D. K. Felbeck

SERIAL NO. SSC-77

FINAL REPORT
(Project SR-124)

on

PART I: CRACK-STARTER TESTS OF SHIP FRACTURE AND PROJECT STEELS

by

P. P. PUZAK, M. E. SCHUSTER, and W. S. PELLINI
Naval Research Laboratory

for

SHIP STRUCTURE COMMITTEE
Convened by
The Secretary of the Treasury

Member Agencies—Ship Structure Committee

Bureau of Ships, Dept. of Navy
Military Sea Transportation Service, Dept. of Navy
United States Coast Guard, Treasury Dept.
Maritime Administration, Dept. of Commerce
American Bureau of Shipping

Address Correspondence To:

Secretary
Ship Structure Committee
U. S. Coast Guard Headquarters
Washington 25, D. C.

SERIAL NO. SSC-77
BuShips Project NS-011-067

JUNE 18, 1954

SHIP STRUCTURE COMMITTEE

MEMBER AGENCIES:

BUREAU OF SHIPS, DEPT. OF NAVY
MILITARY SEA TRANSPORTATION SERVICE, DEPT. OF NAVY
UNITED STATES COAST GUARD, TREASURY DEPT.
MARITIME ADMINISTRATION, DEPT. OF COMMERCE
AMERICAN BUREAU OF SHIPPING

ADDRESS CORRESPONDENCE TO:

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

June 18, 1954

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee sponsored investigations at the Naval Research Laboratory having to do with the properties of ship plate when subjected to drop weight and explosion bulge tests. Herewith is a copy of Part I of the Final Report of this investigation entitled "Crack-Starter Tests of Ship Fracture and Project Steels" by P. P. Puzak, M. E. Schuster and W. S. Pellini. The balance of the Final Report is contained in Part II and is being simultaneously distributed as SSC-78.

Any questions, comments, criticism or other matters pertaining to the Report 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.

Final Report
(Project SR-124)

on

PART I: CRACK-STARTER TESTS OF SHIP FRACTURE AND PROJECT STEELS

by

P. P. Puzak, M. E. Schuster, and W. S Pellini

NAVAL RESEARCH LABORATORY

under

Department of the Navy
BuShips Project No. NS-011-067

for

SHIP STRUCTURE COMMITTEE

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

No.	Title	Page
8	Charpy V energy transition curves of rimmed (top) and semikilled (bottom) ship fracture steels subjected to crack-starter tests.	15
9	Crack-starter, explosion test series of ship fracture steel PEDP depicting T--S fracture transition	17
10	Summary graph depicting correspondence of NBS ship fracture data and NRL crack-starter test data to Charpy V energy.	18
11	Catastrophic ship failure initiated by arc strike defect at 35°F. Correlation of source plate Charpy V and drop-weight data with service performance	22
12	Crack-starter test of ship fracture steel. Crack-starter weld ignored and fracture initiated by natural crack defect in fillet weld.	24
13	Relationship of explosion crack-starter tests to Charpy V transition curves for typical normalized ABS-C (fully killed) type steel.	25
14	Summary of crack-starter tests correlation to Charpy V energy for fully killed steels.	26
15	Relationships of explosion, wide plate, and tear test--fracture transitions to Charpy V energy transitions.	28
16	Relationships of explosion, wide plate, and tear test--fracture transitions to Charpy V energy transitions.	29
17	Relationship of wide plate fracture transitions to Charpy V energy transitions for various fully killed steels.	32
18	Comparison of Charpy V data for six project steels	34
19	Various Charpy V energy transition curves reported for project C (3/4-in.) steel.	35
20	Drop-weight tests of ABS-A and ABS-C steels at temperatures equivalent to Charpy 15 and 20 ft-lb.	39

PART I: CRACK-STARTER TESTS OF SHIP FRACTURE AND PROJECT STEELS

ABSTRACT

The performance of rimmed and semikilled steels involved in ship fractures is investigated by means of crack-starter tests. In these tests a sharp crack is introduced in the steel, and the relative resistance to the initiation and propagation of fracture is established over the range of service temperatures. It is demonstrated that in the presence of the sharp crack the steels have no appreciable ductility when the temperature falls below the Charpy V 10 ft-lb transition; accordingly, fracture initiation is readily developed. The propagation of brittle fractures becomes difficult at temperatures above the Charpy V 15--25 ft-lb transitions. These findings are in agreement with National Bureau of Standards data for ship fracture plates. It is demonstrated that fully killed steels do not follow these rules and that the respective initiation and propagation characteristics of fracture are related to higher Charpy V values. Wide plate, tear and Charpy V test data are discussed with reference to differences related to deoxidation practice.

INTRODUCTION

It is generally recognized that notches or cracks are required to develop brittle fracture at ambient temperatures in structural steels which are classed as highly ductile by conventional tensile tests. In the absence of notches these steels demonstrate high ductility to very low temperature, i.e., behave as predicted by the tensile tests. For example, structural steel prime plate may be deformed extensively by explosion loading to temperatures as low as -60° to -80°F[1,2]. In the presence of sharp crack-like defects, it is possible to fracture such steels at 20° to 40°F without visible deformation by the impact of a dropping weight. Figure 1 illustrates the extensive explosion bulge deformation which may be developed without fracture at -40°F in a prime plate of ABS-A steel and the brittle fracture of a similar steel at 20°F resulting from the presence of arc strikes associated with small cracks.

In order to develop brittle fracture with small or essentially nil deformation, two requirements must be met--not only must a sharp notch be present, but also the steel must be at a proper temperature. Depending on the sharpness of the notch, a temperature transition is obtained such that the steel changes from being insensitive to the presence of the notch to being highly sensitive. It is this change, particularly for the case of sharp, crack-like notches, with which the designer of welded ships and other large structures is concerned. In the simplest possible terms the designer wishes to know the temperature at which high sensitivity to sharp notches is developed for a specific steel. Furthermore, this temperature must be predictable

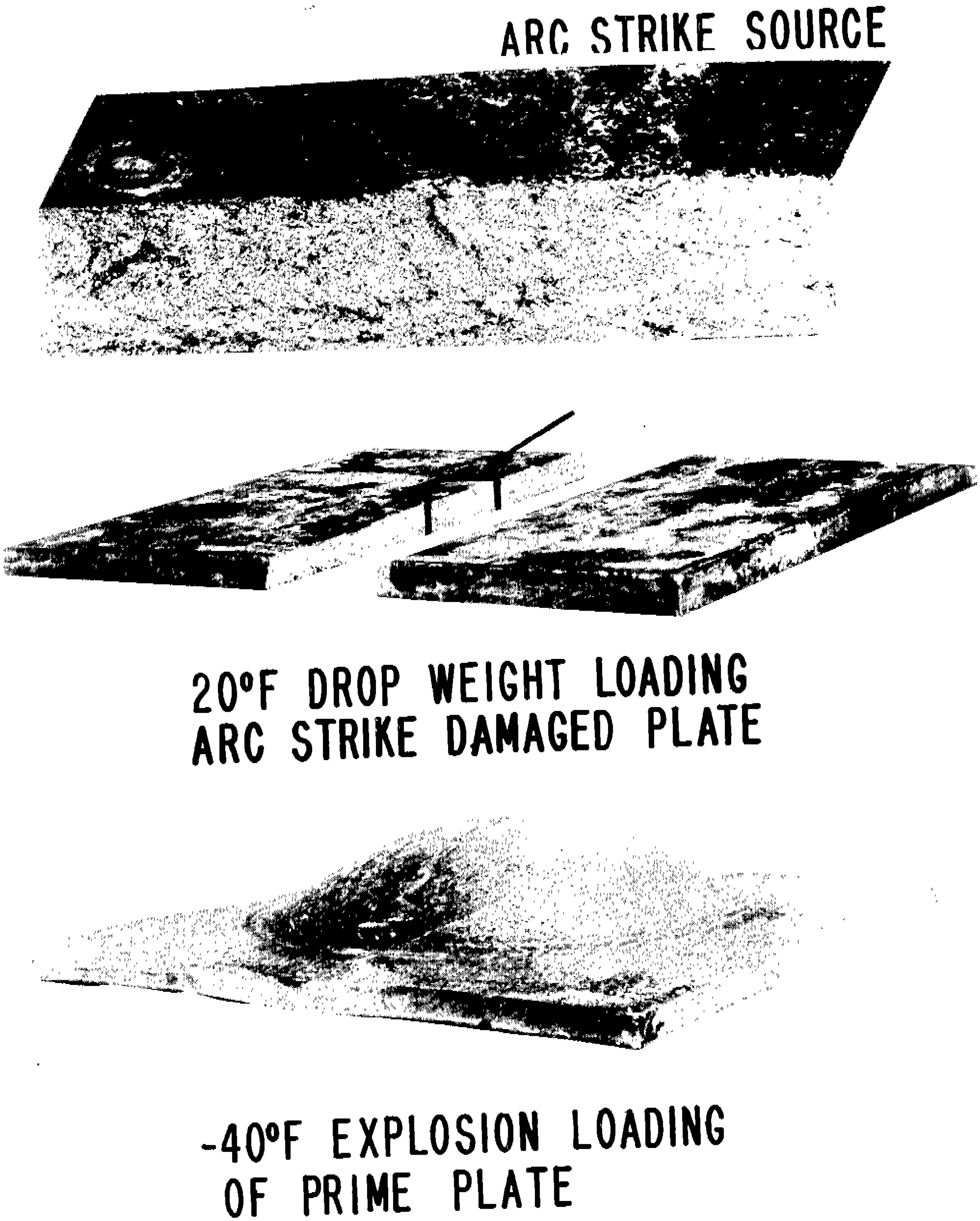

Fig. 1. Relative performance of ABS-A type ship plate in prime condition (bottom) and in presence of sharp crack defects (center). The prime plate represents material taken from stock, and the arc strike plate represents a sample of material taken from a T-2 tanker which fractured at 35°F.

from the results of relatively simple laboratory tests.

In order to obtain this information, the Naval Research Laboratory has conducted extensive tests of ship steels using the sharpest possible type of notch--a cleavage crack. The methods have been described in detail in previous reports[3,4]. Briefly, a bead-on-plate of a highly brittle, hard-surfacing weld is deposited on the test plate; as the weld cracks on loading an ultra sharp notch is introduced in the steel. Two types of "crack-starter" tests were evolved:

1. Drop Weight Test. Used to establish the temperature at which the steel loses its ability to develop more than a minute amount of deformation in the presence of the crack-like notch. In this test a 3 1/2-in. by 14-in. by plate thickness specimen is loaded by the impact of a dropping weight. A stop is used to limit the deformation to 2° of bend angle following the development of the weld crack. Details pertaining to testing equipment and procedures are furnished in the Appendix.

