SERIAL NO. **SSC-97**

THE MECHANISM OF BRITTLE FRACTURE

by

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Distributed by

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Washington 25, D. C.

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ADDRESS CORRESPONDENCE TO:

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

March 25, 1955

Dear Sir:

At the request of the Ship Structure Committee, Mr. T. S. Robertson of the British Admiralty's Naval Construction Research Establishment, Dunfermline, Scotland, recently spent about four weeks in this country. The purpose of this visit was to permit Mr. Robertson to review American activity on the study of Brittle Fracture Mechanics and to acquaint workers here with the research in this field now underway in Great Britain.

In the course of his discussions with various research investigators, Mr. Robertson reported on some recently completed and as-yet unpublished investigations performed in his laboratory. The attached report, entitled "The Mechanism of Brittle Fracture" was prepared by Mr. Robertson to summarize his remarks on this work. This report is being distributed by the Ship Structure Committee for the information of those interested in the study of the mechanics of fracture, and for the particular attention of the persons who were privileged to meet with Mr. Robertson.

The author has indicated that he would be happy to receive comments on his views as expressed in the report. Comments addressed to Mr. Robertson in the care of the Secretary, Ship Structure Committee, will be forwarded.

Very truly yours,

K. K. Cowart

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

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LIST OF FIGURES

THE MECHANISM OF BRITTLE FRACTURE

1. A method of determining the stress-temperature relationship for catastrophic crack propagation is described in the Journal of the Iron & Steel Institute, Vol. 175 of December 1953. A series of tests on plates establishes the general form of graph shown in Fig. 1. There is a constant temperature zone which covers a considerable increase in stress, with a rise in temperature for higher stress values. The other zone shows a critical relationship between quite low stress values and the temperature for arrest of the crack. These two distinct limbs to the curve suggest that two mechanisms of fracture are possible. On the suggestion of Dr. Hume-Rothery, series of tests were carried out on two mild steels of different chemical compositions to determine the effect of change of grain size on brittleness. Two plates 1 1/2-in. thick were chosen, one an ordinary mild steel C = 0.16, Mn = 0.60; and the other, a fine grain aluminum killed mild steel C = 0.16, Mn = 1.07. The plates were machined down to 1 in. thick to remove the decarburized surface.

2. The ordinary mild steel was tested as received; as annealed for two hours at 2350°F; and as normalized after annealing from 1650°F. Graphs of Charpy impact and crack arrest tests are reproduced in Fig. 2. It will be noted that

