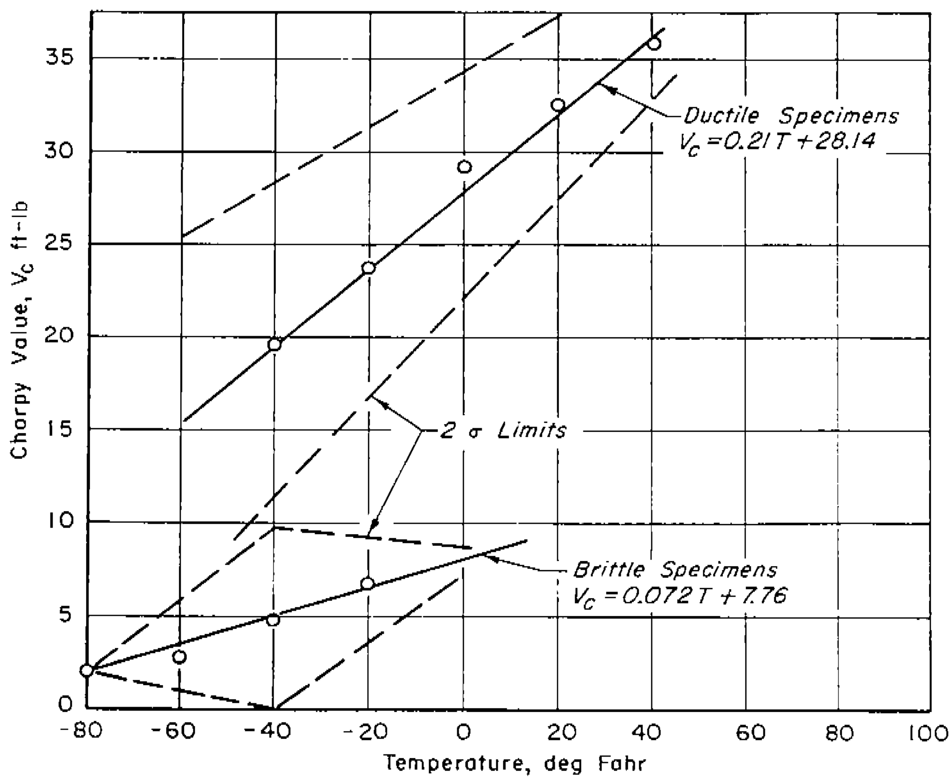

FIG. 6.—Keyhole Charpy Test Characteristics of Type B Steels.

tion temperature of the type B steels is −26 F.

PROBABILITY ANALYSIS OF CHARPY VALUES

The statistical studies already described indicated that impact data from different heats of the same type of steel were not heterogeneous. Therefore, the data for each type of steel were combined to give energy–temperature curves representative of the two grades of material. Such curves are shown in Figs. 5 and 6. Four specimens of each heat were tested at each temperature; the figures represent data for six type A heats and seven type B heats.

Figures 5 and 6 are based on the actual experimental data and the belief that tough and brittle specimens should be treated separately. Using this viewpoint, the lower trend line shows the averages for brittle specimens, and the other line shows the averages for tough specimens. The limits shown on the charts correspond to twice the standard deviation calculated from the values obtained for the brittle or tough groups at each temperature.

The experimental data from specimens of type A steel are illustrated by Fig. 5. The equations giving average Charpy values, V_c, in ft-lb as a function of temperature, T, in deg Fahr for the two types of fracture are:

Ductile Fractures

$$V_c = 0.152T + 20.1 \qquad (1)$$

Brittle Fractures

$$V_c = 0.067T + 5.81 \qquad (2)$$

The graph shows that the dispersion of the impact values for the ductile specimens increases with decreasing temperature, whereas, for the brittle specimens, the dispersion passes through a maximum at 0 F.

The averages for experimental data obtained on specimens of type B steel are shown, with their two sigma limits, in Fig. 6. The equations for calculating

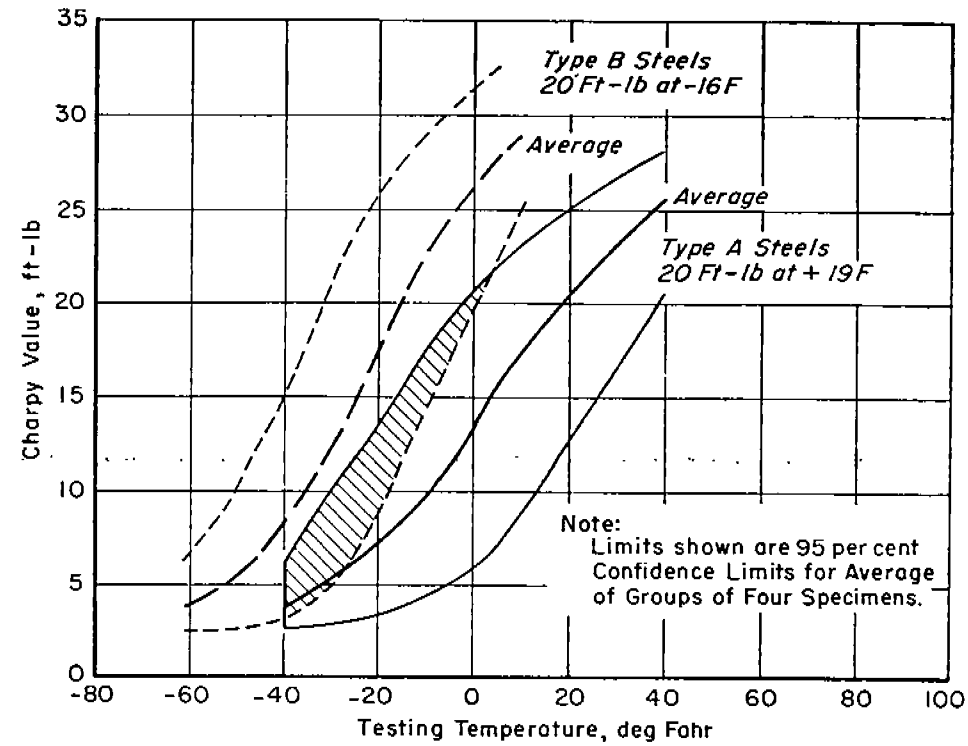

FIG. 7.—Charpy Transition Curves and Their Confidence Limits Calculated by Methods Described in the Appendix.

average Charpy values V_c, in ft-lb as a function of temperature, T, in deg Fahr for these steels are:

Ductile Fractures

$$V_c = 0.21T + 28.14 \qquad (3)$$

Brittle Fractures

$$V_c = 0.07T + 7.76 \qquad (4)$$

Figure 4 and Eqs 1 through 4 permit the calculation of theoretical curves showing the expected average energy value, for a number of determinations on groups of four specimens, as a function of temperature. The method of establishing the curves and their 95 per cent confidence limits involves some difficult statistical procedures. The method of calculation is illustrated in the Appendix. It should be noted here, however, that the statistical probabilities of encountering tough or brittle behavior in each of four specimens were taken into consideration in the calculations. The experimental data from Fig. 4 provide the probability estimates for determining theoretical curves.

The results of the computations are summarized by the calculated curves shown in Fig. 7. It will be noted that the 95 per cent confidence limits are not symmetrical, along the temperature axis, about the theoretical curves for the averages. These limits can be regarded as the limits within which 95 per cent of an infinite number of curves based on averages of four tests would fall.

The theoretical curves in Fig. 7 indicate that the 20-ft-lb transition temperatures for the two grades of steels are:

	Average	95 per cent Confidence Limits
Type A steel.......	19 F	38 F, −3 F
Type B steel.......	−16 F	0 F, −32 F

The limits indicate the chance variations to be expected in experimentally determined transition temperatures. The limits of the theoretical curves include seventeen of the eighteen, or 94.4 per cent, of the experimentally determined transition temperatures listed in Table II. This is additional evidence that steels of the same type are not heterogeneous with respect to the Charpy test. Furthermore, the fact that the experimentally determined transition temperatures fall within the ranges calculated on the assumption that tough or brittle fracture is a probability phenomenon supports the probability concept.

It should be noted that the probabilities of brittle fracture are slightly different for type A and type B steels tested at temperatures giving Charpy values averaging 20 ft-lb. Figure 4 shows that the probability of brittle fracture is 0.19 for type A steels tested at 19 F. The probability of brittle fracture is 0.26 for type B steels tested at their 20-ft-lb transition temperature of −16 F.

COMPARISON OF CHARACTERISTICS OF TYPE A AND TYPE B STEELS IN KEYHOLE CHARPY TESTS

The 95 per cent confidence limits calculated for averages of four tests are plotted in Fig. 7 for the type A and the type B steels. There are several interesting features in this plot. It is apparent that the transition is steeper in the group of steels with higher manganese contents, and the impact value above the transition temperature range is higher. In general, the dispersion is greater for the type A heats. Because of the difference in the steepnesses of the transition curve, the amount of overlap of the limits increases at the lower foot-pound levels. The overlap is 0 at 22 ft-lb and 14 F at 10 ft-lb. The overlap at 20 ft-lb is 3 F.

Because the overlap decreases as the energy level increases, transition temperatures based on higher energy levels discriminate better between the two types of steel. The small overlap of the theoretical curves at the 20-ft-lb level indicates that the Charpy test distinguishes between the two types of steel if this

TABLE IV.—SUMMARY OF TEAR-TEST DATA.

TYPE A HEATS

Temperature, deg Fahr	50	60	70	80	90	100	110
Number brittle	4	9	14	8	6	2	0
Total number of tests	4	11	26	41	21	19	8
Fraction brittle	1.00	0.82	0.54	0.19	0.29	0.11	0.00

TYPE B HEATS

Temperature, deg Fahr	40	50	60	70	80	90
Number brittle	1	5	8	6	2	0
Total number of tests	1	9	21	18	20	8
Fraction brittle	1.00	0.56	0.38	0.33	0.10	0.00

$$\sigma_D = \sqrt{\frac{\sigma_1^2}{N_1}\frac{\sigma_2^2}{N_2}} \qquad (5)$$

where:

σ_1 = standard deviation of first sample,

σ_2 = standard deviation of second sample,

N_1 = number of items in first sample, and

N_2 = number of items in second sample.