2. Explosion Test. Used to establish the temperature range of transition from easy to difficult propagation of fractures. In this test a 14-in. by 14-in. by plate thickness specimen is placed over a circular die and explosion loaded.

Figure 2 illustrates the typical relationship of explosion crack-starter tests of semikilled and rimmed ABS-A type ship plate steels to the Charpy V transition curves relating to energy, fracture appearance and notch deformation. The change from shatter type fractures to fracture refusal corresponds essentially to the range of the Charpy V transitions. The change from complete fracture "T" (through) to partial fracture "S" (stop) is of particular significance in denoting a transition in the properties of the steel with respect to fracture propagation through the lightly loaded edge regions of the test plate. In the T to S range, the thickness of the shear lips developed at the surface of the fracture becomes equal to the .020--.030-in. thickness found to be the maximum observed for the ship fracture plates[3,4].

Figure 3 illustrates the typical relationship of the drop-weight test nil-ductility transition (highest temperature at which the steel is unable to withstand 2° of bend in the presence of the sharp crack) to the Charpy V energy curve. Ordinarily, six to eight specimens are utilized to establish the nil-ductility transition with duplicate or triplicate tests at each critical temperature (10°F above and at the transition temperature). In this case the transition temperature was determined to be 10°F using six specimens, and then a large number of additional tests were performed to illustrate the degree of reproducibility. Of the fourteen tests at 10°F only one specimen

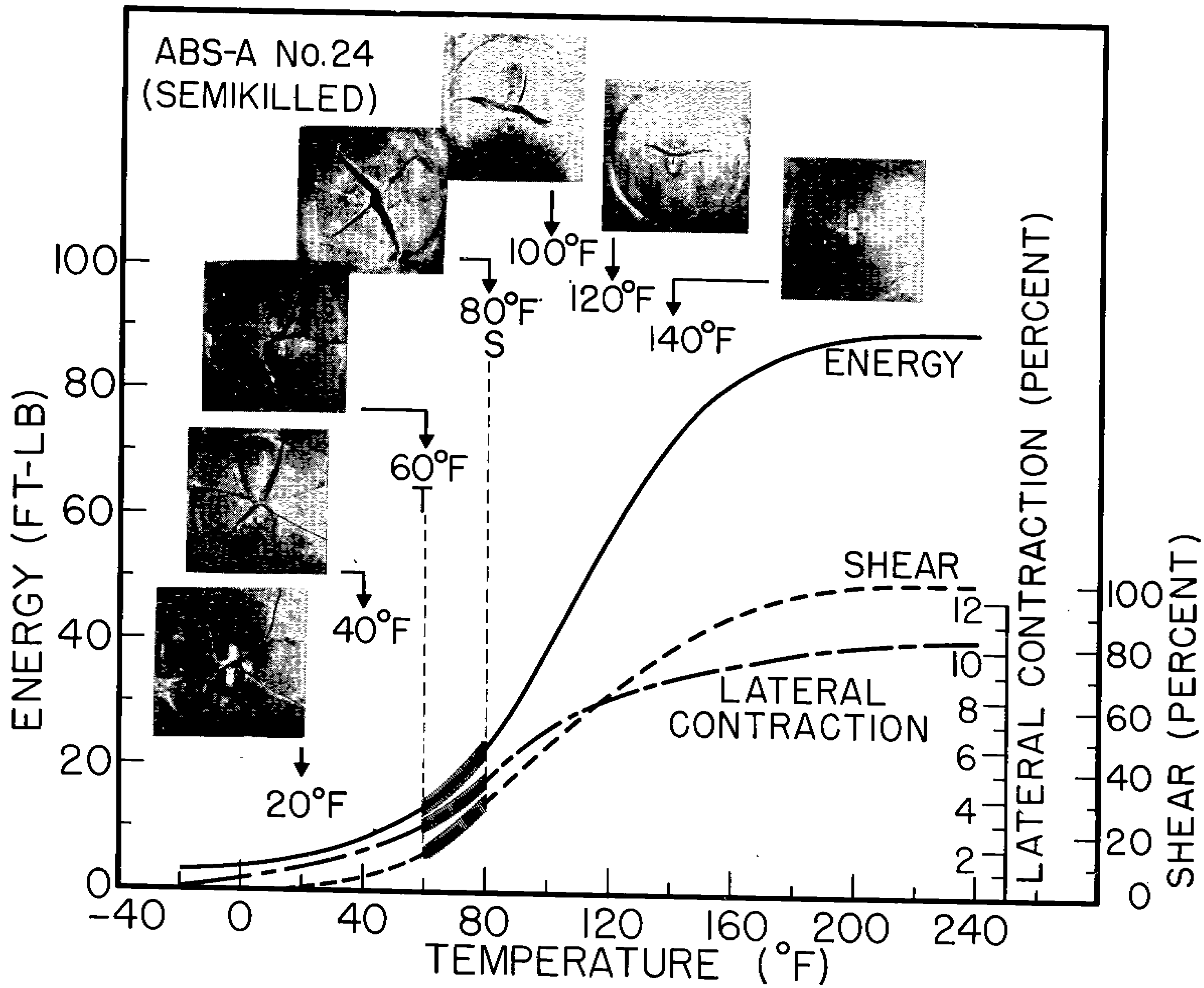

Fig. 2. Relationship of explosion crack-starter tests to Charpy V transition curves for typical ABS-A type steel (0.23%C, 0.45%Mn, 0.05%Si--1-in. thick).

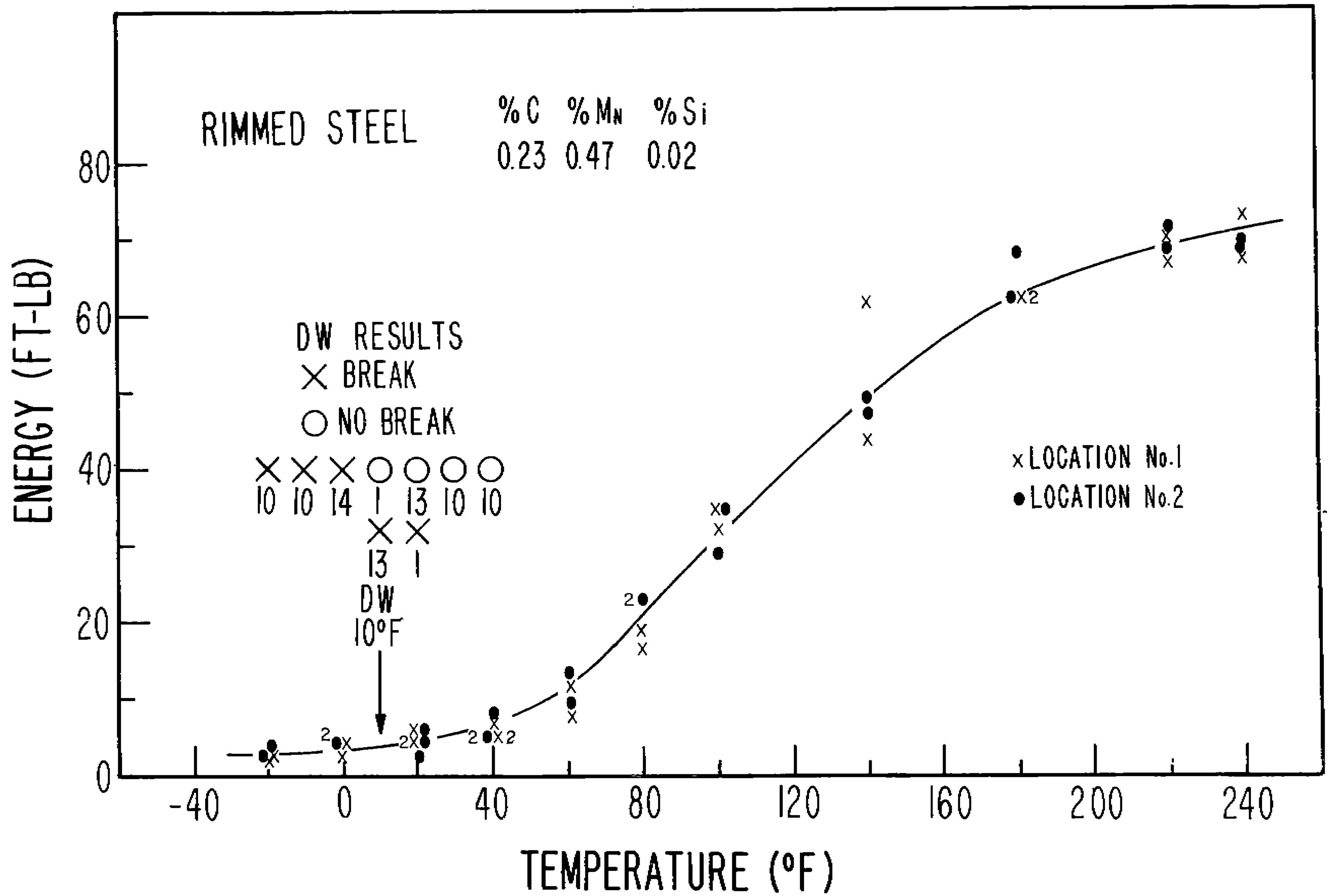

Fig. 3. Correlation of drop-weight nil-ductility transition to Charpy V energy curve. Drop-weight specimens cut randomly from 3/4-in. by 60-in. by 120-in. plate; location 1 and 2 Charpy specimens taken from diagonal corners of plate.

failed to fracture; and of fourteen tests at 20°F, only one specimen developed fracture. At 30°F and 40°F all specimens resisted fracture; and at 0°, -10° and -20°F, all specimens fractured. The test specimens are shown in Figure 4. This high degree of reproducibility which may be suprising for fracture tests results from two fractors:

1. The reproducibility of the notch condition-- the brittle weld always develops the same sharp cleavage crack.
2. The very large change with increasing temperature in the level of deformation required to develop fracture. While 2° of bend could not be developed at 10°F, it is demonstrated (Figure 5) that at 30°F and higher temperatures drastic bending is permitted without fracture.

It is of interest that at temperatures of drop-weight fracture the explosion test plates break "flat", i.e., without visible deformation. At higher temperatures bulging is developed indicating that the fracture was difficult to start and required "forcing".