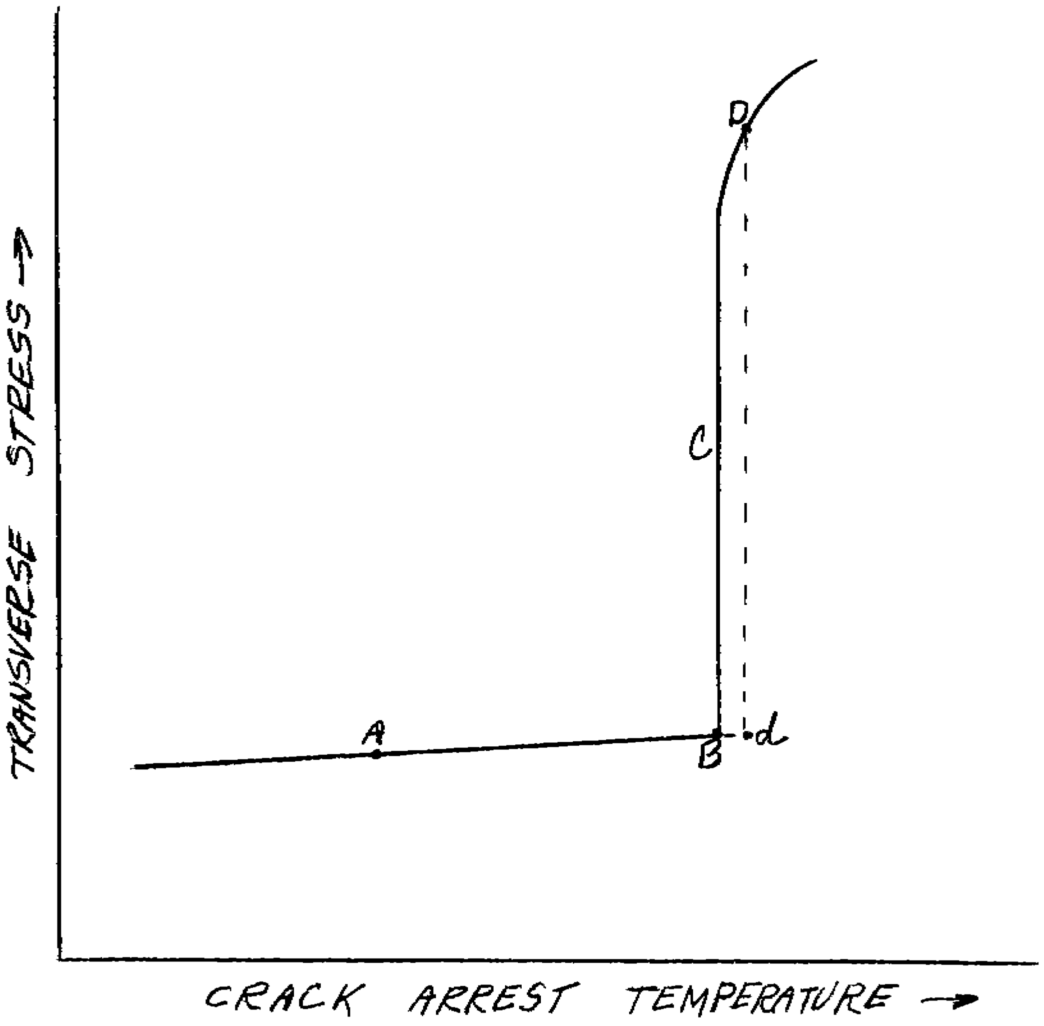
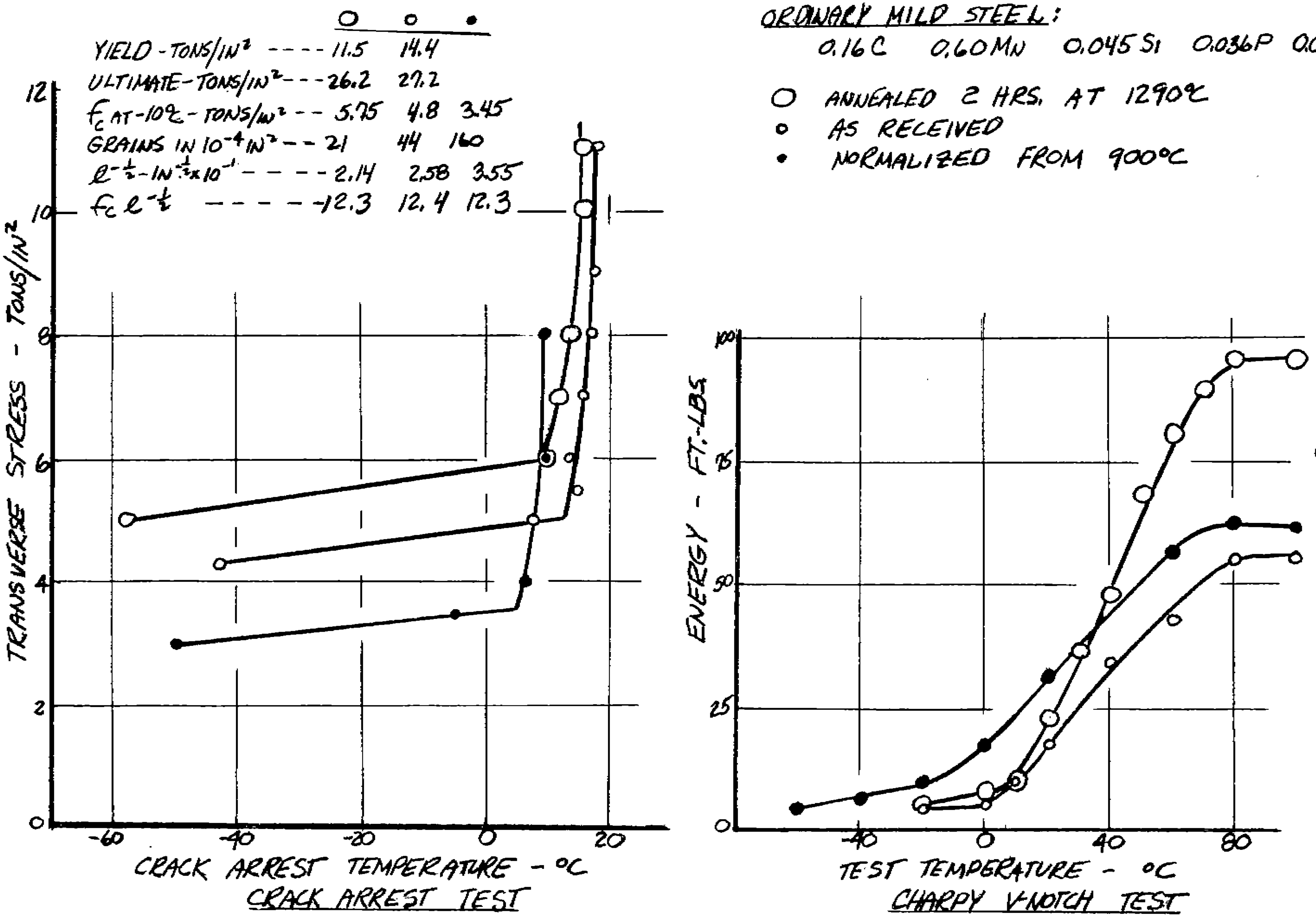


FIG 1. GENERAL FORM OF STRESS-TEMPERATURE RELATIONSHIP FOR CRACK ARREST TEST.