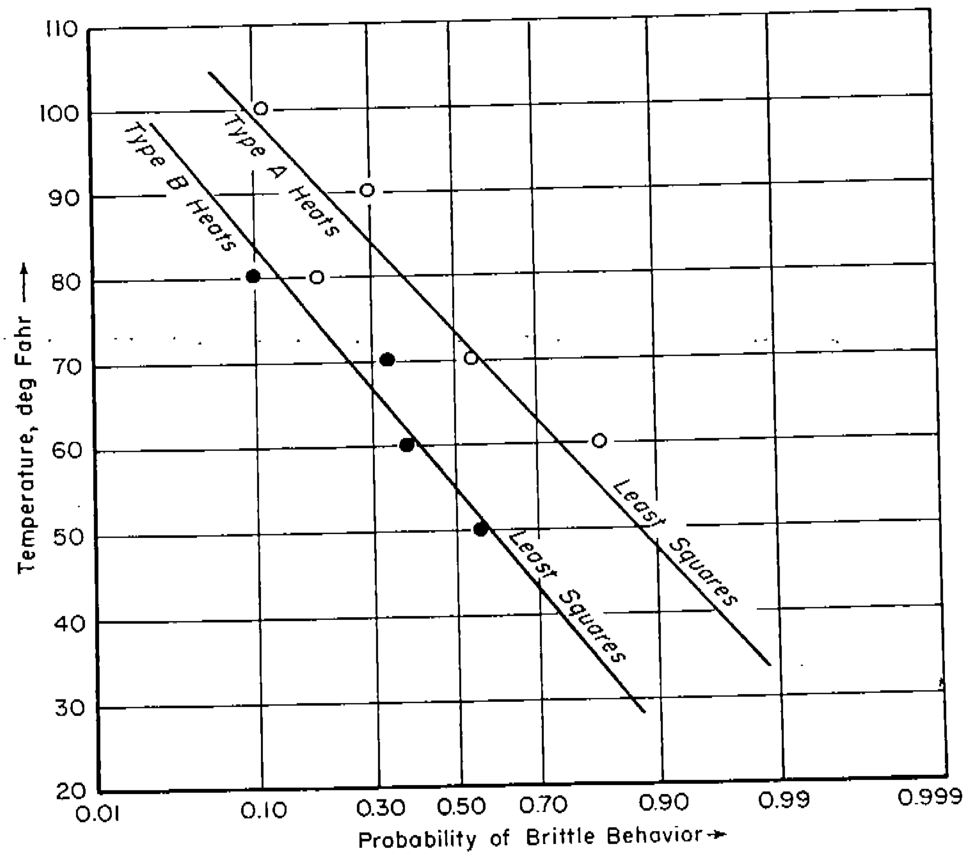

FIG. 8.—Frequencies of Brittle Tear-Test Specimens at Various Testing Temperatures.

criterion is used to define the transition temperature.

Then the question arises of whether or not the experimental Charpy data separate type A and type B steels significantly at the 20-ft-lb level. This can be tested conveniently by examining the significance of the differences of the means for the transition temperatures determined experimentally for the 20-ft-lb level. The standard deviation of the differences of means is given by:

The experimental data for the steels used in the probability analysis given in the footnote of Table II can be substituted in this equation:

$$\sigma_D = \sqrt{\frac{(8.05)^2}{6} + \frac{(7.21)^2}{7}}$$

$$= \sqrt{18.23} = 4.26 \text{ F}$$

Statistical theory teaches that the difference between averages of two groups is significant at the 99.5 per cent confidence level if the difference is at least three times the standard deviation of the differences of the means. In the present case:

$$3\sigma_D = 3 \times 4.26 \text{ F} = 12.78 \text{ F}$$

The observed difference in means, from data in the footnote to Table II, is:

$$+13.5 \text{ F} - (-15.4 \text{ F}) = 28.9 \text{ F}$$

Therefore, the Charpy test shows a significant difference between the mean transition temperatures of the two steels at the 20-ft-lb level.

A final point worth noting is the probability of brittle fracture associated with the 20-ft-lb criterion. It will be recalled that this level corresponds to a probability of brittle fracture of 0.19 for the type A steel and of 0.26 for type B steel. Thus, the same energy level corresponds to different probability criteria for the two types of steel. This results from the different shapes of the transition curves.

The 22.25-ft-lb level should be used if an evaluation of the type B steel is desired at the probability of 0.19 associated with the transition temperature of the type A steel.

Although this is probably of no practical importance in this case, it illustrates an important point, namely, that a selected energy level is not a fundamental criterion of a transition temperature. It is the same for two steels only if they have identically shaped transition curves. If their transition curves differ considerably in shape, this point may be of practical importance. It is believed that choosing a given probability value for brittle fracture is a sounder criterion for transition temperature.

TEAR TESTS

The data obtained on the type A and type B heats by the Navy tear test are summarized in Table IV. A specimen was classified as brittle if it showed less than 50 per cent ductile fracture. The frequencies of brittle fractures *versus* temperature for both steels are plotted on probability paper in Fig. 8. The lines of best fit, again, are "least-squares" lines. Since these lines are nearly parallel, it may be stated that the type A and type B steels have about the same rates of embrittlement with decreasing temperature.

The homogeneity of the tear-test data for both classes of steel was tested by the chi square test. For the type A steels,

At $p = 0.05$, chi square = 7.82
Calculated chi square = 4.91

Thus, it can be concluded that these data are probably not heterogeneous, although there is considerable scatter in the data. For type B steels,

At $p = 0.05$, chi square = 5.99
Calculated chi square = 0.75

The data for the type B steels are definitely not heterogeneous. It is to be noted that, in general, there is more scatter in the probability plots for the tear tests than in those for the impact tests.

Possible reasons for this increased scatter were considered. A major difference in testing technique for the impact test and for the tear test is in the sample size at each testing temperature. In the impact tests, four tests were made consistently at each testing temperature. However, in the tear test, tests are made at a given temperature until a brittle test is encountered, or until four ductile tests are obtained. Thus, the sample size at a given temperature may be one, two, three, or four tests. All such data obtained for each testing temperature were combined to calculate the frequency of brittle tests at each testing temperature; the results are given in Fig. 8. This situation leads to the question of whether or not these frequencies of brittle fracture are weighted either high or low by this testing technique. If more than the "statistically expected" number of brittle fractures occurred on the first tests, then the frequency of brittle tests was weighted to the high side. Likewise, if more than the "statistically expected" number of brittle tests on the third and fourth tests were experienced, then the calculated frequency of brittle tests was weighted to the low side.

TABLE V.—COMPARISON OF DISTRIBUTION OF SAMPLE SIZES IN TEAR TESTS OF TYPE A STEELS.

Event	First Test Brittle	Second Test Brittle	Third Test Brittle	Fourth Test Brittle	All Four Tests Ductile	Divergence Between Observed and Expected
60 F						
Expected	7	2	0	0	0	
Observed	7	2	0	0	0	0
70 F						
Expected	8	4	2	1	0	
Observed	8	5	0	1	1	4
80 F						
Expected	5	3	2	2	2	
Observed	4	0	3	1	6	10
90 F						
Expected	2	1	1	1	3	
Observed	1	4	0	1	2	6

Total divergence = 0 + 4 + 10 + 6 = 20
Average divergence = 20/20 = 1.00

The above problem resolves itself to the question of the probability of one, two, three, and four successive ductile tests at a given temperature. These probabilities depend on the probability of brittle fracture on a single test.

Let p = probability that a single test will be brittle (taken from trend line in Fig. 8), and $q = 1 - p$ = probability that a single test will be ductile. Then the probability that successive tests will be ductile is given by:

$$(1 - p)^n$$

TABLE VI.—COMPARISON OF DISTRIBUTION OF SAMPLE SIZES IN TEAR TESTS OF TYPE B STEELS.

Event	First Test Brittle	Second Test Brittle	Third Test Brittle	Fourth Test Brittle	All Four Tests Ductile	Divergence Between Observed and Expected
50 F						
Expected	3	1	1	0	0	
Observed	1	3	1	0	0	4
60 F						
Expected	3	2	1	1	1	
Observed	1	3	2	2	0	6
70 F						
Expected	2	1	1	1	2	
Observed	2	2	2	0	1	4
80 F						
Expected	1	1	1	0	3	
Observed	1	1	0	0	4	2

Total divergence = 4 + 6 + 4 + 2 = 16
Average divergence = 16/20 = 0.80

The required probabilities are the following:

(*a*) Probability that first test will be brittle = p.

(*b*) Probability that the second test will be brittle = $(1 - p)p$.

(*c*) Probability that the third test will be brittle = $(1 - p)^2p$.

(*d*) Probability that the fourth test will be brittle = $(1 - p)^3p$.

(*e*) Probability that all four tests will be ductile = $(1 - p)^4$.

For a group of tests, the five above possibilities should occur in the ratio of their probabilities. This, then, is the basis for calculating the expected distribution of sample sizes at a given temperature. The "least-squares" lines of Fig. 8 are used as the best estimate of the probability of brittle fracture at a given temperature.

The expected and observed distributions of sample sizes at 60, 70, 80, and 90 F for the type A steels are summarized in Table V employing all the data presented in Table II. The maximum divergence occurs in the tests at 80 and 90 F, which, interestingly, are the points farthest from the line in Fig. 7. The point at 80 F is less than expected and at 90 F it is more than expected. Examination of Table V shows that the data for 80 F are so weighted that the calculated frequency of brittle behavior is low, whereas at 90 F they are so weighted as to give a high value. Thus, the divergence of the data for type A steels in Fig. 8 appears to be a result of lack of randomness of sample sizes at these particular values of the probability of brittle behavior. The irregularity in sample sizes arose from the occurrence of slightly more brittle fractures in "first" specimens and the unexpectedly tough behavior of specimens at 80 F.

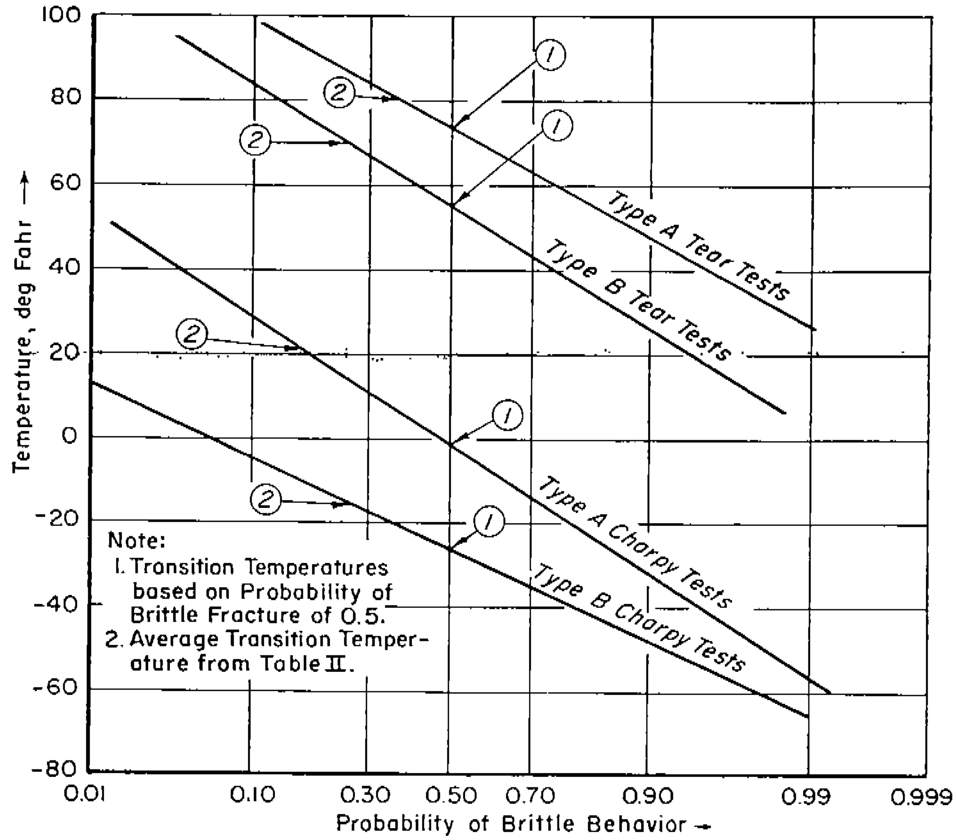

FIG. 9.—Probability of Brittle Behavior in Notched-Bar Tests at Various Temperatures.