If sharp crack faults were actually responsible for the initiation of ship fractures, it should be expected that the crack-starter tests should show the same correlation to the Charpy V energy curve as demonstrated by the NBS investigation of fractured ship plates[5,6]. The loading conditions in the

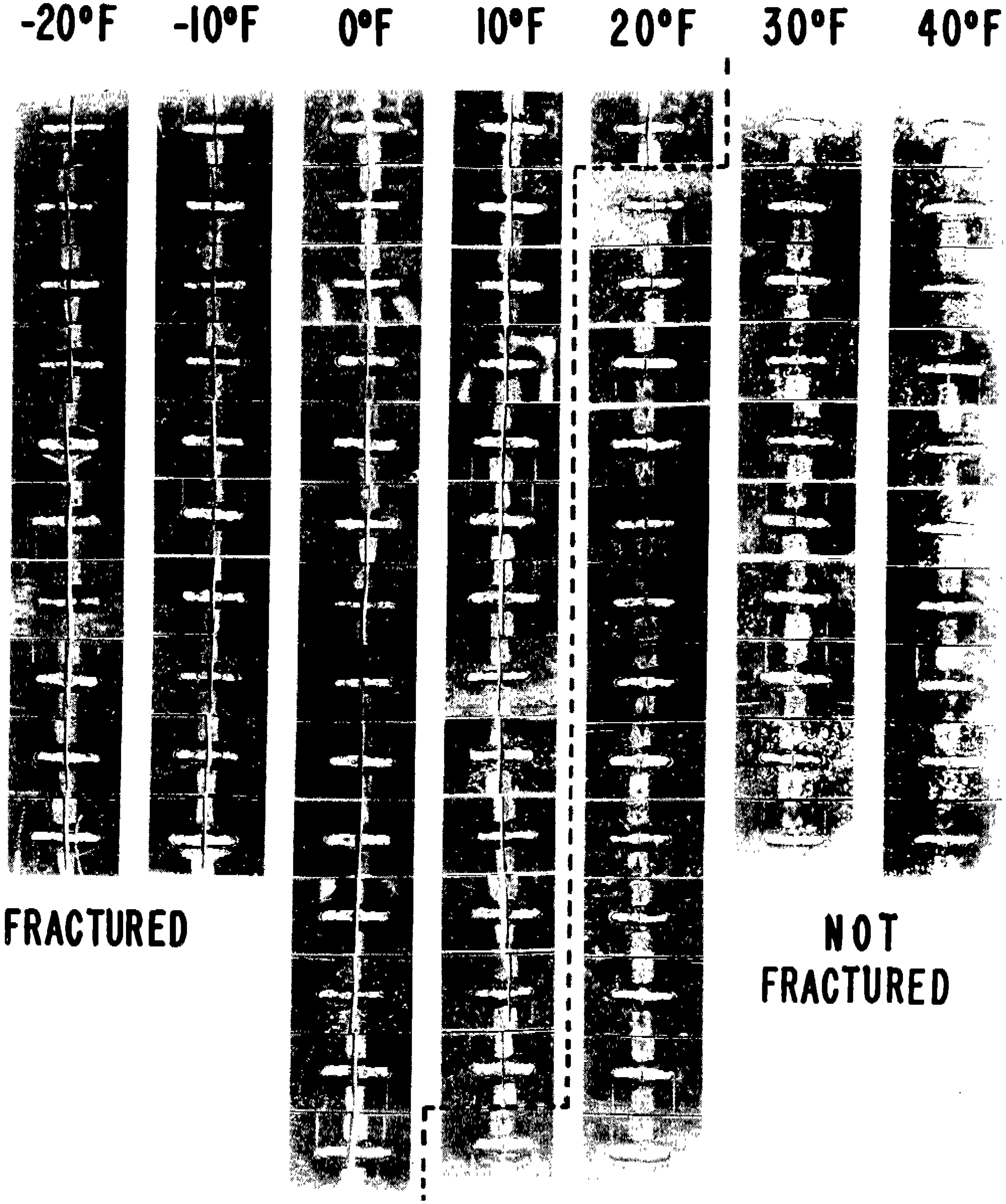

Fig. 4. Drop-weight test specimens used to establish data presented in Figure 3.

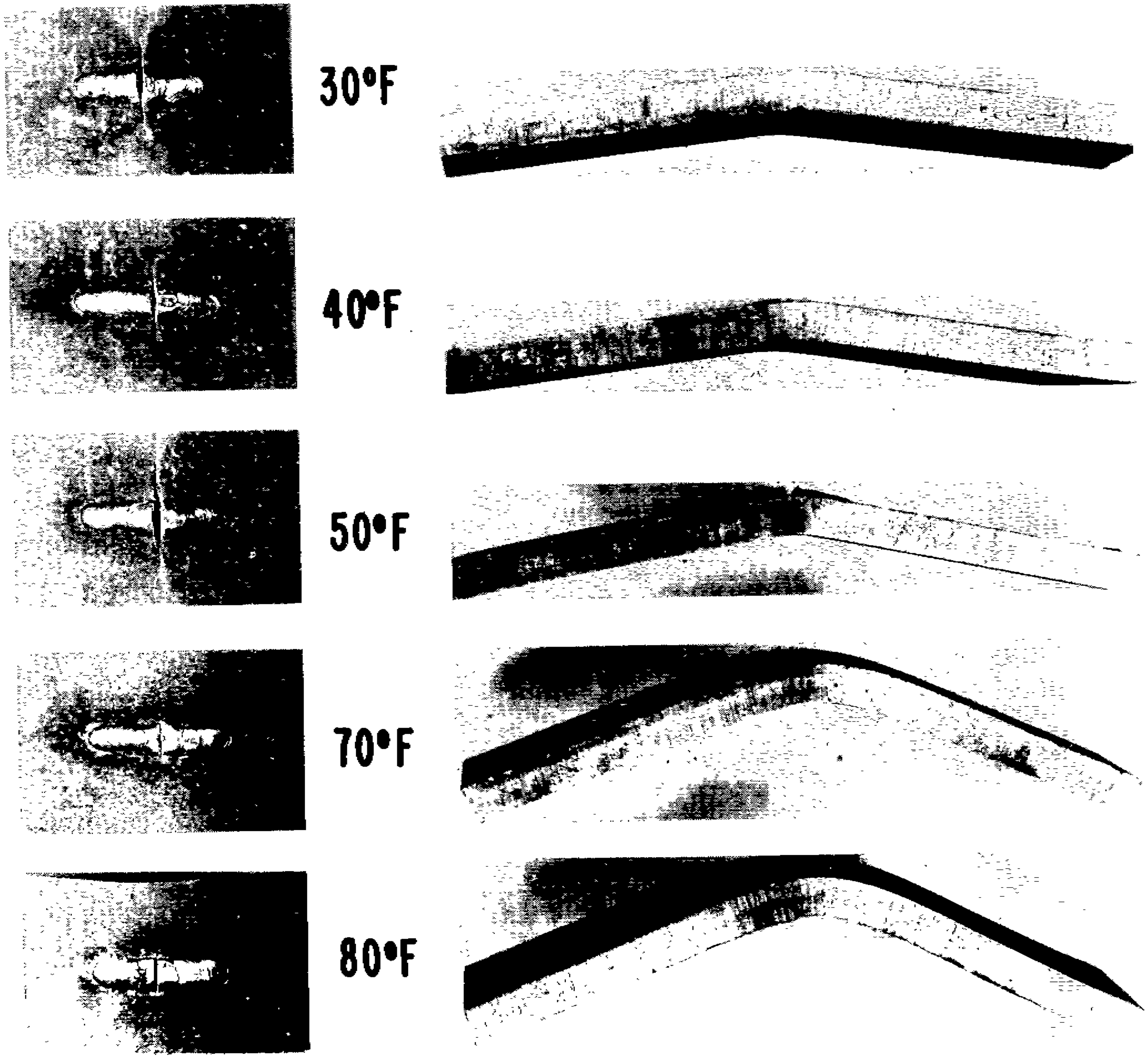

Fig. 5. Illustration of drastic bending without fracture possible at 30°F and higher temperatures for steel shown in Figures 3 and 4.

ships are such that fracture must initiate at essentially nil deformation levels (very small amounts of deformation at positions of unfavorable design). This may be recognized as the test condition which is imposed by the drop-weight test (Figure 6, left). Once started, the fractures of ship structures must necessarily propagate through regions of elastic loading. The edge regions of the explosion test plates are supported by the die and therefore do not develop bulge (plastic) deformation such as the central regions. Thus, the edge regions provide a critical evaluation for the fracture resistance of elastic load regions (Figure 6, right).

The above stated considerations represent the theory of the test procedures; the proof of the applicability of the theory must be found in the test results. The initial test results of ABS-A type steels indicated that the drop-weight test correlated with fracture initiation conditions of ship fracture "source" plates and that the T-S fracture transition of the explosion test correlated with the limiting conditions of fracture propagation as judged by ship fracture "through" and "end" plates. In order to obtain a more rigorous check of the correlation features, the Ship Structure Committee requested crack-starter tests of actual ship fracture steels. During the progress of the investigation, it was deemed of interest to compare the results of various conventional full plate thickness notch tests (wide plate and tear tests) with crack-starter tests. For this