	○	∘	●
YIELD - TONS/IN²	11.5	14.4	
ULTIMATE - TONS/IN²	26.2	27.2	
f_c AT -10°C - TONS/IN²	5.75	4.8	3.45
GRAINS IN 10^{-4} IN²	21	44	160
$\ell^{-\frac{1}{2}}$ - IN$^{-\frac{1}{2}} \times 10^{-1}$	2.14	2.58	3.55
$f_c \ell^{-\frac{1}{2}}$	12.3	12.4	12.3

ORDINARY MILD STEEL:

0.16C 0.60Mn 0.045Si 0.036P 0.032S

○ ANNEALED 2 HRS. AT 1290°C
∘ AS RECEIVED
● NORMALIZED FROM 900°C

CRACK ARREST TEST

CHARPY V-NOTCH TEST

FIG. 2 ORDINARY MILD STEEL
EFFECT OF GRAIN SIZE

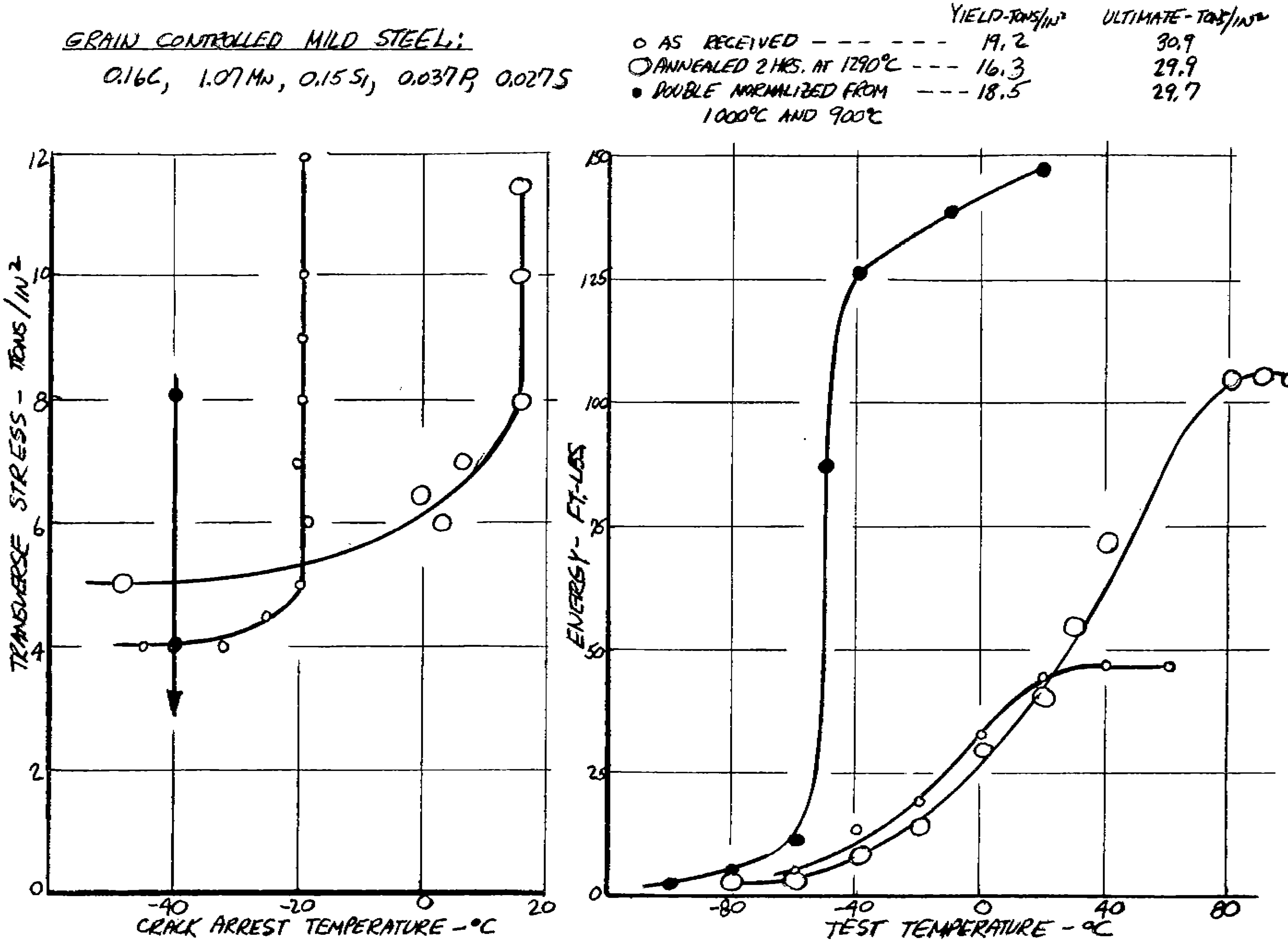
the "as received" material gives a higher Charpy transition temperature but that annealing, while it increases the energy, does not improve the Charpy behavior. Normalizing from 1650°F certainly improves the performance slightly. The upper arrest temperatures follow the indications of the Charpy tests, but the critical stress values show great differences in the three series of tests.