The expected and observed distributions of sample sizes at 50, 60, 70, and 80 F for the type B steels are summarized in Table VI. The average divergence is less than that for type A steels, and the divergences for individual temperatures are all relatively low. Thus, the type B heat tests exhibited a behavior such like that predicted from a probability basis. This is borne out by the reduced scatter of the points for type B heats in Fig. 8.

A basic question is whether or not these divergencies in frequencies of brittle behavior in Fig. 8 would be minimized by filling out four tests in each group. This question must remain unanswered at present because of lack of samples. There seemed to be no particular individual heats which contributed to the unusual distribution of sample sizes. This variation of distribution of sample sizes from that expected on a probability basis may be simply a matter of chance. For instance, in tossing a coin, the probability of obtaining "heads" is $p = 0.5$. A coin was tossed ten times and the number of heads counted. This was repeated for ten trials. The number of "heads" in the ten trials was the following: 6, 6, 7, 4, 2, 4, 5, 7, 5, 7. The meaning of $p = 0.5$ is that, as the number of samples is made infinitely large, the probability of "heads" or "tails" approaches 0.5 as a limiting value.

Comparison of Characteristics of Type A and Type B Steels in Tear Tests

Table II showed that the average transition temperatures in the tear test were 80 and 70 F for type A and type B steels, respectively. These temperatures are the averages for the highest temperatures at which one specimen of each heat exhibited a brittle fracture.

Figure 9 summarizes the probability analyses of notched-bar data given separately in Figs. 4 and 8. The average difference between trend lines for type A and type B steels is about 25 F in Charpy tests and approximately 20 F in tear tests. The probability plots indicate that the tear test is capable of discriminating between the two types of steel almost as well as the Charpy test. The fact that the preceding paragraph listed an average difference between grades of only 10 F shows that the criterion employed did not use the data efficiently.

Figure 9 indicates that defining the transition temperature as the highest temperature at which a brittle fracture is encountered did not rate the two types of steel on a fair basis. The probability of a brittle fracture in specimens tested at the transition temperature differs for the two grades. The probability of brittle fracture for specimens of type A steel tested at 80 F is 0.37; the probability of brittle fracture in samples of type B steel tested at 70 F, the transition temperature for this grade, is 0.25. This means that type A steels are more likely to exhibit brittle fracture than type B steels when both are tested at the appropriate transition temperatures, as defined in the first paragraph of this section. If, however, either $p = 0.25$ or $p = 0.37$ is used consistently as the criterion, the transition temperatures of the two grades differ by 18 F. If $p = 0.5$ is selected as the criterion for transition temperature, type A steels would have a transition temperature of 73 F and type B steels would have 55 F, again a difference of 18 F.

Summary and Conclusions

1. Statistical analyses of notched-bar data and comparisons of analytical and tensile data demonstrate that reproducible properties can be obtained on semikilled steels made in the laboratory over a 3-yr period.

2. Increasing the manganese content from 0.45 to 0.76 per cent and decreasing the carbon content from 0.22 to 0.20 per cent improves the notched-bar toughness of semikilled steels. The change in keyhole Charpy transition temperature produced by the change in composition was 36 F. Similar changes in American Bureau of Shipping specifications for ship plate caused an average change of 31 F in Charpy transition temperature of commercial plate (12). This shows that conclusions based on small induction-furnace heats agree closely with experience for open-hearth steels.

3. Defining the Charpy transition

temperature as the temperature corresponding to 20 ft-lb gave slightly different probabilities of brittle fracture for the two grades of steel. The difference was small and not of practical importance.

4. The tear test did not separate the two grades of steel very well when the transition temperature was defined as the highest temperature at which a brittle fracture was detected. This resulted from the fact that the transition temperatures for the two grades corresponded to different probabilities of brittle fracture.

5. The tear test detected the effect of the changes in carbon and manganese contents when the data were considered on a probability basis. Treating the data in that fashion indicated the tear test to be almost as sensitive as the Charpy test.

6. The results justify reconsideration of the definition of transition temperature for tear tests. They also suggest that three or four specimens should be tested at each appropriate temperature and the data be treated on a probability basis.

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REFERENCES

(1) M. L. Williams, M. R. Meyerson, G. L. Kluge, and L. R. Dale, "Investigation of Fractured Steel Plates Removed from Welded Ships," Ship Structure Committee, June 1, 1951.

(2) E. P. Klier, F. C. Wagner, and M. Gensamer, "Correlation of Laboratory Tests With Ship-Plate Fracture Tests," *Welding Journal*, Research Supplement No. 27, pp. 71s-96s (1948).

(3) R. D. Stout and L. G. McGeady, "Notch Sensitivity of Welded Steel Plate," *Welding Journal*, Research Supplement No. 28, pp. 1s-9s (1949).

(4) P. P. Bijlaard, "Brittle Fractures in Welded Bridges," *Engineering News-Record*, April 26, 1951, pp. 46–48.

(5) N. A. Kahn and E. A. Imbembo, "A Method of Evaluating Transition From Shear to Cleavage Failure in Ship Plate," *Welding Journal*, Research Supplement No. 30, No. 2, pp. 79s–90s (1951).
N. A. Kahn and E. A. Imbembo," Notch-Sensitivity of Ship Plate, Correlation of Laboratory-Scale Tests with Large-Scale Plate Tests," Symposium on Deformation of Metal as Related to Forming and Service, Am. Soc. Testing Mats., p. 15 (1947). (Issued as separate publication *ASTM STP No. 87*.)

(6) A. F. Scotchbrook, B. G. Johnston, and R. D. Stout, "Scatter in Transition Curves," *Welding Journal*, Research Supplement, No. 30, April, 1951, pp. 266s-271s.

(7) J. Rinebolt and N. J. Harris, "Statistical Analysis of Tests of Charpy V-Notch and Keyhole Bars," *Welding Journal*, Research Supplement No. 30, pp. 202s-208s (1951).

(8) H. Levy, and E. E. Preidel, "Elementary Statistics," Ronald Press Co., New York, N. Y. (1945).

(9) J. F. Kenney, "Mathematics of Statistics," D. Van Nostrand Co., Inc., New York, N. Y. (1941 Edition).

(10) H. M. Banta, R. H. Frazier, and C. H. Lorig, "An Investigation of the Influence of Deoxidation and Chemical Composition on Notched-Bar Properties of Semikilled Ship Steel," Ship Structure Committee, *Report No. 49*, November, 1951.

(11) R. H. Frazier, F. W. Boulger, and C. H. Lorig, "An Investigation of the Influence of Deoxidation and Chemical Composition on Notched-Bar Properties of Semikilled Ship Steel," Ship Structure Committee, *Report No. 53*, December, 1951.

(12) "Investigation of the Charpy Impact Properties of Ship Plates Manufactured to 1948 and Older ABS Specifications," American Bureau of Shipping, New York, N. Y., September, 1949.

(13) R. W. Vanderbeck and M. Gensamer, "Evaluating Notch Toughness," *Welding Journal*, Research Supplement No. 29, pp. 37s-48s (1950).

APPENDIX

CALCULATION OF THE MEAN AND 95 PER CENT CONFIDENCE LIMITS OF THE AVERAGE IMPACT VALUE OF FOUR TESTS

Mean of the Average Impact Values of Four Tests:

Consider a certain temperature T. The problem is to predict the mean of the average impact value of all sets of four tests made at this temperature.

The distribution of these values is a combination of five distributions corresponding to the cases for which 0, 1, 2, 3, or 4 of the tests exhibit brittle failure. Consider these distributions.

First, let x and y denote the impact values of ductile and brittle tests, respectively, and let x and y be distributed normally with means $\bar{x}$ and $\bar{y}$ and standard deviations σ_x and σ_y.

Consider the functions:

$$\begin{aligned} A_0 &= \tfrac{1}{4}(x_1 + x_2 + x_3 + x_4) \\ A_1 &= \tfrac{1}{4}(x_1 + x_2 + x_3 + y_1) \\ A_2 &= \tfrac{1}{4}(x_1 + x_2 + y_1 + y_2) \\ A_3 &= \tfrac{1}{4}(x_1 + y_1 + y_2 + y_3) \\ A_4 &= \tfrac{1}{4}(y_1 + y_2 + y_3 + y_4) \end{aligned}$$

The subscripts on the x's and y's are used to differentiate between different tests in each set of four tests (that is, x_1 of A_0 is not necessarily equal to x_1 of A_1, etc.). However each x_i (i = 1, 2, 3 or 4) has the same distribution as x and each y_i (i = 1, 2, 3 or 4) has the same distribution as y. Then, since x and y are distributed normally it can be shown that each A_i is distributed normally, with easily determinable mean and standard deviation. As an example, for A_2:

$$\begin{aligned} A_2 &= \tfrac{1}{4}(\bar{x}_1 + \bar{x}_2 + \bar{y}_1 + \bar{y}_2) \\ \sigma_{A_2} &= \tfrac{1}{4}(\sigma_{x_1}{}^2 + \sigma_{x_2}{}^2 + \sigma_{y_1}{}^2 + \sigma_{y_2}{}^2)^{\frac{1}{2}} \end{aligned}$$

Since x_i and y_i are distributed as x and y, respectively:

$$\begin{aligned} \bar{x}_1 &= \bar{x}_2 = \bar{x}_i = \bar{x} \\ \sigma_{x_1} &= \sigma_{x_2} = \sigma_{x_i} = \sigma_x \\ \bar{y}_1 &= \bar{y}_2 = \bar{y}_i = \bar{y} \\ \sigma_{y_1} &= \sigma_{y_2} = \sigma_{y_i} = \sigma_y \end{aligned}$$