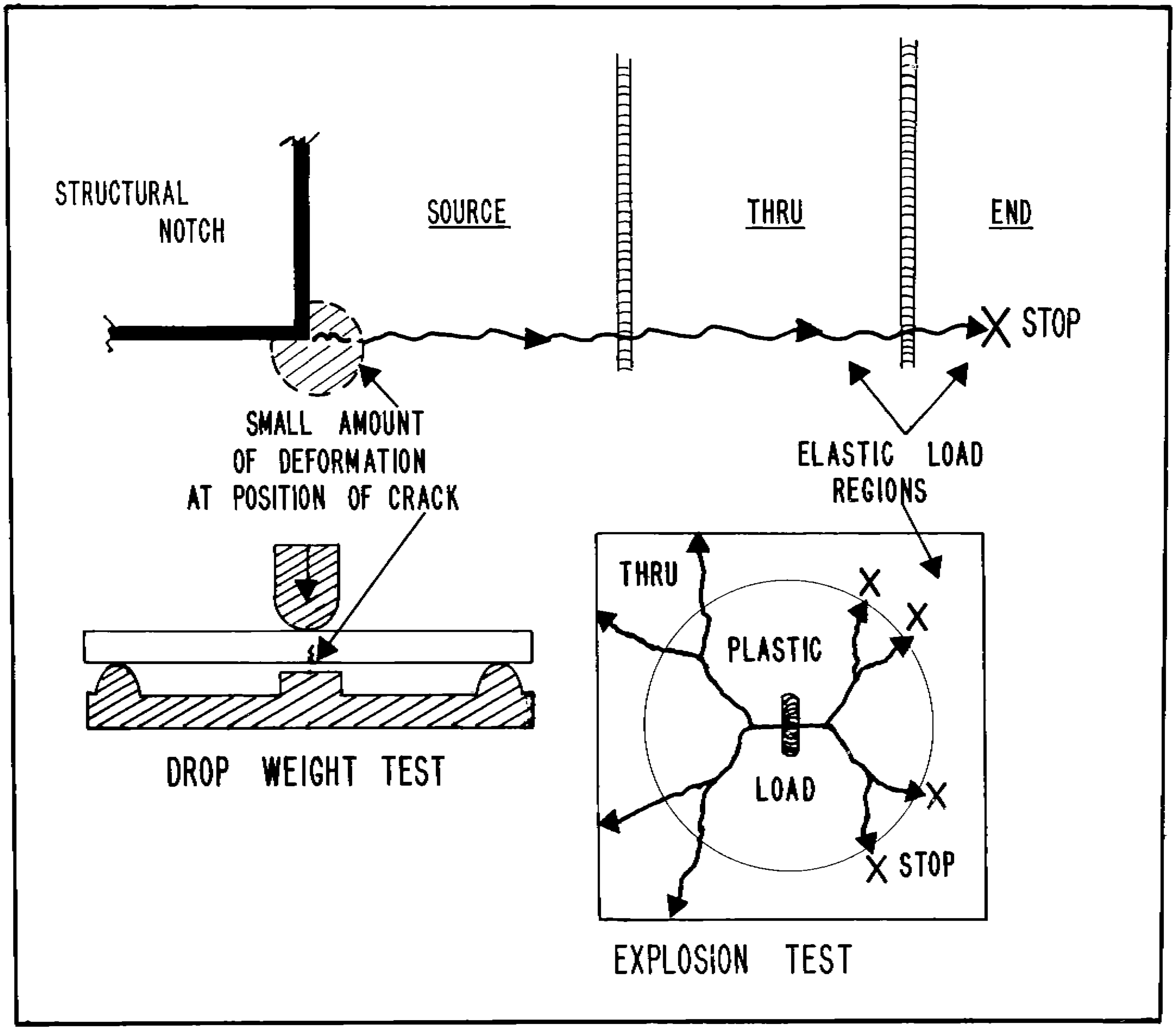

Fig. 6. Correspondence of drop-weight test to conditions of fracture initiation in service and relationship of "thru" and "stop" (T--S) behavior in explosion test to propagation or stoppage of fractures in service.

purpose "project steels" used in previous investigations were made available for crack-starter tests.

TEST RESULTS

The Charpy V transition curves of all of the ABS-A type steels which have been subjected to crack-starter tests are presented in Figure 7. The range of these curves is illustrated to fall in the center of the range which covers all ship fracture steels investigated by the NBS. Figure 8 presents the Charpy V energy transition curves obtained for eighteen ship fracture plates (eleven NBS ship No. 52, seven NBS ship No. 91). Rimmed steel curves are grouped at the top, and semikilled steel curves at the bottom of the figure. In comparison to the range of Charpy V energy transitions for all of the ship fracture steels tested by the NBS, these steels are observed to represent average material, i.e., on the basis of Charpy V energy 15 ft-lb distribution (Figure 7), these steels fall within the limits encompassing approximately 80% of all ship fracture steels tested by National Bureau of Standards.

The heavy band portions superimposed on the curves of Figure 8 represent the temperature positions of the explosion crack-starter test T--S points. The lower end of the band represents the highest temperature at which the brittle cracks propagated <u>THROUGH</u> (<u>T</u>) the lightly loaded holddown regions of the test plate, and the upper end of the band represents the

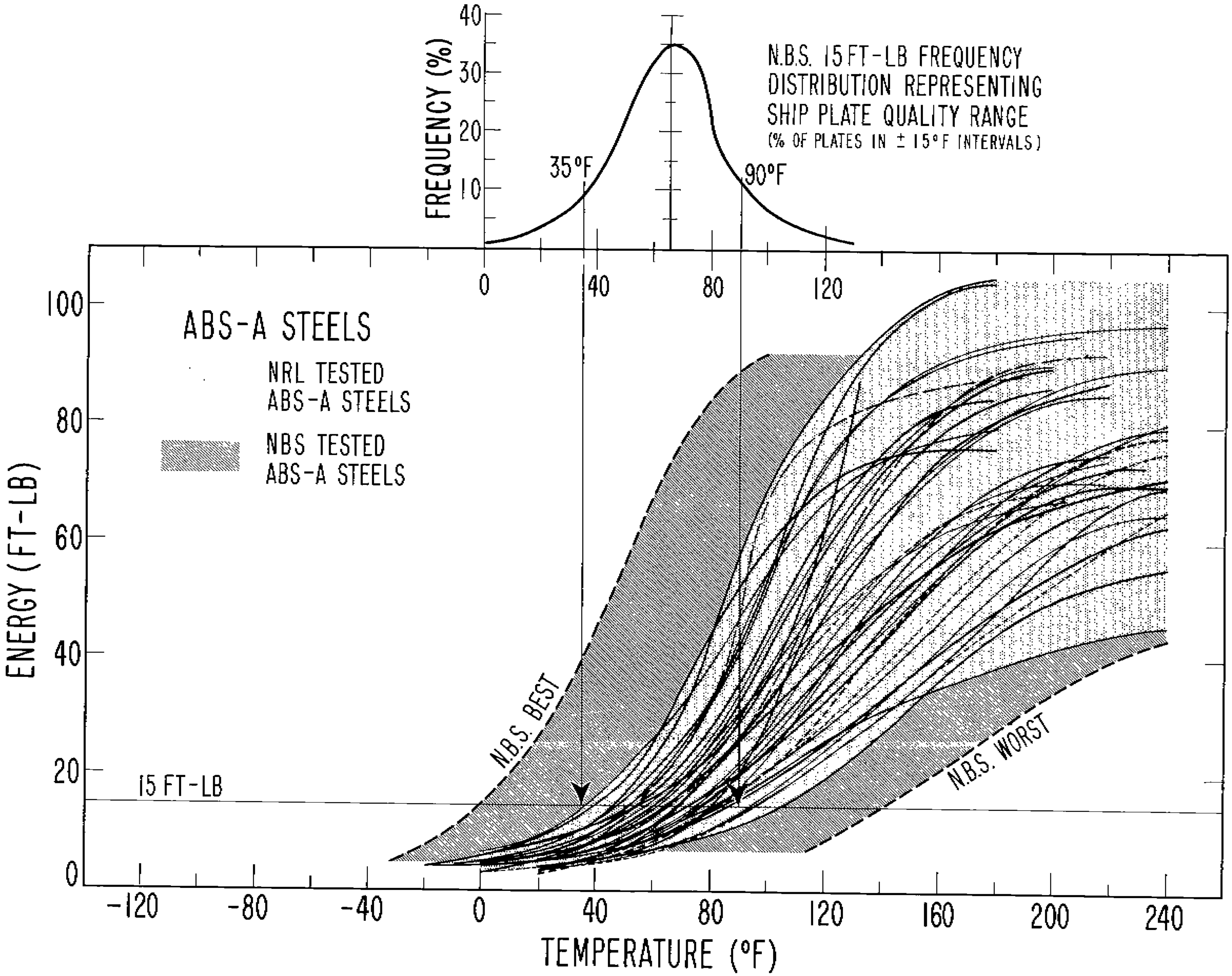

Fig. 7. Charpy V energy transition curves of all ABS-A type steels subjected to crack-starter tests in comparison to National Bureau of Standards Charpy data for ship fracture steels.

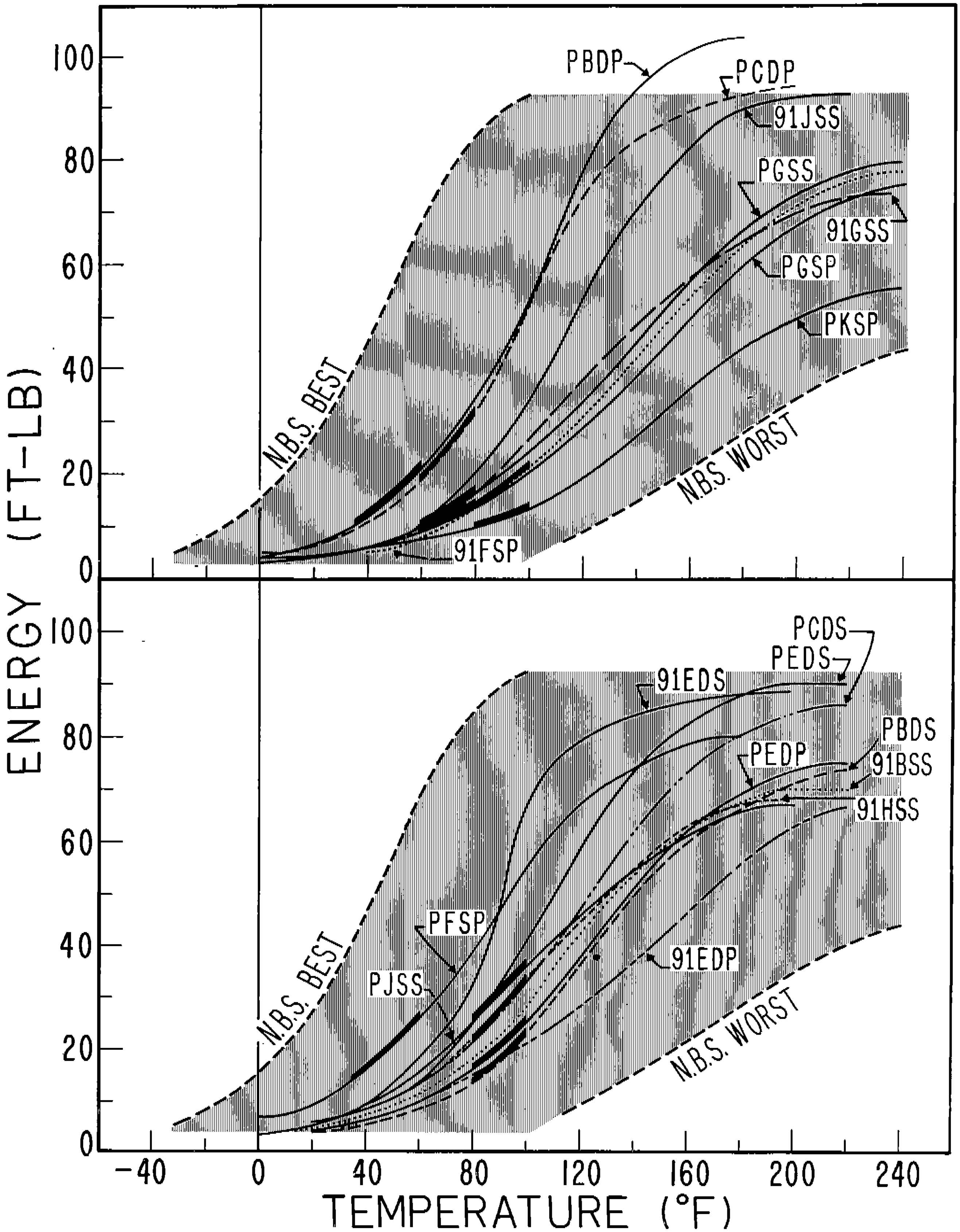

Fig. 8. Charpy V energy transition curves of rimmed (top) and semikilled (bottom) ship fracture steels subjected to crack-starter tests.

test temperature (20°F higher) at which the brittle cracks are confined (STOP)(S) to the plastically deformed, central regions of the bulge. Figure 9 illustrates the fracture characteristics at various temperatures for one of the ship fracture steels. Table 1 lists the chemistry and provides a summary of the crack-starter test data for the various ship fracture steels.