3. The grain sizes of the three samples were measured and were found to be 21, 44, and 160 grains in 10^{-4} sq. in. for the annealed, as received and as normalized samples. The critical strengths proved to follow the order of grain size, i.e., the larger sized material exhibits greater strength than the small grained.

4. Fig. 3 shows impact and crack arrest results for the grain controlled steel as received; as annealed for two hours at 2350°F; and as double normalized from 1830° and 1650°F after two hours at 2350°F. Again the upper arrest temperatures follow the indications of the impact tests, but the as received material shows up better in the crack tests than in the Charpy. The grain size of these series are shown in Fig. 4, and these are, respectively, 49, 142, and 225 grains in 10^{-4} sq. in. for annealed, as received and double normalized plate. It will be seen that the upper arrest temperature in this case increases

GRAIN CONTROLLED MILD STEEL:

0.16C, 1.07 Mn, 0.15 Si, 0.037 P, 0.027 S



CRACK ARREST TEST

CHARDY V-NOTCH TEST

FIG. 3. GRAIN CONTROLLED MILD STEEL
EFFECT OF GRAIN SIZE

	GRAINS IN 10^{-4} IN^2	ℓ^{-1} 10^2 IN^{-1}	$\ell^{-\frac{1}{2}}$ 10^1 IN$^{-\frac{1}{2}}$	f_c AT -20°C TONS/IN^2	$f_c \ell^{-\frac{1}{2}}$	$f_c \ell^{-1}$
LARGE GRAIN – – –	49	7	2.64	5.5	14.5	42
AS RECEIVED – – – –	142	11.9	3.45	4.2	14.5	47
DOUBLE NORMALIZED –	225	15	3.82	(3.8)	(14.5)	52.5