Thus,

$$\bar{A}_2 = \tfrac{1}{4}(\bar{x} + \bar{x} + \bar{y} + \bar{y}) = \tfrac{1}{2}(\bar{x} + \bar{y})$$

and

$$\sigma_{A_2} = \tfrac{1}{4}(\sigma_x^2 + \sigma_x^2 + \sigma_y^2 + \sigma_y^2)^{\frac{1}{2}} = \frac{\sqrt{2}}{4}(\sigma_x^2 + \sigma_y^2)$$

Now let p be the probability of obtaining a brittle specimen in one test and $q = 1 - p$ be the probability of obtaining a ductile sample in one test. Then the probability, p_i, of obtaining i brittle and $(4 - i)$ ductile tests in a set of four tests is given by:

$$p_i = \frac{4!}{i!\,(4-i)!}\, p^i q^{(4-i)} \qquad (i = 1, 2, 3, 4)$$

Then the mean of the average impact values of sets of four tests is:

$$\begin{aligned} m &= p_0\bar{A}_0 + p_1\bar{A}_1 + p_2\bar{A}_2 + p_3\bar{A}_3 + p_4\bar{A}_4 \\ &= p^4\tfrac{1}{4}(\bar{x}_1 + \bar{x}_2 + \bar{x}_3 + \bar{x}_4) \\ &\quad + 4p^3q\,\tfrac{1}{4}(\bar{x}_1 + \bar{x}_2 + \bar{x}_3 + \bar{y}_1) \\ &\quad + 6p^2q^2\,\tfrac{1}{4}(\bar{x}_1 + \bar{x}_2 + \bar{y}_1 + \bar{y}_2) \\ &\quad + 4pq^3\,\tfrac{1}{4}(\bar{x}_1 + \bar{y}_1 + \bar{y}_2 + \bar{y}_3) \\ &\quad + q^4\,\tfrac{1}{4}(\bar{y}_1 + \bar{y}_2 + \bar{y}_3 + \bar{y}_4) \\ &= p^4(\bar{x}) + 4p^3q(\tfrac{3}{4}\bar{x} + \tfrac{1}{4}\bar{y}) + 6p^2q^2(\tfrac{1}{2}\bar{x} + \tfrac{1}{2}\bar{y}) \\ &\quad + 4pq^3(\tfrac{1}{4}\bar{x} + \tfrac{3}{4}\bar{y}) + q^4(\bar{x}) \\ &= \bar{x}(p^4 + 3p^3q + 3p^2q^2 + pq^3) \\ &\quad + \bar{y}(q^4 + 3q^3p + 3q^2p^2 + qp^3) \\ &= \bar{x}p(p + q)^3 + \bar{y}q(p + q)^3 \\ &= p\bar{x} + q\bar{y} \end{aligned}$$

That is, the mean of the average impact values of sets of four tests at a temperature T is simply the mean impact value for one ductile test multiplied by the probability of getting a ductile specimen in one test plus the mean impact value for one brittle test multiplied by the probability of getting a brittle specimen in one test.

95 per cent Confidence Limits of the Average Impact Values of Four Tests:

Given a temperature T, the problem is to find an upper limit U and a lower limit L such that the probability of getting a set of four tests with an average impact value greater than U is 0.025 and, similarly, the probability of getting a set of four tests with an average impact value less than L is 0.025.

Consider the functions A_i with means $\bar{A}_i$ and standard deviations σ_{A_i}, as defined above.

The probability P_i that $A_i \geq U$ and the probability P_i' that $A_i \leq L$ are computed from the formulas:

$$P_i = \frac{1}{\sqrt{2\pi}\sigma A_i} \int_U^{\infty} e^{-\frac{(A-\bar{A}_i)^2}{2\sigma A_i^2}} dA$$

$$P_i' = \frac{1}{\sqrt{2\pi}\sigma A_i} \int_{-\infty}^{L} e^{-\frac{(A-\bar{A}_i)^2}{2\sigma A_i}} dA$$

Then, if the probability of obtaining i brittle samples is p_i (computed above), the probability that a sample of four tests with an average value greater than U or less than L would be obtained is:

$$\sum_{i=0}^{4} p_i P_i \quad \text{or} \quad \sum_{i=0}^{4} p_i P_i' \quad \text{respectively.}$$

As an example, consider the case for which the probability of brittle fracture of type A steel is 0.2. From Fig. 4, this corresponds to a temperature of 18 F. Figure 5 indicates that, at 18 F, $\bar{x} = 22.85$, $\bar{y} = 7.00$, $\sigma_x = 2.47$, and $\sigma_y = 1.08$.

Then:

$$m = (0.8)(22.85) + (0.2)(7.00) = 19.68$$

To find the 95 per cent confidence limits U and L, first calculate the following table, using $\bar{x}$, $\bar{y}$, σ_x, and σ_y and the formula

$$p_i = \frac{4!}{i!(4-i)!} p^i q^{(4-i)} \sigma! \quad (i = 1, 2, 3, 4)$$

i	$\bar{A}_i$	σA_i	p_i
0	22.85	1.235	0.4096
1	18.89	1.103	0.4096
2	14.93	0.953	0.1536
3	10.96	0.775	0.0256
4	7.0	0.540	0.0016

U and L are found by trial and error. The lower limit L will be found first. Consider the expression for P_i'.

Write

$$t_i = \frac{A - \bar{A}_i}{\sigma A_i}.$$

Then:

$$P_i' = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t_{iL}} e^{-t^2/2} dt$$

where:

$$t_{iL} = \frac{L - A_i}{\sigma A_i}$$

The value of this integral is tabulated as a function of t_{iL} (9).

Assume, as a first approximation, a value $L_1 = 11.00$. Then the following tabulation can be calculated:

i	t_{iL_1}	P_i	p_i	$P_i p_i$
0	−9.595	...	0.4096	...
1	−7.153	...	0.4096	...
2	−4.123	1×10^{-6}	0.1536	...
3	+0.051	0.5203	0.0256	0.0133
4	+7.41	1.0000	0.0016	0.0016
				P =0 .0149

This indicates that L_1 was too low. Therefore, choose $L_2 = 12.00$.

Neglecting cases for which $i = 1$ and 2, the following tabulation is constructed:

i	t_{iL_2}	P_i'	p_i	$P_i' p_i$
2	−3.075	0.0011	0.1536	0.0002
3	+1.342	0.9102	0.0256	0.0233
4	+9.259	1.0000	0.0016	0.0016
				P = 0.0251

For $L_3 = 11.99$, we find $P = 0.0250$.

To find U, consider the expression for P_i. Write again:

$$t = \frac{A - \bar{A}_i}{\sigma A_i}$$

Then:

$$P_i = \frac{1}{\sqrt{2\pi}} \int_{t_{iU}}^{\infty} e^{-t^2/2}\,dt,$$

where:

$$t_{iU} = \frac{U - A_i}{\sigma A_i}$$

Assume, as a first approximation, $U_1 = 24.00$. Then again a tabulation is computed:

i	t_{iU_i}	P_i	p_i	p_iP_i
0	0.931	0.1759	0.4096	0.0720
1	4.633	$<1 \times 10^{-5}$	0.4096	...
2	9.517	$<1 \times 10^{-5}$	0.1536	...
3	16.826	$<1 \times 10^{-5}$	0.0256	...
4	31.481	$<1 \times 10^{-5}$	0.0016	...
				0.0720

Since P_1, P_2, P_3, and P_4 are negligible, they are neglected here. Then, considering only P_0 here, the table on pp. 225–227 of Reference (9) shows that, for $t_{0U} = 1.544$, $P_0 = 0.06104$, from which $p_0P_0 = 0.0250$. Thus,

$$U = (1.544)\sigma_{A_0} + \bar{A}_0 = (1.544)(1.235) + (22.85) = 24.76.$$

DISCUSSION

Mr. R. W. Vanderbeck[1] (*presented in written form*).—The authors have analyzed behavior in the transition temperature zone on a probability basis. In another paper[2] of this Symposium, numerous keyhole Charpy impact data have been analyzed in a similar manner, and the results definitely indicate that the relationship between test temperature and probability of brittle behavior can be represented by a straight line on probability paper. The method used by the authors to obtain the line of best fit, however, is not believed to be an accepted method for this type of analysis. The reliability of each observed percentage of brittle behavior depends on how many specimens were broken to determine this percentage and also on a weighting coefficient which varies in value for different probabilities of brittle behavior.[3] The percentages of brittle behavior close to 50 per cent are given the most weight, and those furthest removed from 50 per cent the least weight. The least-squares method used by the authors is not believed to weight the observations according to their statistical reliability. Therefore, too much emphasis is being placed on some points and not enough on others. For the type of behavior observed, probit analysis[3] of the data should provide a better evaluation of the "line of best fit." Such an analysis also permits the calculation of confidence limits on this line.

Referring to Fig. 4, the authors state that "the slope of the trend line in the probability plot for the type B steels is somewhat greater than for the type A steels. This means that the B steels are more sensitive to changes in temperature." I do not believe, however, that these slopes are by any means significantly different. It is suggested that the regression lines be recalculated by probit analysis (this alone should alter the slopes to a certain extent) and that the significance of any difference be determined. Moreover, use may also be made of the data at the temperatures at which all brittle or all tough behavior was obtained.

Since the regression lines in Fig. 4 are based upon data from a number of different heats, even if a real difference in slope were found to exist, this might be a reflection of the differences in mean transition temperature among the heats of the two grades rather than a difference in slope for the individual heats of the two grades. Another way of stating this is that, even if the slopes of the individual heats of type A and type B steel were the same, the slope obtained by grouping the type A heats might differ from that obtained by grouping the type B heats

[1] Research Associate, U. S. Steel Corp., Pittsburgh, Pa.

[2] R. W. Vanderbeck, R. W. Lindsay, H. D. Wilde, W. T. Lankford, S. C. Snyder, "Effect of Specimen Preparation on Notch Toughness Behavior of Keyhole Charpy Specimens in the Transition Temperature Zone," p. 306.

[3] D. J. Finney, "Probit Analysis," Second Edition, University Press, Cambridge, p. 31 (1952).

because of different distributions of their mean transition temperatures.

It is surprising to note in Figs. 5 and 6 that the dispersion of the impact values for the brittle specimens passes through a maximum in the vicinity of the middle of the transition range. This has not been found to be so for steels that we have examined. For example, the accompanying Fig. 10 shows the results of 200 keyhole Charpy impact tests on one piece of $\frac{3}{4}$-in. thick ABS type B hull steel. Twenty tests were conducted at each of 10 temperatures. The specimens were randomized with respect to both position in the plate and order of drilling. It will be observed that the dispersion of the energy values for the brittle specimens is about the same at all temperatures.