Figure 10 summarizes the correspondence of the NBS ship fracture data and the NRL crack-starter test data. The NBS investigation demonstrated that "source" plates were characterized by Charpy V energy values of 11.4 ft-lb maximum (average 7.4 ft-lb) at the fracture initiation temperature. As denoted by the schematic illustration at the left of the figure, the NBS ship fracture data and the drop-weight test data are in agreement that the Charpy V 10 ft-lb transition temperature marks the critical temperature for fracture initiation of ABS-A steels. The drop-weight test data indicate that without exception the thirty-five ABS-A steels tested, including seventeen ship fracture plates, required temperatures of less than that of the Charpy V 10 ft-lb transition for fracture initiation in the absence of appreciable deformation. The average Charpy V energy at the drop-weight transition temperature of 6.1 ft-lb for the seventeen ship fracture steels and 5.9 ft-lb for all ABS-A steels are for all practical purposes exactly equivalent to the NBS 7.4 ft-lb average value.

When considering the NBS data for "thru" plates it must be

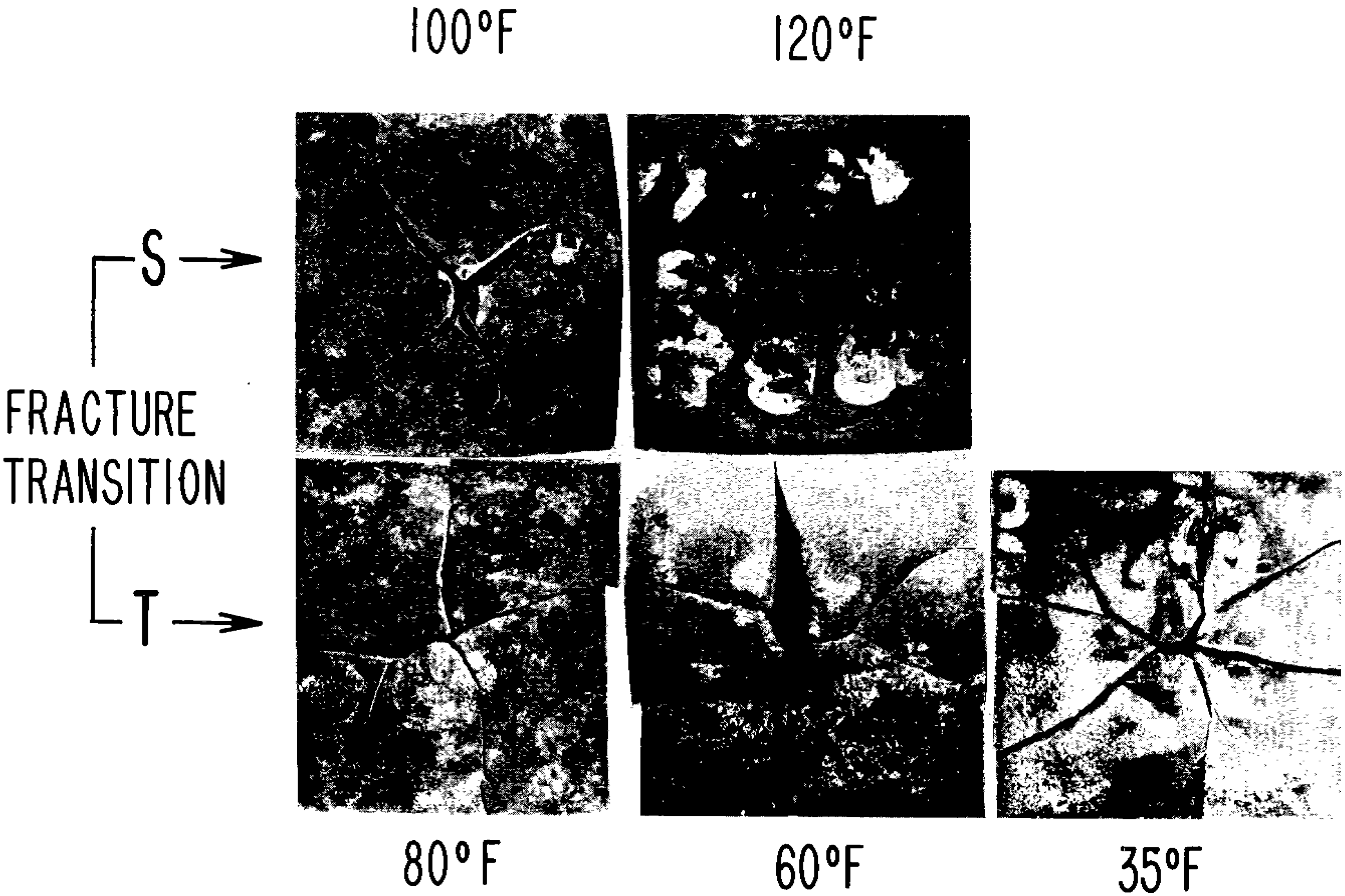

Fig. 9. Crack-starter, explosion test series of ship fracture steel PEDP depicting T--S fracture transition.

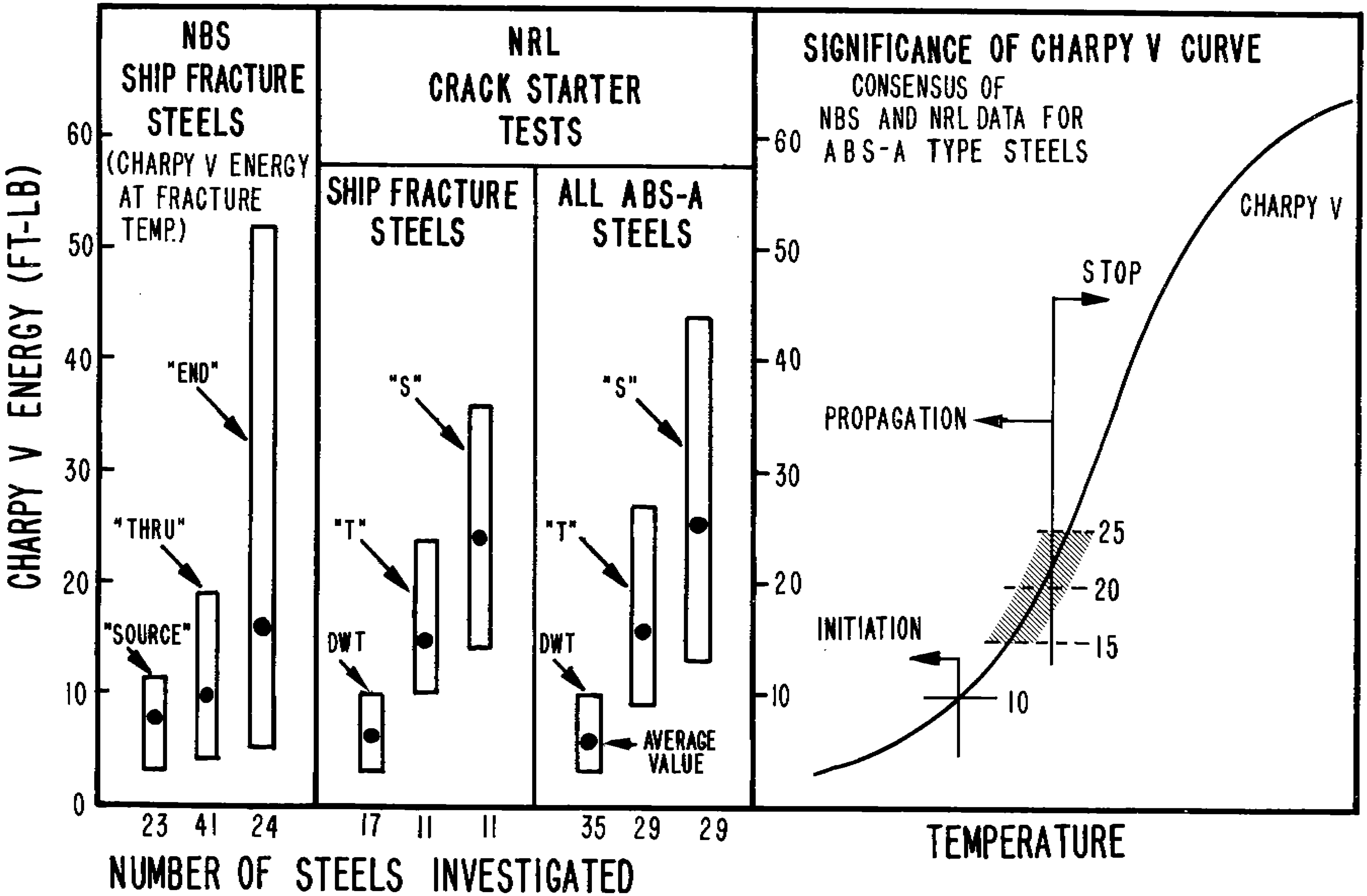

Fig. 10. Summary graph depicting correspondence of NBS ship fracture data and NRL crack-starter test data to Charpy V energy.