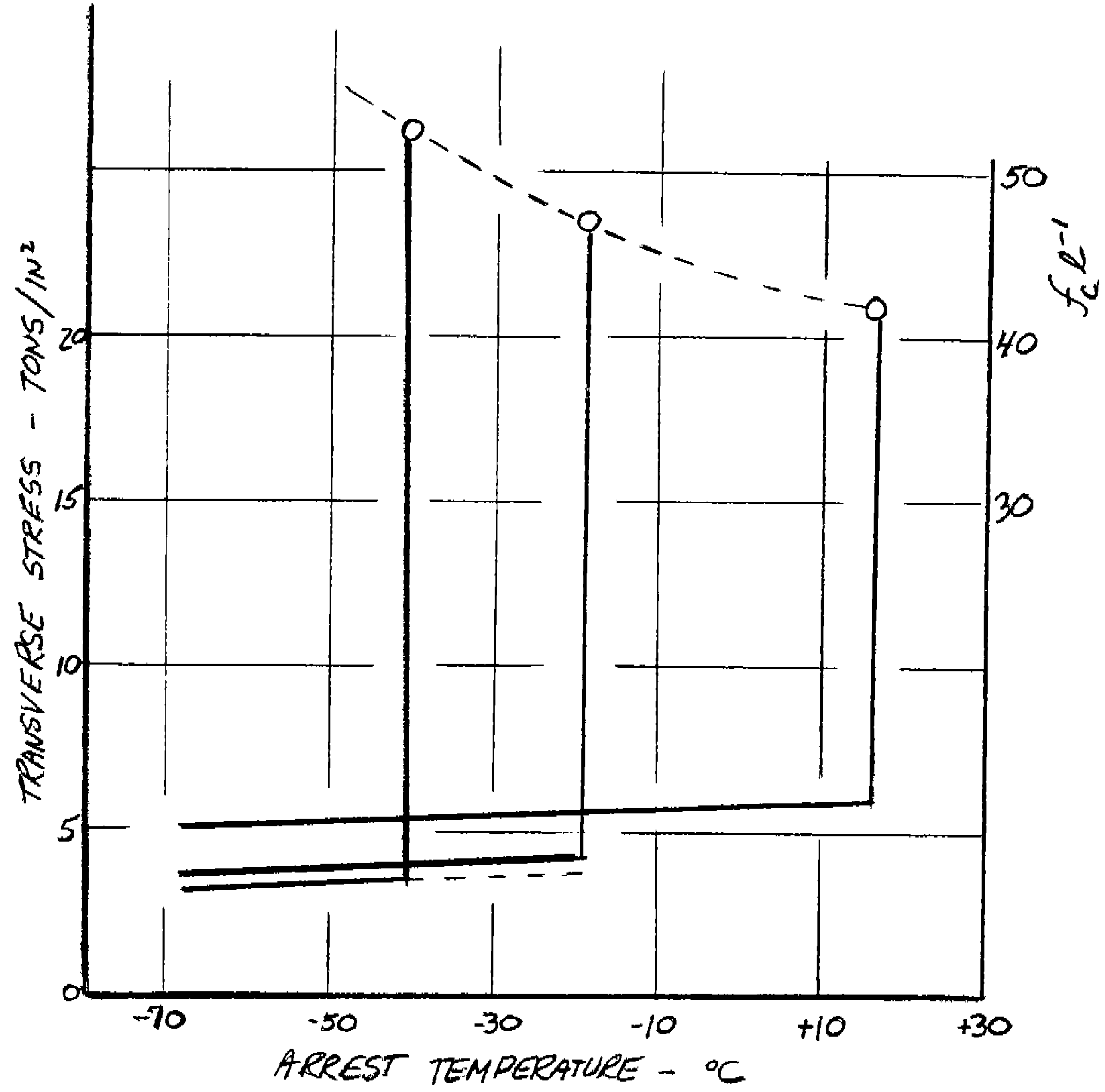


FIG. 4 EFFECT OF GRAIN SIZE ON UPPER ARREST AND CRITICAL STRESS

with grain size, while for the two series in which there was enough material to complete the tests the critical strength, as in the ordinary mild steel, falls with decrease of grain size.

5. This apparent anomaly shown by the critical strength is contrary to the findings of Petch, but Mott, in his report on the 1945 Cambridge Conference on Brittle Fracture, published in <u>Engineering</u> of 2nd January 1948, develops some ideas which seem to offer a reasonable explanation. He indicates that, for a Griffith crack held open by a nominal stress f, the stress just beyond the apex of the crack will be given by $f_o = E\sqrt{\frac{a}{r}}$, where a is of the order of the atomic distance and r is the distance inside the solid metal in the plane of the crack. Further, for a crystal size b he considers that the crack will propagate from crystal to crystal when $E\sqrt{\frac{a}{b}}$, the mean stress in the crystal caused by a crack in an adjacent crystal, is greater than f_o, the cleavage strength of the crystal, i.e., $E\sqrt{\frac{a}{b}} > f_o$. If the applied nominal stress for fracture arrest at a given temperature is indicated by f_c and it is postulated that this stress is increased by a stress concentration factor n, determined by the geometry of a Griffith type crack, to the value f_o required for rupture of the crystal, then we have

$$n\left[f_c b^{-\frac{1}{2}}\right] = Cb^{-1} = \frac{C}{b}$$

$$n K = \frac{C}{b} \quad ?$$

$$n = \frac{K'}{b}$$

$$nf_c = f_o = Ea^{\frac{1}{2}} b^{-\frac{1}{2}}$$

and since E and a do not alter

$$nf_c = Cb^{-\frac{1}{2}}$$ ✓

thus n will vary as $b^{-\frac{1}{2}}$

and $f_c b^{-\frac{1}{2}} = Kf_o$, or using the usual notation for grain size

$$f_c \ell^{-\frac{1}{2}} = \text{Const.}$$

Now f_o will vary with temperature, so in the mild steel the values of critical stress have been chosen at -10°C: These are tabulated in Fig. 2. Values of $\ell^{-\frac{1}{2}}$ are also tabulated, and the product $f_c \ell^{-\frac{1}{2}}$ proves indeed to be a constant. Thus by introducing a concept of stress concentration due to grain size, it appears that a physical law relating grain size with critical stress can be postulated. In Fig. 4 the results for the annealed and as received grain controlled material also give the same values for the product $f_c \ell^{-\frac{1}{2}}$. The value for the small grain (double normalized) material has been calculated from this constant, and a hypothetical graph for critical stress has been drawn. The value of the constant has risen from 12.3 (for the mild steel) to 14.5 in this tougher steel.