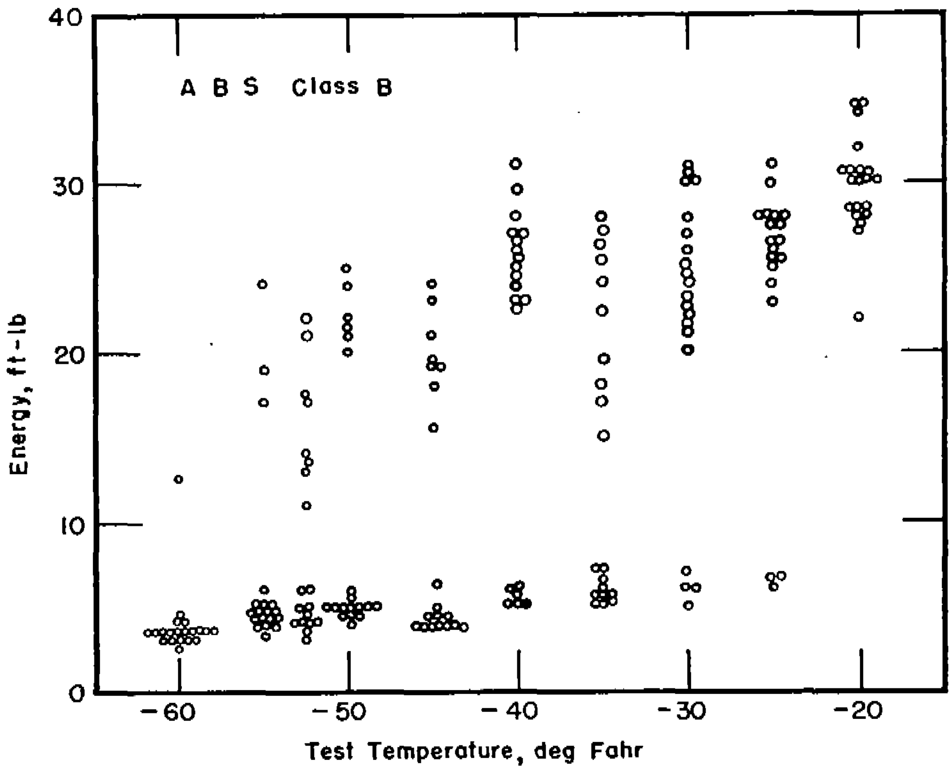

FIG. 10.—Keyhole Charpy Impact Test Results on ABS Type B Hull Steel.

With regard to the statistics used, I should like to raise two additional questions. I believe that standard deviations were based upon the formula:

$$\sigma = \left(\frac{\Sigma(x - \bar{x})^2}{N}\right)^{1/2}$$

Would it not be more appropriate to divide by $N - 1$ as advocated at present by most authorities?[4] The use of just N is proper if the true mean of the population is known, but, since we only have an estimate of the mean, the sum of the squares of the deviations from the estimated mean will be smaller than the sum of the squares of the deviations from the true mean. This is compensated for by dividing by $N - 1$ instead of by N.

To determine the standard deviation of the difference between two means, the authors use the following formula:

$$\sigma_D = \sqrt{\frac{\sigma_1^2}{N_1} + \frac{\sigma_2^2}{N_2}}$$

[4] K. A. Brownlee, "Industrial Experimentation," Fourth Edition, His Majesty's Stationery Office, London, p. 27 (1949).

This formula is used when the true variances are not equal.[5, 6] If that is the case, the ordinary t test should not be used to judge the significance of the difference between the two means.

If the true variances are judged to be equal, however, σ_D is calculated as follows:[5]

$$\sigma_D = \sqrt{\frac{\sigma_1^2(N_1 - 1) + \sigma_2^2(N_2 - 1)}{N_1 + N_2 - 2}\left(\frac{1}{N_1} + \frac{1}{N_2}\right)}$$

and the t test may then be used to judge the significance of the difference between the two means.

To judge whether the variances are equal or unequal, the F test or ratio of the variances is employed.

MR. L. P. DIAMOND[7]* (*presented in written form*).—A closer examination and extension of the statistics presented in Table II of this paper reveals the following:

RELATIVE VARIABILITY EXPRESSED AS A PERCENTAGE OF THE AVERAGE.

Steel	Keyhole Charpy	Tear Test
Type A	65	17
Type B	53	10

The relative variability is obtained by dividing the standard deviation by the average and multiplying by 100. These figures show a much lower relative variability among the heats for the tear test than that for the Charpy test. In view of the evidence presented in the paper of the homogeneity among the heats, the tear test is more indicative of that fact than is the Charpy. In addition, if the heats are homogeneous, it may be inferred that the tear test is more reproducible than the Charpy, on a relative basis, by a factor of about 4.

The high variability of the Charpy test is further evidenced by the value of +52 for heat A6424. If we divide the difference between this heat and its nearest neighbor, in order of magnitude, by the entire range of the data for the Charpy test for type A steel, that is $\frac{(52 - 33)}{(52 - 4)}$, we obtain a value of 0.4. This is close to the 10 per cent level of significance (0.41) of a Q criterion for the rejection of an extreme value. No such apparently extreme value occurs in the tear test data.

If we also extend the use of the t distribution beyond that mentioned in the paper, still employing the data of Table II, significant mean differences may be calculated. A significant mean difference may be defined as the minimum difference between any two averages (in a group of common variance) which is necessary to discriminate between the averages at a given probability value. Thus

	Charpy	Tear Test
Significant mean difference at the 5 per cent level	17	18

It is evident that there is no appreciable difference between the Charpy test and tear test in their ability to discriminate between averages.

Finally, reproducibility or precision is a function of the variability evidenced by the data. In the state of the art of determining properties of metals there may be several admissible ways of defining averages or central tendencies depending upon interpretation and final use. But it may be observed that the tear test is capable of discriminating at least as well as the Charpy and with fewer specimens.

[5] W. J. Dixon and F. J. Massey, Jr., "Introduction to Statistical Analysis," First Edition, McGraw-Hill Book Co., New York, N. Y., pp. 103–105 (1951).

[6] Alice A. Aspin, "Tables for Use in Comparisons Whose Accuracy Involves Two Variances Separately Estimated," *Biometrika*, Vol. 36, pp. 290–296 (1949).

[7] Supervisory Analytical Statistician, Material Laboratory, New York Naval Shipyard.

* The opinions contained herein are the private ones of the discussor and are not to be construed as reflecting the views of the Navy Department or the Naval Service at large.

MR. R. H. FRAZIER (*authors' closure*). —The discussions by R. W. Vanderbeck and L. P. Diamond are very much appreciated.

Probit analysis as suggested by Vanderbeck would give additional information and would probably weigh the data correctly. The lines of best fit have been calculated, using probit analysis. The slopes of these lines and the temperature at which 50 per cent of the specimens are expected to be brittle are as follows:

Test Specimen	Type of Steel	T_{50}, deg Fahr	95 per cent Confidence Limits of T_{50}, deg Fahr	Slope	95 per cent Confidence Limits of the Slope
Charpy........	A	0	±9.0	22	±7.6
Charpy........	B	26	±8.2	17	±5.5
Tear..........	A	73	±5.2	20	±6.7
Tear..........	B	56	±8.3	21	±13.8

Comparisons based on probit analysis indicate that the slopes of the trend lines for the Charpy data for the two types of steel do not differ significantly.

Mr. Vanderbeck's statement that the standard deviations of the transition temperatures were calculated by using N instead of $N - 1$ in the denominator of the formula is correct. This practice is recommended in the ASTM Manual of Presentation of Data published in 1951. We are aware of the fact, however, that some texts on statistics define the standard deviation and the variance on the more conservative basis. In the present case, either formula gives approximately the same estimate of uncertainty in averages or reproducibility of the data. For example, the standard deviations for the data shown in Table II are given below.

If the variances are judged to be equal, the standard deviations of the differences in the mean Charpy transition temperatures can be calculated by the formula quoted by Vanderbeck. That formula gives a standard deviation of the difference in the means of 4.6 F instead of 4.26 F reported in the paper. As concluded in the paper, the difference in the mean Charpy transition temperatures of the two types of steel is significant at a confidence level above 99 per cent.

Mr. Diamond suggests that the variability be expressed on a relative rather than absolute scale by dividing the standard deviation by the average transition temperature. This would appear to be justified only if variability increases with transition temperature. The authors have seen no evidence supporting this opinion. Although the information is scanty, published Charpy data on several grades of steel indicate that the standard deviation does not increase with transition temperature.

The conditions of the present case were not considered suitable for extreme Charpy value.

Mr. Diamond agrees with the conclusion that both Charpy and tear tests are capable of discriminating between average transition temperatures equally well. This appears to be true only when the data are used efficiently as in Fig. 9. It should be noted that the differences in tear test transition temperatures given in Table II are not statistically significant. This casts considerable doubt on the opinion that it is safe to test fewer specimens in tear tests than in Charpy tests.

STANDARD DEVIATION, DEG FAHR, FOR DATA IN TABLE II.

	a	b
Charpy tests on Type A steel..................	13.6	14.4
Charpy tests on Type B steel..................	6.8	7.3
Tear tests on Type A steel..	13.7	14.6
Tear tests on Type B steel..	7.1	7.5

[a] Based on formula $\sigma = \left(\frac{\Sigma(x - \bar{x})^2}{N}\right)^{\frac{1}{2}}$ for standard deviation of a sample.

[b] Based on formula $\sigma = \left(\frac{\Sigma(x - \bar{x})^2}{N - 1}\right)^{\frac{1}{2}}$ for standard deviation of a "population."

PART II

REPRODUCIBILITY OF KEYHOLE CHARPY AND TEAR TEST DATA ON LABORATORY HEATS OF SEMIKILLED STEEL

SUMMARY

Part I of this report concluded that the method of defining the tear test transition temperature should be reconsidered. Later calculations, based on 130 observations on Type A steel, indicate the advantages of defining the transition temperature on a probability basis. If twenty specimens are tested at temperatures covering the transition zone, the transition temperature, based on equal probabilities of ductile and brittle fractures, can be determined with a standard deviation of 6.6°F. The comparable limit of uncertainty for transition temperatures, corresponding to the highest temperature where at least one brittle specimen is found when testing groups of four, is 11°F.

A large number of tear test data were used to establish the relationships between transition temperatures defined in different ways. The study indicates that transition temperatures, based on 50 per cent brittle fracture texture, are equivalent to those based on $p = 0.5$ for brittle specimens. Both give lower transition temperature values than the Kahn-Imbembo criterion.

Even when tear test transition temperatures are defined on a probability basis, they do not correlate very precisely with Charpy transition temperatures. Estimates of one

transition temperature, based on data obtained in the other type of test, are likely to be in serious error.