TABLE 1

CRACK-STARTER TEST RESULTS OF SHIP FRACTURE STEELS

EXPLOSION FRACTURE TRANSITION

Plate No.	Drop-Weight °F	Drop-Weight ft-lb	Thru (T) °F	Thru (T) ft-lb	Stop (S) °F	Stop (S) ft-lb	%C	%Mn	%Si	%P	%S
PBDP	10	5	35	10	60	21	.12	.36	.01	.006	.030
PCDP	0	5	60	19	80	32	.11	.33	.01	.019	.035
PKSP	50	7	80	10	100	14	.19	.31	.01	.020	.028
PGSS	10	4	60	10	80	16	.21	.36	.01	.030	.028
PGSP	0	4	60	14	80	20	.20	.37	.01	.020	.025
91FSP	0	3	80	14	100	21	.22	.37	.01	.008	.030
91JSS	20	4	--	--	--	--	.21	.37	.01	.005	.024
91GSS	20	5	--	--	--	--	.27	.37	.01	.010	.035
PEDS	50	10	--	--	--	--	.25	.45	.04	.010	.028
PEDP	40	6	80	16	100	25	.23	.41	.04	.006	.028
PJSS	--	--	80	24	100	36	.26	.39	.10	.020	.028
PBDS	35	5	80	13	100	22	.24	.39	.03	.030	.028
PFSP	20	9	35	13	60	26	.25	.36	.04	.020	.028
PCDS	35	7	80	21	100	32	.21	.42	.02	.020	.025
91BSS	30	6	--	--	--	--	.29	.42	.07	.010	.039
91EDS	40	9	--	--	--	--	.19	.48	.09	.009	.030
91HSS	10	5	--	--	--	--	.31	.49	.10	.012	.037
91EDP	60	10	--	--	--	--	.27	.52	.08	.010	.031

recognized many plates in the path of fracture were potentially of "source" type. The most significant aspect of the "thru" plate data is the fact that no plates of more than 19 ft-lb Charpy V energy at fracture temperature fall into this class. This signifies that values in excess of 19 ft-lb always precluded the propagation of fractures. In all cases plates which showed more than 19 ft-lb fell into the "end" type as shown by the "end" group. The fact that plates of less than 19 ft-lb were also contained in the "end" grouping may be explained by stress factors, inasmuch as fracture propagation may be prevented by low stress level (or compression regions) as well as by material properties.

The explosion crack-starter tests do not have the variable of low or compression stresses to cause fracture stoppage at temperatures of low Charpy V energy values. If fracture stoppage is obtained at the edge regions, it must be due solely to material properties which preclude propagation. The overlap in the Charpy V energy values for "T" and "S" type behavior which indicates the change from easy to difficult fracture propagation is in the range of 13 to 27 ft-lb when considering extremes. If averages are considered, the overlap is 15 to 25 ft-lb. This signifies that in most cases 15 ft-lb was the highest value which permitted propagation, and 25 ft-lb the lowest value which prevented propagation. In all cases values in excess of 27 ft-lb prevented propagation, and values of less than 13 ft-lb permitted propagation.

The explosion tests thus define the 15 to 25 ft-lb transition range as the critical temperature range of change with respect to fracture propagation when considering material properties only. This is in excellent agreement with the NBS finding that 19 ft-lb was the highest value for a "thru" plate.

On the basis of these data it may be concluded that the crack-starter tests show excellent correlation with service and agree with the NBS findings that the significance of the Charpy V transition curve to service is as illustrated in Figure 10 (right).

The test results of two of the NBS ship No. 52 (a T-2 type tanker which broke in half at a temperature of 35°F while tied at a dock in relatively smooth water) ship fracture steels are of sufficient interest to be discussed in detail. Figure 11 depicts the ship failure which initiated in an arc strike of one of the starboard deck plates (PEDS). At the ship failure temperature the source plate developed 7 ft-lb Charpy V energy. The nil-ductility (drop-weight test) transition for this plate was 50°F at which 10 ft-lb Charpy V energy was developed. The drop-weight test results indicate at the ship failure temperature of 35°F the source plate was 15°F below the nil-ductility transition (50°F) of the plate, i.e., the steel was potentially susceptible to fracture initiation in the presence of sharp crack defects.

Another item of interest is the initiation of fracture from

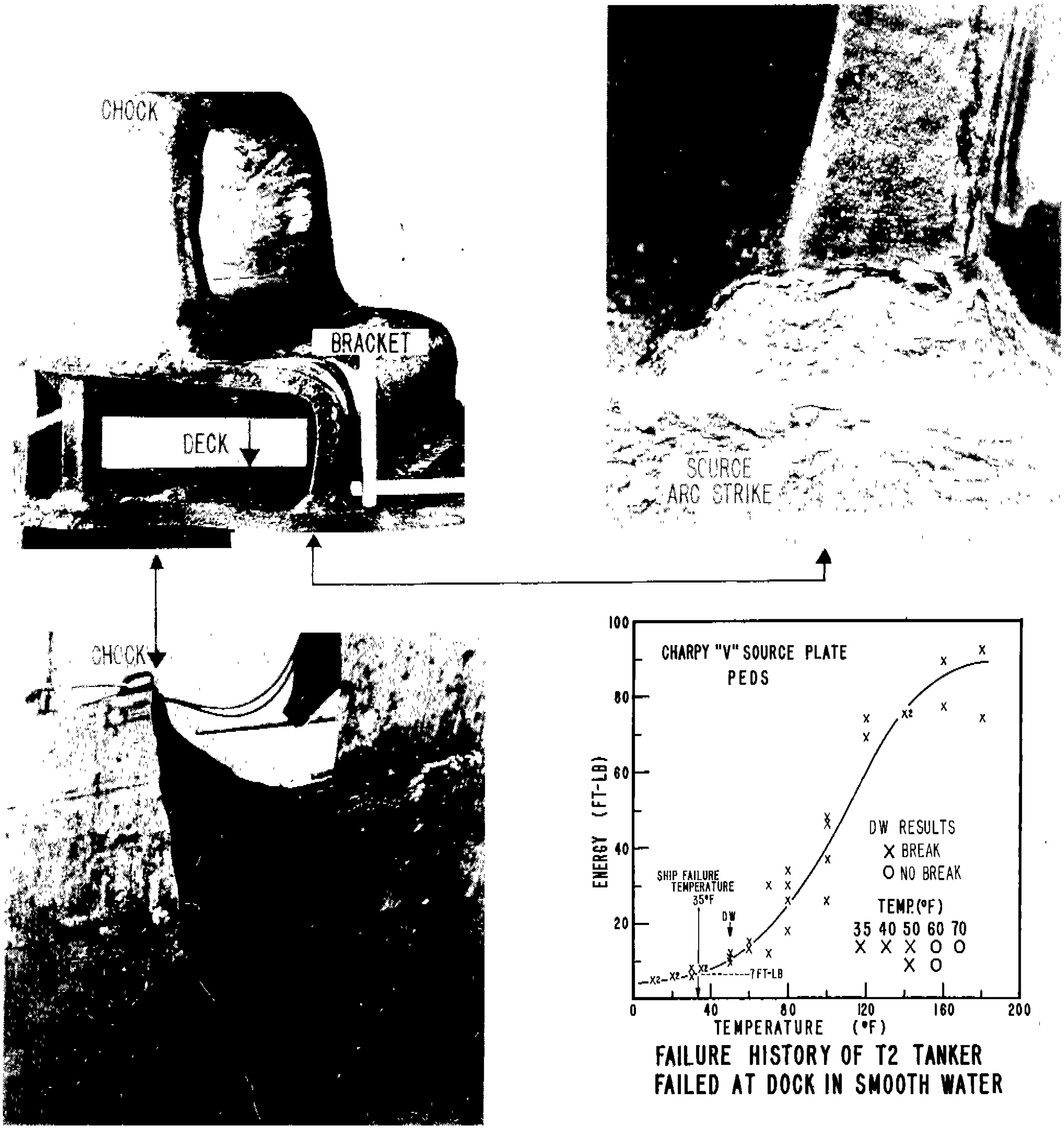

Fig. 11. Catastrophic ship failure initiated by arc strike defect at 35°F. Correlation of source plate Charpy V and drop-weight test data with service performance.

a narrow fillet weld which was evidently used for a clip or similar attachment during the construction of the ship. Figure 12 illustrates that the crack-starter weld was ignored and that the fracture initiated from a natural crack defect in the fillet weld.

COMMENTS RELATING TO CRACK-STARTER TESTS OF STEELS OTHER THAN ABS-A

It should be recognized that the correlation of crack-starter tests to Charpy V energy curves for fully killed steels such as the ABS-C type and the Navy HTS type is not the same as found for the semikilled and rimmed ABS-A type steels. Figure 13 illustrates that the T--S transition for these steels occurs at temperatures corresponding to higher positions on the Charpy V curves. The drop-weight test also shows relationships to higher positions on the Charpy V energy curve. Figure 14 summarizes the results of T--S and drop-weight nil-ductility determinations for ABS-C and HTS steels which have been tested to date[7]. It is noted that the average Charpy V energy at the drop-weight transition for ABS-C steels is 16.2 ft-lb and for the HTS steels 24.4 ft-lb. The T--S range for these two steels averages 40 to 54 ft-lb and 61 to 83 ft-lb, respectively.

CORRELATION OF CRACK-STARTER TESTS WITH WIDE PLATE AND TEAR TESTS

Wide plate and tear tests may be considered plate fracture tests featuring machined or saw cut notches. The results of these tests are evaluated on the basis of the range of temperature over