6. In the case of the ordinary mild steel, the material as received was not normalized, whereas it was known to be normalized in the fine grained steel. This may possibly

explain why the upper arrest temperatures do not, as in the fine grain steel, follow the grain size. In view of the nature of the relationship just established, it is now possible to put forward a mechanism for brittle fracture which explains the form of curve obtained in crack arresting tests. It is suggested that the material ahead of the crack remains elastic during all fractures which arrest in the critical stress portion of the graph and therefore obey the simple stress concentration grain size relationship throughout. The brittle strength of the material within the crystal varies only slightly with temperature, increasing as the temperature rises. Eventually, when the upper arrest temperature is reached, the material ahead of the crack yields. When this occurs, the stress in the material fed into the crack remains at the yield stress value, rising no higher than this value even though the nominal stress in the plate is raised. Thus the temperature of upper arrest remains constant for quite an appreciable increase in transverse stress. The diagram in Fig. 5 shows the kind of action which is envisaged. Curve A represents a possible state of stress ahead of the crack for a transverse stress and temperature at A on the arrest curve of Fig. 1. Curve B corresponds to a point B in Fig. 1 just at the knee of the arrest curve. Curve C represents a still higher transverse stress which would normally raise all ordinates by the same proportion, but since yield supervenes, the top of the