MATERIALS

Data obtained on 95 plates of steel were used to compare different criteria for defining the transition temperature in Navy tear tests. The 3/4-in. plates were rolled from 24 experimental open-hearth ingots. The steels represented two combinations of carbon and manganese which gave tensile strengths of approximately 62,500 lb. per sq. in. The nominal compositions were 0.20% carbon, 0.76% manganese, and 0.22% carbon and 0.45% manganese. The steels varied in aluminum contents and had been rolled at different finishing temperatures. The effects of the variations in composition and processing treatments are described in a separate report(14)*.

The compositions of the plates tested during this study are listed in Table 7. The steel plants supplied 3/4-in. plates and 1 3/4-in. slabs. The latter were rolled to 3/4-in. plates in the laboratory, using finishing temperatures of 1650°, 1850°, and 2050°F.

TESTING PROCEDURES

Tests were made on keyhole Charpy bars taken parallel to the rolling direction of the plates and notched through the

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*See References, page 22

TABLE 7. COMPOSITIONS AND ROLLING TEMPERATURES OF EXPERIMENTAL OPEN-HEARTH STEELS

Heat No.	Chemical Composition, per cent					
	C	Mn	P	S	Si	Al*
V1	0.26	0.45	0.008	0.032	0.09	0.003
V2	0.27	0.45	0.009	0.032	0.07	0.007
V3	0.28	0.46	0.009	0.032	0.09	0.011
V4	0.29	0.45	0.009	0.032	0.07	0.018
V5	0.21	0.67	0.012	0.033	0.07	0.002
V6	0.19	0.67	0.011	0.032	0.07	0.007
V7	0.22	0.67	0.012	0.033	0.07	0.011
V8	0.19	0.66	0.011	0.033	0.08	0.015
W1	0.23	0.52	0.013	0.037	0.09	0.001
W2	0.23	0.52	0.011	0.037	0.10	0.004
W3	0.23	0.52	0.012	0.041	0.09	0.005
W4	0.23	0.52	0.013	0.039	0.10	0.025
W5	0.23	0.78	0.012	0.025	0.09	0.001
W6	0.22	0.80	0.013	0.026	0.08	0.003
W7	0.20	0.80	0.012	0.025	0.08	0.007
W8	0.21	0.78	0.013	0.026	0.08	0.032
Z1	0.19	0.67	0.012	0.028	0.040	0.002
Z2	0.19	0.68	0.013	0.028	0.040	0.001
Z3	0.18	0.68	0.012	0.027	0.040	0.013
Z4	0.19	0.68	0.013	0.027	0.040	0.044
Z5	0.27	0.50	0.017	0.041	0.057	0.003
Z6	0.27	0.51	0.017	0.042	0.058	0.002
Z7	0.27	0.49	0.017	0.042	0.058	0.009
Z8	0.27	0.50	0.018	0.042	0.058	0.030

*The aluminum values for the last eight steels are for acid soluble amounts; the others are for total aluminum contents.

plate thickness. Four specimens from each plate were broken at each temperature, and the Charpy transition temperature was taken as the temperature at which the average curve crossed the 12 ft-lb level. Tear test specimens were also taken parallel to the rolling direction. Four tear specimens were broken at temperatures 10°F apart throughout the transition zone. This practice permitted the tear test transition temperature to be defined by three different criteria. These definitions for transition temperature are:

1. The highest temperature at which one or more of four specimens exhibits a fracture area with less than 50 per cent shear texture. This is the definition used by Kahn and Imbembo[5].
2. The temperature corresponding to 50 per cent shear texture when average percentages of shear texture in fractured surfaces are plotted against testing temperature. This definition is used by some steel companies.
3. The temperature at which the probability of brittle specimens is 0.5 when brittle specimens are defined as those having less than 50 per cent shear texture on the fractured surface. The reasons for suggesting this criterion are discussed in Part I of this report.

The results of the notched bar tests are summarized in Table 8. The original data are reported separately[14], but

TABLE 8. TRANSITION TEMPERATURES IN NOTCHED BAR TESTS

Heat No.	Rolling Temp, °F	12 ft-lb Keyhole Charpy Transition Temp, °F	Navy Tear Test Transition Temp, °F Kahn	50% Brittle Fracture	50% Brittle Tests
W1	1700	-19	80	80	81
W2	1750	-17	90	85	87
W3	1750	+2	100	94	98
W4	1700	-15	80	68	70
W5	1700	-8	110	103	108
W6	1725	-4	110	104	105
W7	1800	-43	80	70	71
W8	1725	-37	80	54	57
W1	1650	-34	50	45	40
W2	1650	-17	40	44	40
W3	1650	-33	70	48	49
W4	1650	-34	70	58	59
W5	1650	-50	30	36	35
W6	1650	-43	40	46	45
W7	1650	-63	60	50	53
W8	1650	-62	30	20	23
W1	1850	-10	80	73	64
W2	1850	-10	60	67	55
W3	1850	-38	80	58	63
W4	1850	-31	70	71	66
W6	1850	-17	60	66	65
W7	1850	-49	60	59	57
W8	1850	-40	40	39	40
W1	2050	-18	60	35	40
W2	2050	-14	70	68	65
W3	2050	-25	60	57	55
W4	2050	-22	70	63	58
W5	2050	-13	100	62	75
W6	2050	-5	70	73	66
W7	2050	-37	70	59	64
W8	2050	-40	70	50	53

TABLE 8. (CONTINUED)

Heat No.	Rolling Temp, °F	12 ft-lb Keyhole Charpy Transition Temp, °F	Navy Tear Test Transition Temp, °F		
			Kahn	50% Brittle Fracture	50% Brittle Tests
V1	1950	+22	90	90	90
V2	1965	+28	120	105	105
V3	1850	+11	100	91	93
V4	1990	+27	120	106	110
V5	2000	-4	70	64	55
V6	1980	0	60	50	50
V7	2000	-21	70	66	67
V8	1990	-16	60	59	61
V1	1650	-14	70	71	68
V2	1650	-1	90	80	80
V3	1650	-16	80	76	73
V4	1650	-20	60	66	65
V5	1650	-23	50	38	36
V6	1650	-30	30	30	29
V7	1650	-50	40	34	30
V8	1650	-64	30	27	26
V1	1850	+2	100	91	90
V2	1850	+9	90	91	90
V3	1850	-5	80	86	85
V4	1850	-5	100	88	85
V5	1850	-10	50	43	35
V6	1850	-27	40	44	41
V7	1850	-41	70	51	52
V8	1850	-34	80	54	58
V1	2050	-3	110	102	103
V2	2050	+8	90	95	95
V3	2050	+8	100	97	95
V4	2050	-1	110	101	100
V5	2050	-23	90	51	59
V6	2050	-18	60	61	55
V7	2050	-22	60	63	64
V8	2050	-31	50	53	47

TABLE 8. (CONTINUED)

Heat No.	Rolling Temp, °F	12 ft-lb Keyhole Charpy Transition Temp, °F	Navy Tear Test Transition Temp, °F Kahn	50% Brittle Fracture	50% Brittle Tests
Z1	1820	-18	60	66	65
Z2	1810	-10	60	54	57
Z3	1830	-16	70	57	55
Z4	1830	-37	50	39	38
Z5	1980	-1	90	89	90
Z6	1950	+2	110	96	100
Z7	1855	+9	90	89	90
Z8	1890	0	80	73	75
Z1	1650	-37	50	46	45
Z2	1650	-31	60	56	62
Z3	1650	-38	50	39	42
Z4	1650	-53	30	21	19
Z5	1650	-14	90	75	76
Z6	1650	-16	90	87	83
Z7	1650	-2	60	60	62
Z8	1650	-14	60	54	54
Z1	1850	-30	60	63	61
Z2	1850	-16	80	71	75
Z3	1850	-21	70	59	59
Z4	1850	-35	60	52	50
Z5	1850	-10	90	86	85
Z6	1850	-7	90	87	90
Z7	1850	+12	80	70	71
Z8	1850	-10	80	67	64
Z1	2050	-12	100	93	92
Z2	2050	-4	100	88	89
Z3	2050	-4	90	82	80
Z4	2050	-17	90	80	83
Z5	2050	+8	110	108	107
Z6	2050	+9	90	91	90
Z7	2050	+21	100	97	99
Z8	2050	+18	80	83	81

it can be mentioned that twenty specimens of each steel were usually tested.

Before discussing the relationships among the transition temperatures listed in Table 8, the uncertainties involved in experimentally determined transition temperatures will be considered.

EXPECTED UNCERTAINTY IN TEAR TEST TRANSITION TEMPERATURES

The data on Type A heats in Table 4 of Part I of this report can be used for estimating the uncertainty attached to tear test transition temperatures defined on different bases. This can be done for the Kahn definition and for p = 0.5 probability of brittle fractures at the transition temperature.

Fig. 10 is a plot on probability paper of data obtained from 130 specimens of Type A steel. Four specimens were tested at 50°F; groups ranging from 8 to 41 specimens were tested at the other temperatures. The trend line and 95 per cent confidence limits were determined by probit analysis. The temperature corresponding to a probability of brittle fracture p = 0.5 is 73° F. This is the transition temperature for that criterion. The 95 per cent confidence limits for this transition temperature are 73 ± 5.2 °F or 67.8 and 78.2°F, based on testing 130 specimens.