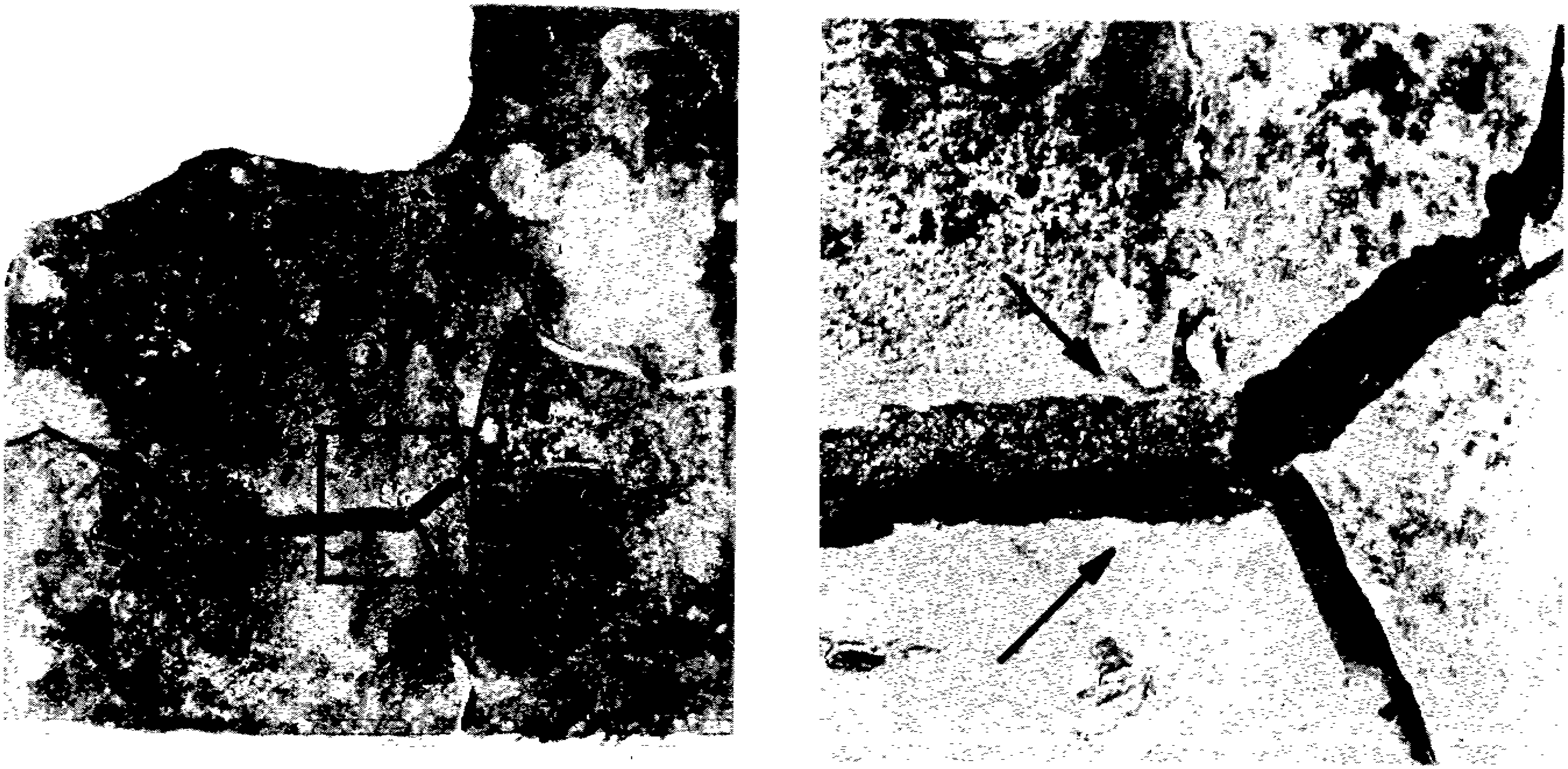

Fig. 12. Crack-starter test of ship fracture steel. Crack-starter weld ignored and fracture initiated by natural crack defect in fillet weld. Test at 60°F, plate PBDS.

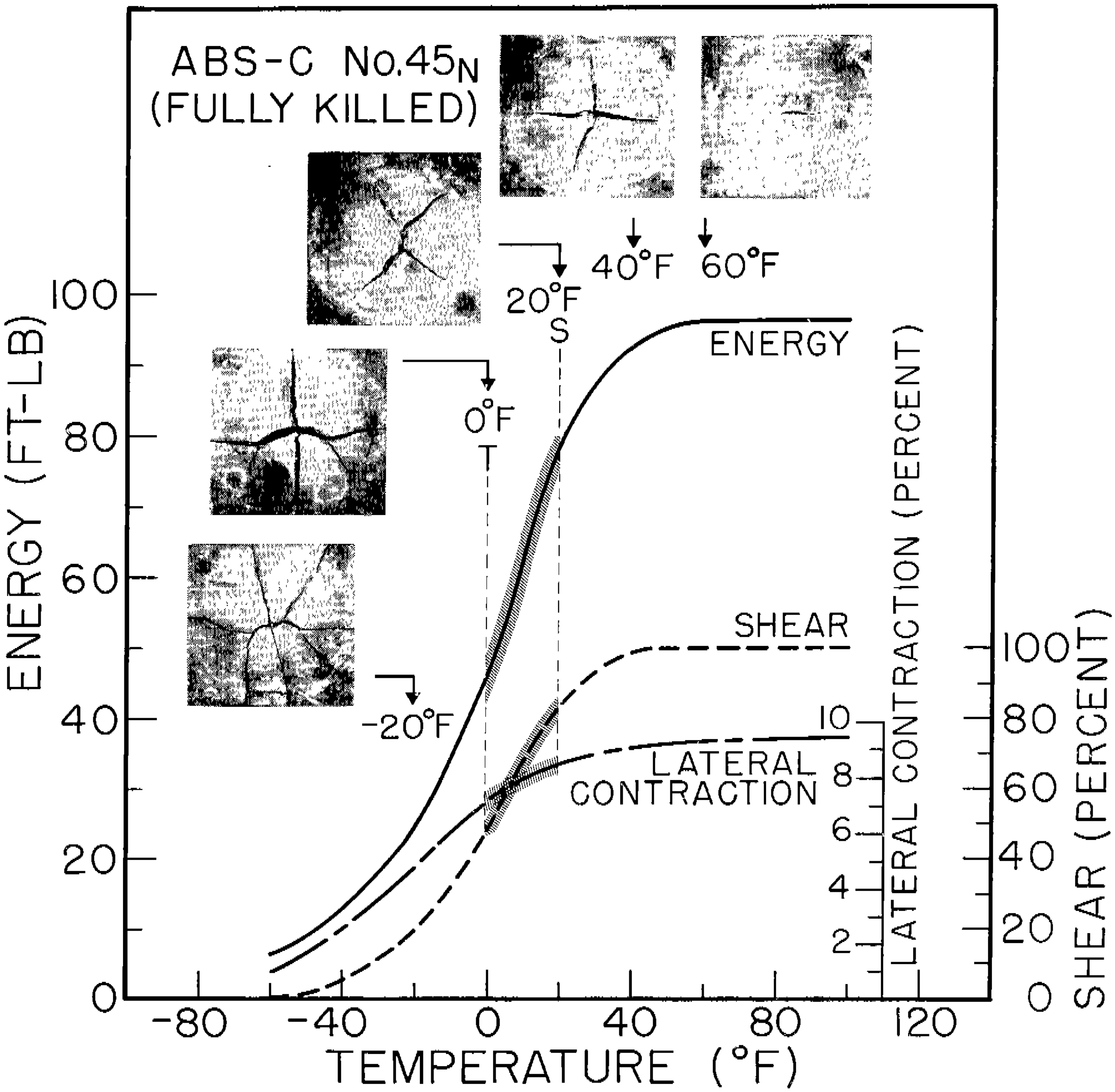

Fig. 13. Relationship of explosion crack-starter tests to Charpy V transition curves for typical normalized ABS-C (fully killed) type steel. Note higher position on Charpy V curves of T--S range as compared to ship plate steel in Figure 2 (0.17%C, 0.77%Mn, 0.23%Si, 0.02%Al--1-in. thick).

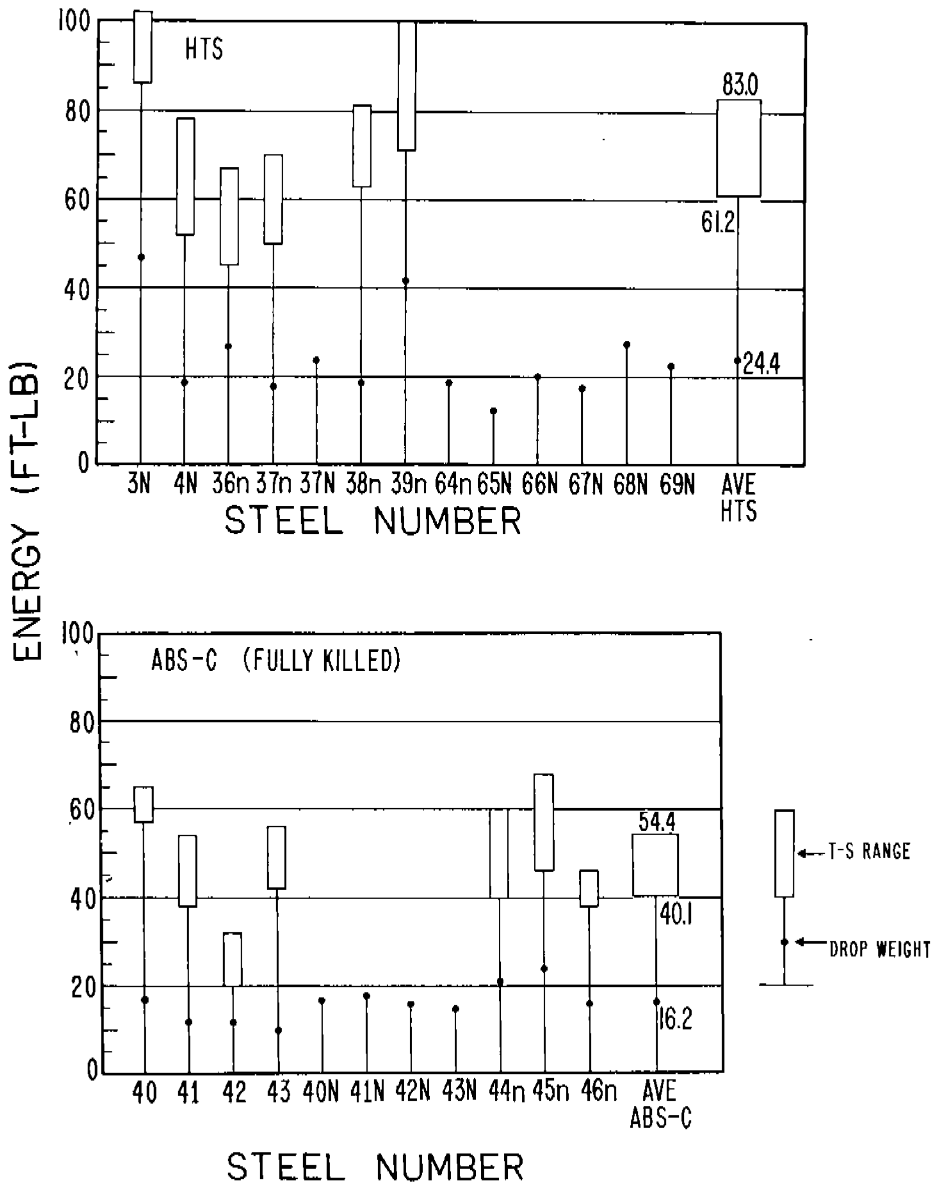

Fig. 14. Summary of crack-starter tests correlation to Charpy V energy for fully killed steels (N = mill normalized, n = laboratory normalized).

which a "scatterband" of high and low values of cleavage fracture is developed. The fracture transitions reported[8,9,10,11,12] for the wide plate tests correspond to the full spread of the "scatterband" range, while the transitions reported[13,14] for the tear tests represent the highest temperature at which one or more of four specimens broke with more than 50% cleavage fracture.