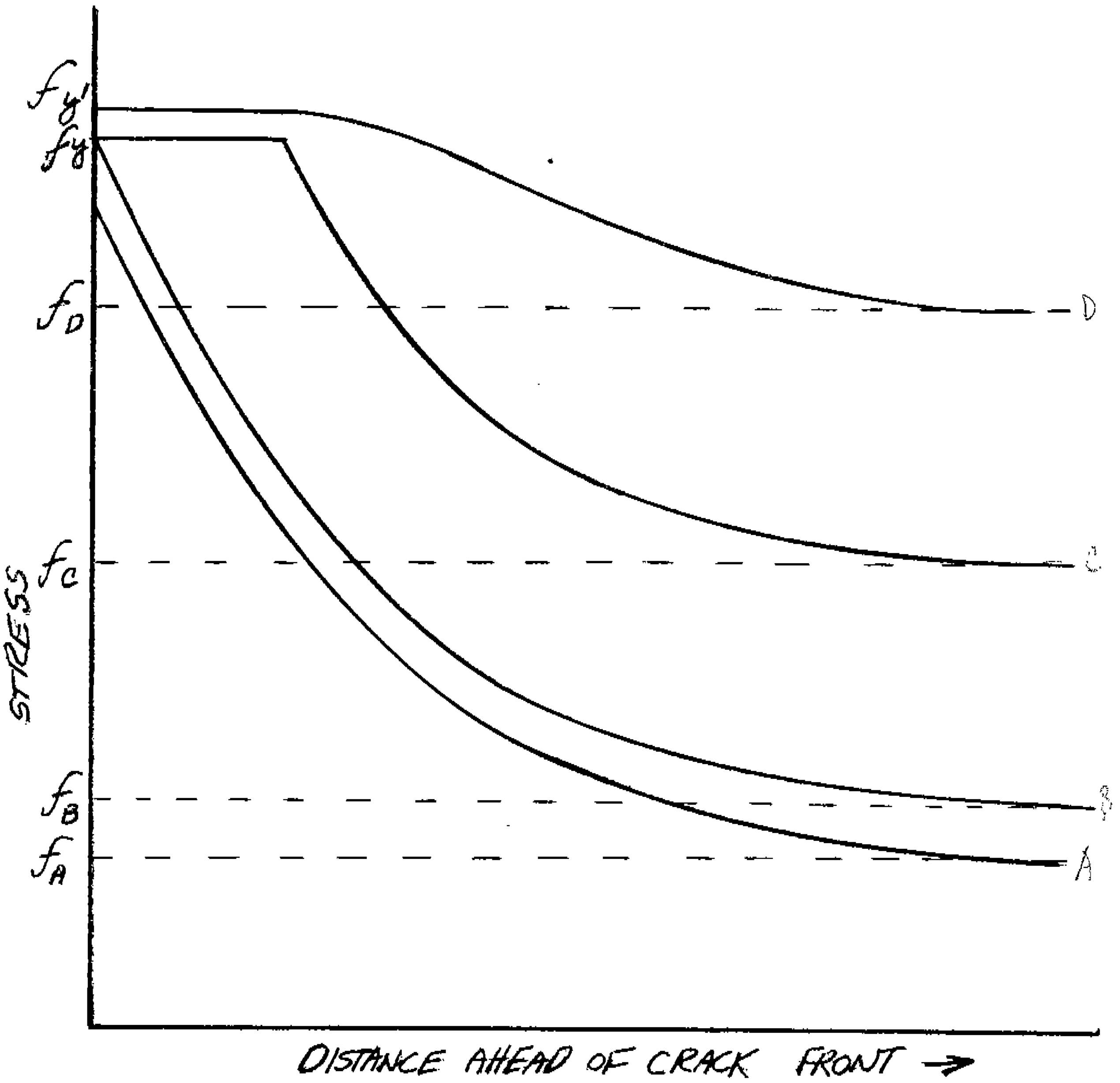


FIG 5. STRESS AHEAD OF CRACK FRONT FOR VARIOUS NOMINAL TRANSVERSE STRESS CONDITIONS

curve is flattened and does not exceed the yield stress f_y for the material. But this local yielding holds down the expected rise in the stress which would produce brittle cracking to the value produced by f_B, so that the crack stops at the same temperature as for f_B. Thus, for a considerable increase in nominal stress, the temperature of arrest remains constant. This explains WHY A TRANSITION TEMPERATURE, a question which is often asked.

7. When the transverse stress is raised still further, say to f_D in Figs. 1 and 5, the material fed into the crack must have suffered considerable yield before it reaches the crack front. This will result in cold working of the material with consequent rise of its yield point to f_y' and an increase in the cracking stress available. It is then to be expected that this material will break with a brittle fracture at an increased temperature. This temperature will be found at d, vertically below D, in Fig. 1 where the critical arrest graph has been extrapolated to give the increase in cracking stress corresponding to the amount of cold work. The arrest temperature will continue thereafter to rise as the stress is increased. Many of the curves reproduced in the Iron & Steel Institute paper show this tendency, and some later work shows that as nominal yield stress is approached this rise is quite marked, some steels showing a much steeper temperature rise than others.

8. There are two distinct knees in others of the curves. This can be attributed to two dominant grain sizes, the smaller giving low critical stress and a knee at the correspondingly low upper arrest; then the larger grains take over at a higher critical stress and continue until the upper arrest temperature is reached. These observed characteristics of the curves give considerable experimental reinforcement to what is now advanced as a possible mechanism for catastrophic brittle failure.

9. It is possible, by using the diagram of Fig. 4, to use some further ideas suggested in Mott's paper. He states that Sir William Bragg indicates that for a small volume of metal of linear dimension λ the shear yield stress cannot be less than $E\frac{a}{\lambda}$. Applying the idea of stress concentration to yield in shear, this would mean that effective shear stress concentration would be of the order $\frac{1}{\lambda}$ where λ is the grain size, i.e., shear stress concentration would be proportional to ℓ^{-1}. Now, if the critical stress value at the junction with the upper arrest limb of the graph is multiplied by ℓ^{-1} for these three graphs, we get values of $f_c\ell^{-1}$ of 42, 47, and 52.5, respectively, for the annealed, as received and double normalized material at the temperatures corresponding to the three knees in the graphs. Plotting these results as ordinates, we see that the curve--dotted in Fig. 4--shows an increase in yield resistance with decrease in grain size at the arrest

temperatures. The significance of this curve lies in the possibility that there is a mechanism such as that just investigated which will explain how a smaller grain size may result in a lower transition temperature and yet give a lower critical strength. The last plotted points represent to some scale the resistance to yielding of known grain sizes when tested at critical temperatures below which brittle fracture would not be arrested. If the shape of such curves can be determined, it should be possible to forecast how the material will respond to changes in grain size. It is reasonable to expect that these properties will be allied to the high speed yield resistance of the material. Some tests will be carried out at Cambridge, England, on the two plates under investigation to determine the high speed yield characteristics at different temperatures for different grain sizes. A possible curve of this sort is shown plotted in Fig. 6. Yield strength has been assumed to rise linearly with falling temperature and to fall inversely as grain size. Assuming that material of one grain size has been tested and that the stress arrest temperature graph is as drawn in Fig. 7, an ordinate proportional to $F_c \ell^{-1}$ would be drawn to $F_B \ell^{-1}$ at the upper arrest temperature, and from this a scale factor would be worked out to simplify conversion to actual experimental high speed yield values. A new line giving calculated values of f_{cl} for a different