If the transition temperature were to be determined by testing 20 specimens, the 95 per cent confidence limits would

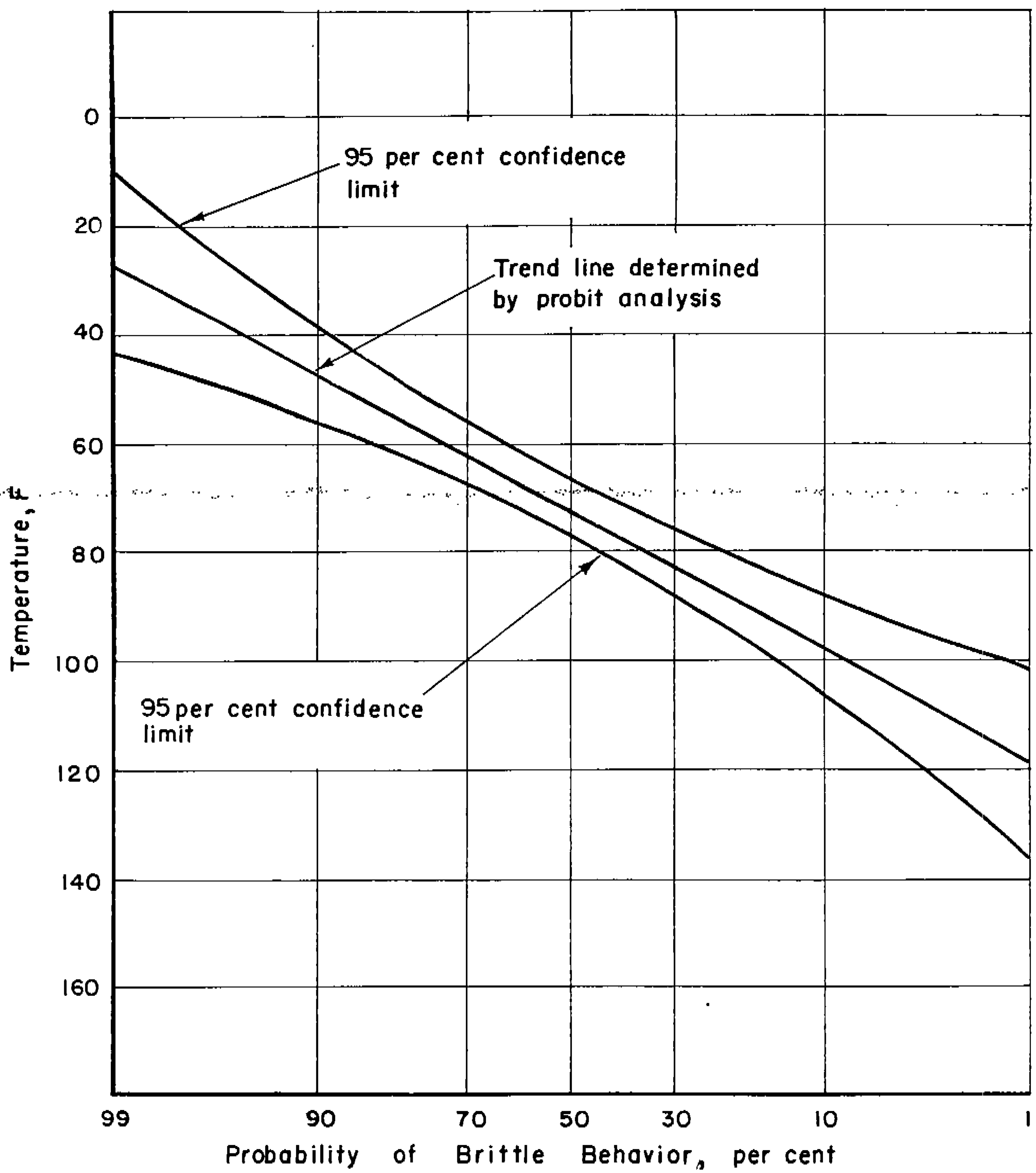

FIGURE 10. PROBABILITY OF BRITTLE BEHAVIOR IN NAVY TEAR TESTS ON TYPE A STEELS AT VARIOUS TEMPERATURES

0-22383

be farther apart. They would be increased by a factor $\sqrt{\frac{130}{20}}$ or 2.55. This means that by using the probability of brittle fracture $p = 0.5$ to define the transition temperature, 95 determinations out of 100 would lie within a 26.5°F (2.55 x 10.4°F) interval. The expected distribution is illustrated by the lower chart in Fig. 11.

Similar deductions can be made about the uncertainty of the Kahn transition temperature by considering the probabilities of encountering brittle or ductile specimens when testing groups of four specimens at five temperatures. It would not always be necessary to test 20 specimens because the testing temperatures are chosen according to the sequence in which brittle specimens are encountered. The Kahn transition temperature is the highest temperature at which at least one specimen of four is brittle and 10°F below the temperature at which four specimens are ductile. Hence, it can be defined by as few as five specimens. Since it is usually based on fewer observations, the Kahn transition temperature would be expected to have wider limits of uncertainty.

Table 9 lists the probabilities of encountering brittle specimens when testing groups of four samples at various temperatures. They are based on the trend line in Fig. 10. The last two columns give the probabilities of encountering four consecutive ductile specimens or at least one brittle specimen

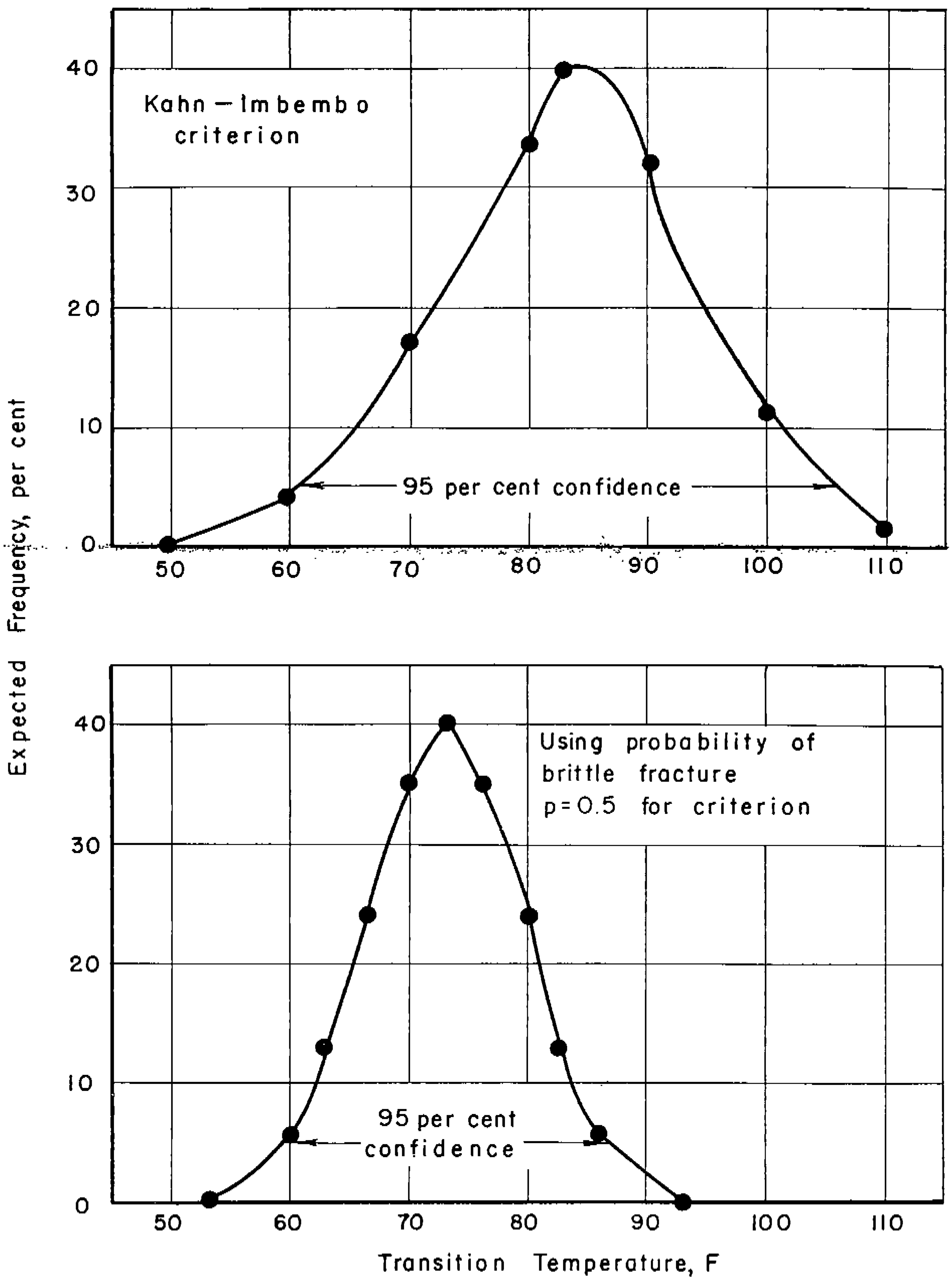

FIGURE 11. COMPARISON OF DISPERSION OF TEAR-TEST TRANSITION TEMPERATURES BASED ON TESTING 20 SAMPLES

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TABLE 9. PROBABILITIES CALCULATED ON BASIS OF FIGURE 10 FOR PREDICTING BEHAVIOR OF GROUPS OF FOUR TEAR TEST SPECIMENS OF TYPE A STEEL TESTED AT VARIOUS TEMPERATURES

Testing Temp, °F	Probabilities					
	First Specimen Brittle	Second Specimen Brittle	Third Specimen Brittle	Fourth Specimen Brittle	All Four Ductile	At Least 1 of 4 Brittle
60	0.76	0.1824	0.0438	0.0105	0.0033	0.9967
70	0.55	0.2475	0.0909	0.0495	0.0408	0.959
80	0.35	0.2275	0.1478	0.0941	0.1785	0.8215
90	0.19	0.1539	0.1246	0.1010	0.4303	0.5697
100	0.08	0.0736	0.0677	0.0623	0.7164	0.2836
110	0.03	0.0291	0.0282	0.0274	0.8855	0.1145

in a group of four. From these values, the Kahn transition temperatures to be expected when testing Type A steel can be deduced. If testing is started at 60°F, for example, the probability of setting the Kahn transition temperature at 80°F depends on the probability of finding at least one brittle specimen out of four at 80°F or lower temperatures and on the probability of testing four ductile specimens at 90°F. According to Table 9, the probability of the Kahn transition temperature being 80°F is:

$$0.997 \times 0.959 \times 0.8215 \times 0.43 = 0.338.$$

Similar calculations for the other temperatures lead to the upper chart shown in Fig. 11. This chart shows that the 95 per cent confidence limits for the Kahn transition temperature covers a range of 44°F. It is a wider range than that for the lower chart because it depends on information provided by eight specimens or less even when more are tested.

The frequency charts in Fig. 11 show that when 20 specimens are available the transition temperature can be determined more precisely using the probability criterion. The charts indicate that the Kahn criterion is less desirable for research purposes because it leads to wider uncertainty limits.

Perhaps it should be mentioned that the data in Table 9 suggest that the Kahn transition temperature may be influenced by the sequence in which tear tests are made. It appears that starting tests at low temperatures leads to lower values of the Kahn transition temperature. This can be illustrated by calculations from the data in Table 9. If tests are started at 60° or 70°F, the probabilities are 0.338 and 0.321 that the Kahn transition temperatures would be 80° and 90°F, respectively. When starting tests at 110°F, the probability is 0.224 that 80°F and 0.362 that 90°F would be chosen by the Kahn criterion. Biasing the Kahn transition temperature toward the direction from which it is approached occurs because of the way in which it is defined.

CORRELATION ANALYSIS OF TEAR TEST DATA

The relationships among the transition temperatures listed in Table 2 were examined by standard[9] methods of statistical analysis. The results of the correlation analyses are summarized in Table 10.

It is apparent that transition temperatures, defined on the basis of probability of brittle fracture $p = 0.5$ and on the basis of 50 per cent brittle texture, are in closest agreement. Fig. 12 illustrates this correlation. The slope of the trend line is 1.014, and the correlation coefficient is 0.986. The scatter from the trend line is small, and the standard error is only 3.70°F. These data show that transition temperatures defined on the basis of 50 per cent brittle fracture texture are equivalent to those established by

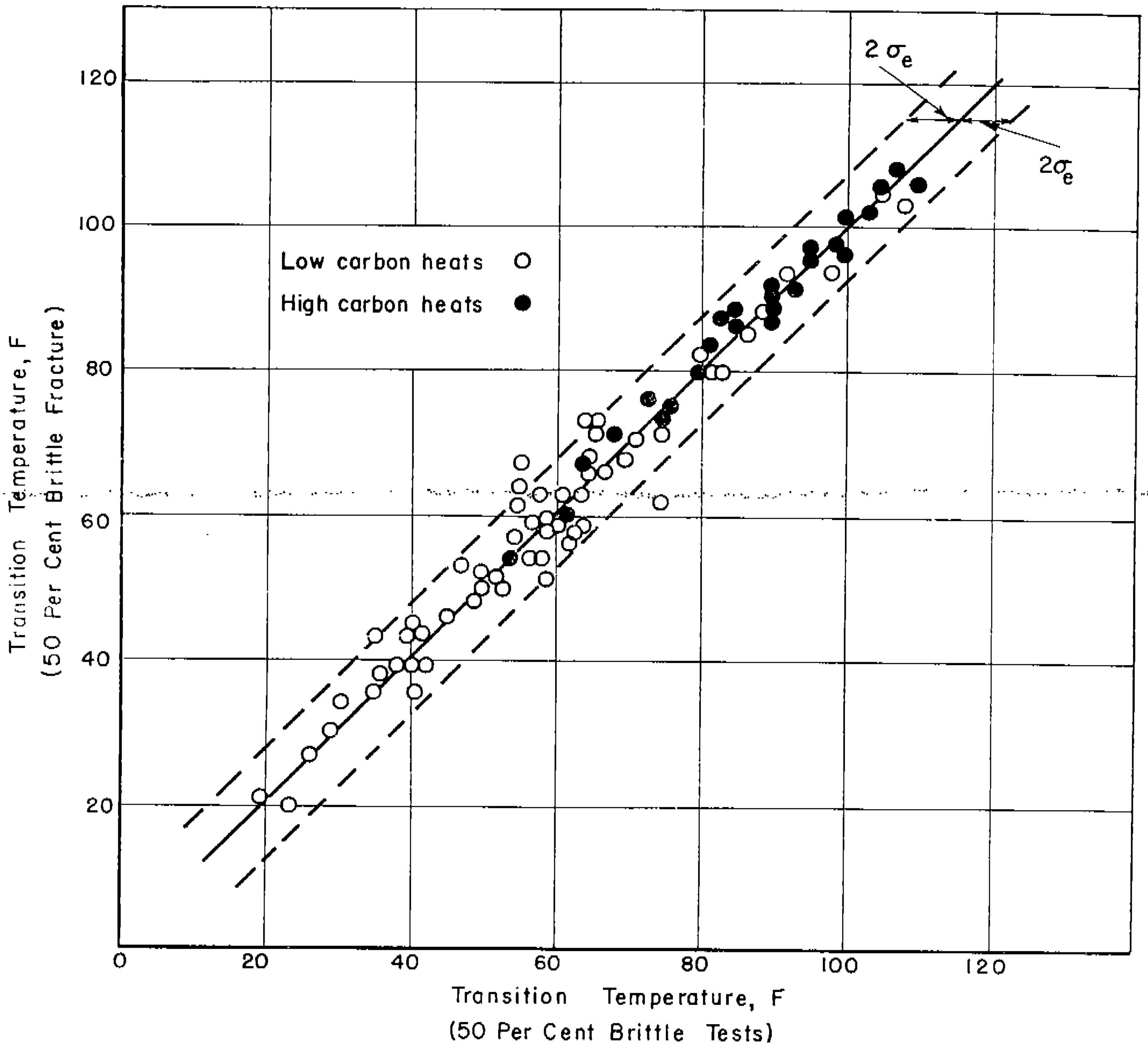

FIGURE 12. COMPARISON OF TEAR-TEST TRANSITION—TEMPERATURE CRITERIA

0-22385

TABLE 10. CORRELATION BETWEEN TRANSITION TEMPERATURES* ESTABLISHED BY DIFFERENT CRITERIA IN TESTS ON 95 MATERIALS. FOUR SPECIMENS WERE TESTED AT EACH TEMPERATURE OF INTEREST.

Symbol	Attribute
X_1	12 ft-lb keyhole Charpy transition temperature
X_2	Kahn's definition, tear test transition temperature
X_3	50 per cent brittle fracture texture, tear test transition temperature
X_4	0.5 probability of brittle fracture, tear test transition temperature

Attributes	Regression Equation	Correlation Coefficient	Standard Error of Estimate
X_1, X_2	$X_2 = 0.8010\ X_1 + 87.36$	0.723	15.31°F
X_1, X_3	$X_3 = 0.8455\ X_1 + 81.61$	0.791	13.07°F
X_1, X_4	$X_4 = 0.8455\ X_1 + 81.34$	0.769	14.03°F
X_2, X_3	$X_3 = 0.8859\ X_2 + 1.95$	0.919	8.44°F
X_2, X_4	$X_4 = 0.9349\ X_2 - 1.85$	0.943	7.32°F
X_3, X_4	$X_4 = 1.014\ X_3 - 1.18$	0.986	3.70°F

*All temperatures in degrees Fahrenheit

p = 0.5 for brittle specimens. In either case, data obtained from all specimens tested contribute to establishing the transition temperature. As explained in the previous section, this establishes transition temperatures with smaller limits of uncertainty.

The correlation between the Kahn transition temperature and the temperature at which the fracture surfaces average 50 per cent brittle texture is shown in Fig. 13. There is considerably more scatter from the trend line than in Fig. 12. Table 10 shows that the correlation coefficient is lower and the standard error is higher, 8.44°F. Much of the scatter from the trend line in Fig. 13 is attributed to the wide uncertainty limits for the Kahn transition temperature. Four points, all on the high side, fall outside the two sigma limits on the chart. This behavior suggests that the Kahn criterion occasionally sets the transition temperature too high. It appears that erroneous ratings by this criterion are more likely to be on the conservative side.

CORRELATION OF CHARPY AND TEAR TEST TRANSITION TEMPERATURES

Both Charpy and tear tests are used to evaluate the susceptibility of steels to brittle fractures. Since both tests employ notches and are used for the same purpose, it is natural to seek factors useful for estimating transition temperatures for one type of test from data obtained by the

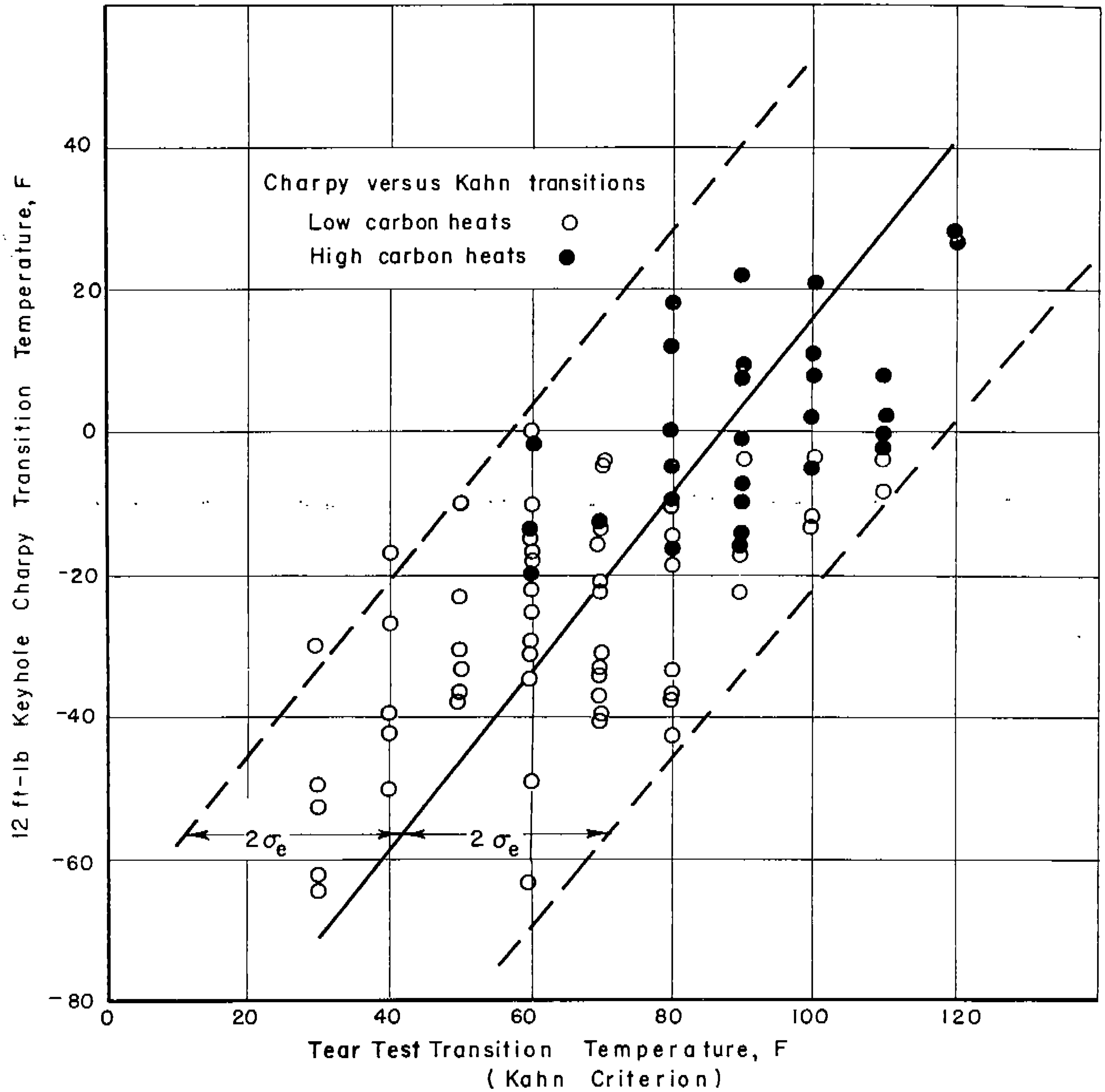

FIGURE 14. POOR CORRELATION BETWEEN TRANSITION TEMPERATURES ESTABLISHED BY CHARPY AND TEAR TESTS USING THE KAHN-IMBEMBO CRITERION O-22387