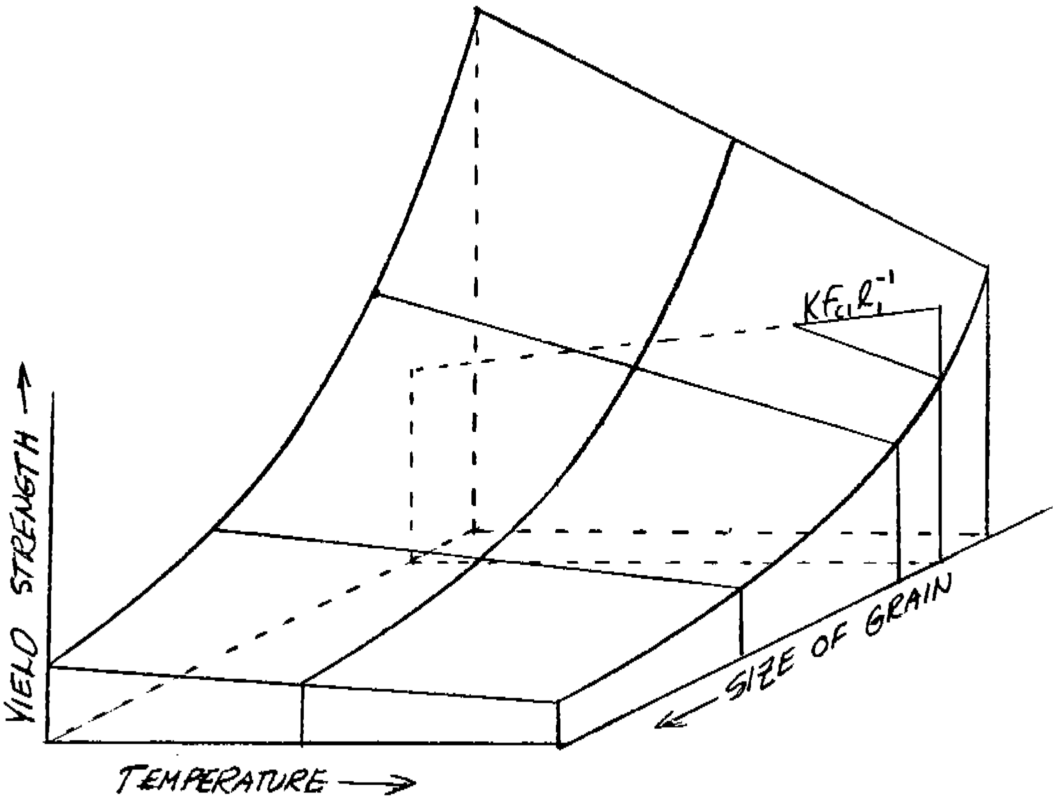


FIG. 6. POSSIBLE RELATIONS AMONG YIELD STRENGTH, SIZE OF GRAIN AND TEMPERATURE

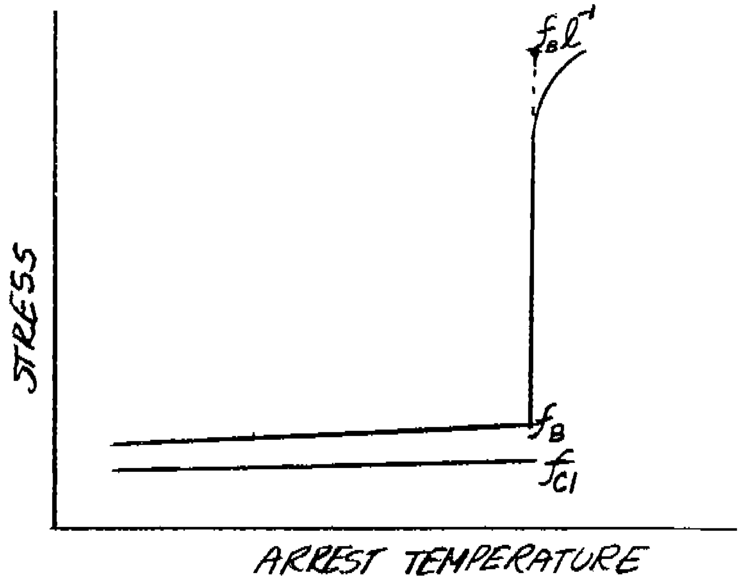


FIG. 7

grain size would be constructed on the graph. From this line, by multiplying its ordinates by ℓ_1^{-1} and by the scale factor found earlier, a line would be constructed on the plane representing the appropriate grain size in Fig. 6. This line, marked $Kf_{c1}\ell_1^{-1}$, would cut the surface of the figure at the new upper arrest temperature. From an examination of the surface of Fig. 6, it will be seen that if, at the particular grain size in question, the surface slopes greatly relative to the base plane, a small fall in upper arrest temperature will result from change in grain size and the converse, if the slope of the surface is small. It would therefore be expected that, for the ordinary mild steel, the surface would slope steeply at the temperature of upper arrest and for the fine grained steel the slope would be small. If the foregoing mechanism is valid, this should be shown up by the high speed tests on the two steels and will afford a first check on what at present must only be described as a tentative practical mechanism for brittle fracture.