Six project steels and four ship fracture steels which had previously been subjected to wide plate and tear tests were available for explosion and drop-weight crack-starter tests. Figures 15 and 16 depict the results of the wide plate, tear and explosion tests as related to the Charpy V energy transitions established for these steels at NRL. Drop-weight test results and related Charpy V energy values are shown in Table 2.

The following may be concluded:

1. Explosion test fracture transitions (T--S) generally occur at a temperature range which overlaps the range displayed in the wide plate tests.
2. When the wide plate transitions (or the T--S fracture transition) are related to the Charpy V energy curves, significantly higher energy values are obtained for the fully killed steel (D_n) as compared to the rimmed and semikilled ABS-A type steels (E, A, C, PBDP, PCDP, PJSS, and PBDS).

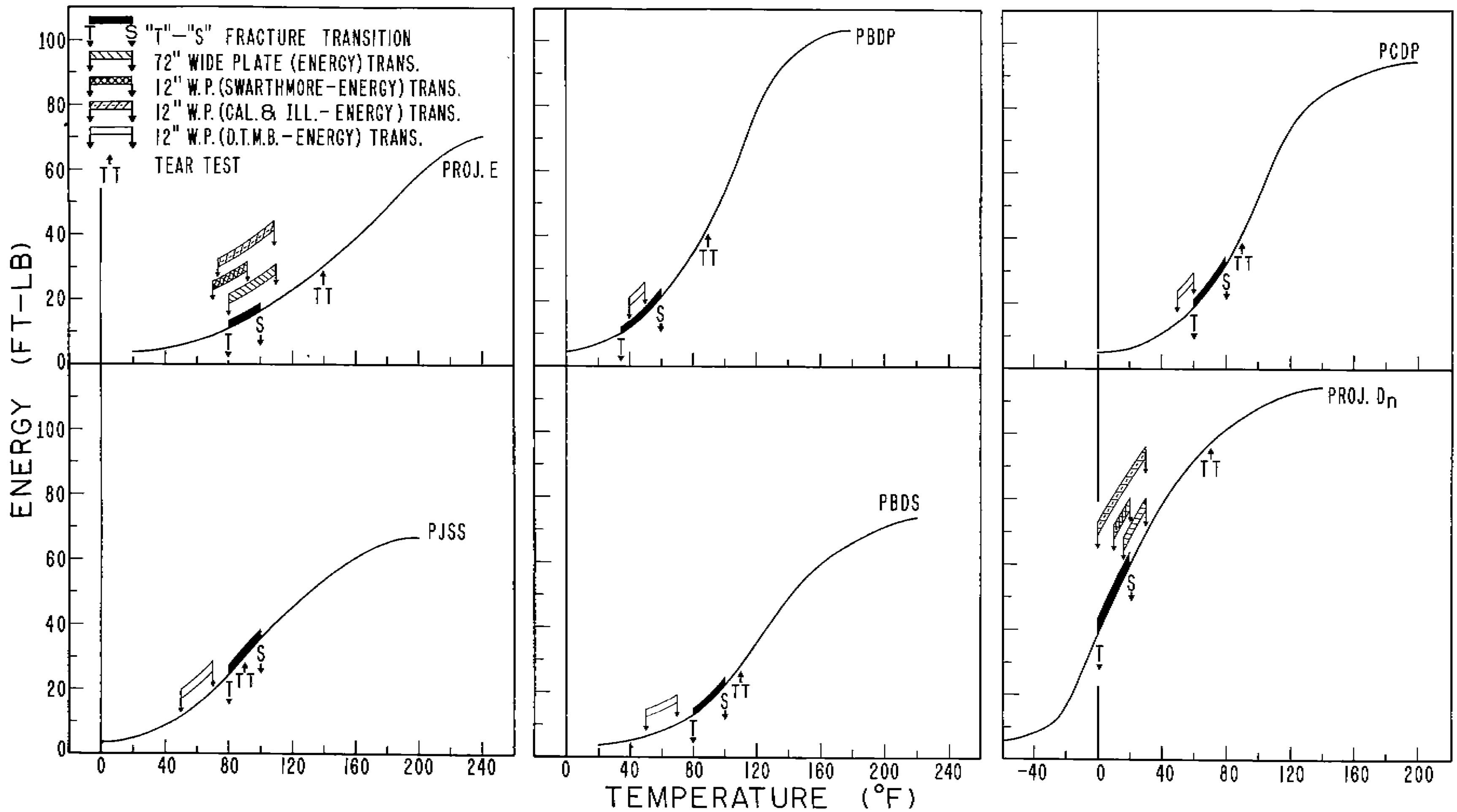

Fig. 15. Relationships of explosion, wide plate, and tear test--fracture transitions to Charpy V energy transitions.

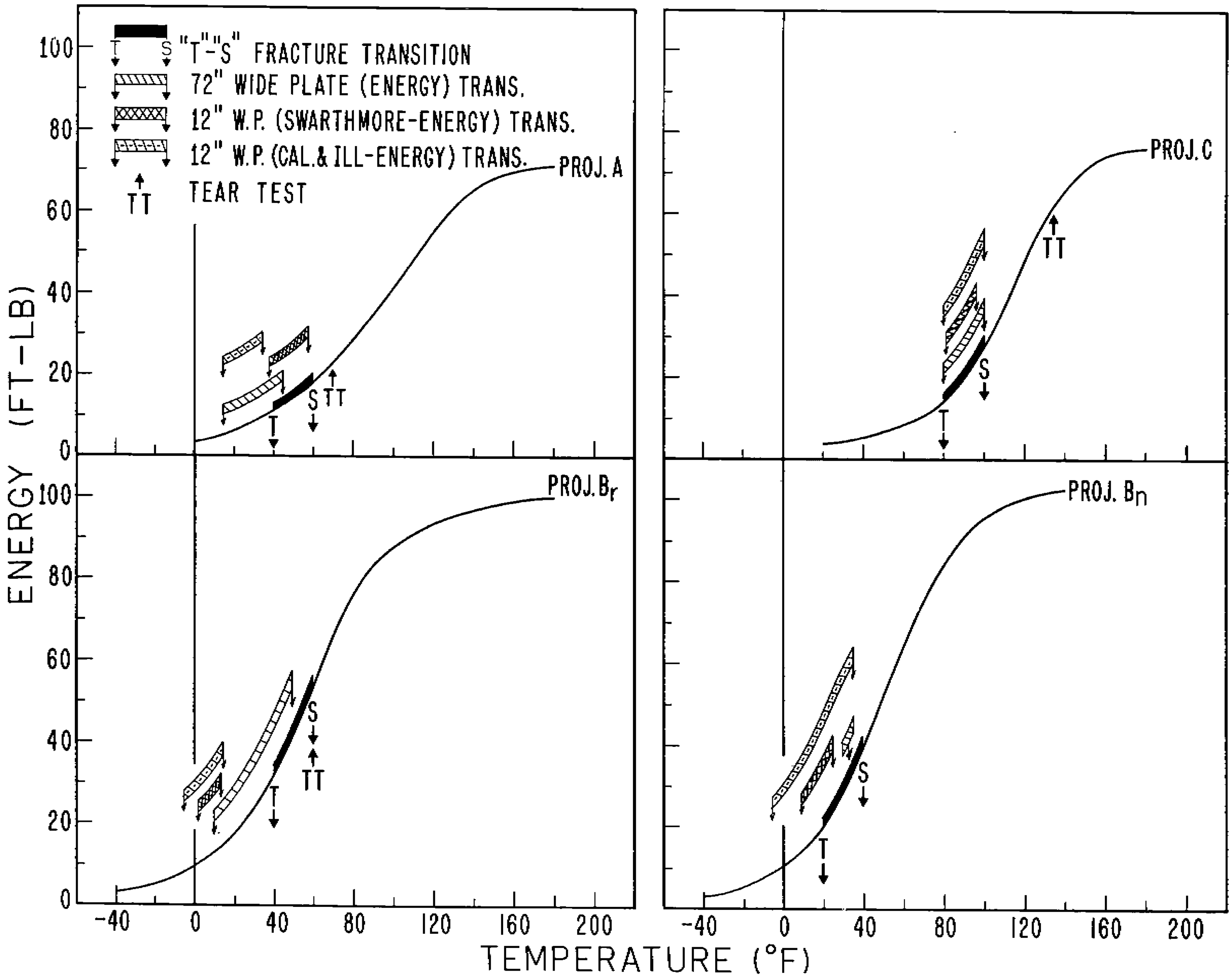

Fig. 16. Relationships of explosion, wide plate, and tear test--fracture transitions to Charpy V energy transitions.

TABLE 2

CRACK-STARTER TEST RESULTS OF PROJECT STEELS

EXPLOSION FRACTURE TRANSITION

Project No.	Drop Weight °F	Drop Weight ft-lb	Thru (T) °F	Thru (T) ft-lb	Stop(S) °F	Stop(S) ft-lb	%C	%Mn	%Si	%P	%S
E	30	4	80	11	100	16	.25	.35	.02	.008	.040
A	20	6	40	11	60	18	.23	.48	.02	.009	.039
C	30	5	80	14	100	28	.21	.44	.05	.010	.037
B_r	0	10	40	32	60	53	.16	.72	.05	.013	.032
B_n	-10	9	20	21	40	40	.16	.73	.04	.011	.033
D_n	-20	16	0	39	20	61	.18	.54	.25	.015	.029

This pattern of behavior persists if wide plate data for additional fully killed steels are considered, Figure 17). In other words, wide plate test data corroborate crack-starter test results in indicating that fully killed steels are susceptible to fracture at temperatures of higher Charpy V energy than noted for ABS-A type steels.

3. The tear test transitions generally occur at higher positions than the fracture transitions displayed in wide plate and explosion bulge tests. For the various ABS-A steels the correlation with Charpy V energy varies from 22 to 60 ft-lb (22, 60, 55, 30, 40, 40, 35) with the range of 30 to 40 being most common. In relation to the NBS, NRL, and wide plate data, the tear test appears to provide a conservative estimate of the danger temperature with respect to propagation.

COMMENTS RELATIVE TO PROJECT STEEL CHARPY V DATA

From previous investigations involving project steels, it has been reported and widely quoted that Charpy specimens are not amenable to correlation studies. This contention was based in great part on results for project steels A and C for which widely different fracture transitions in wide plate tests but

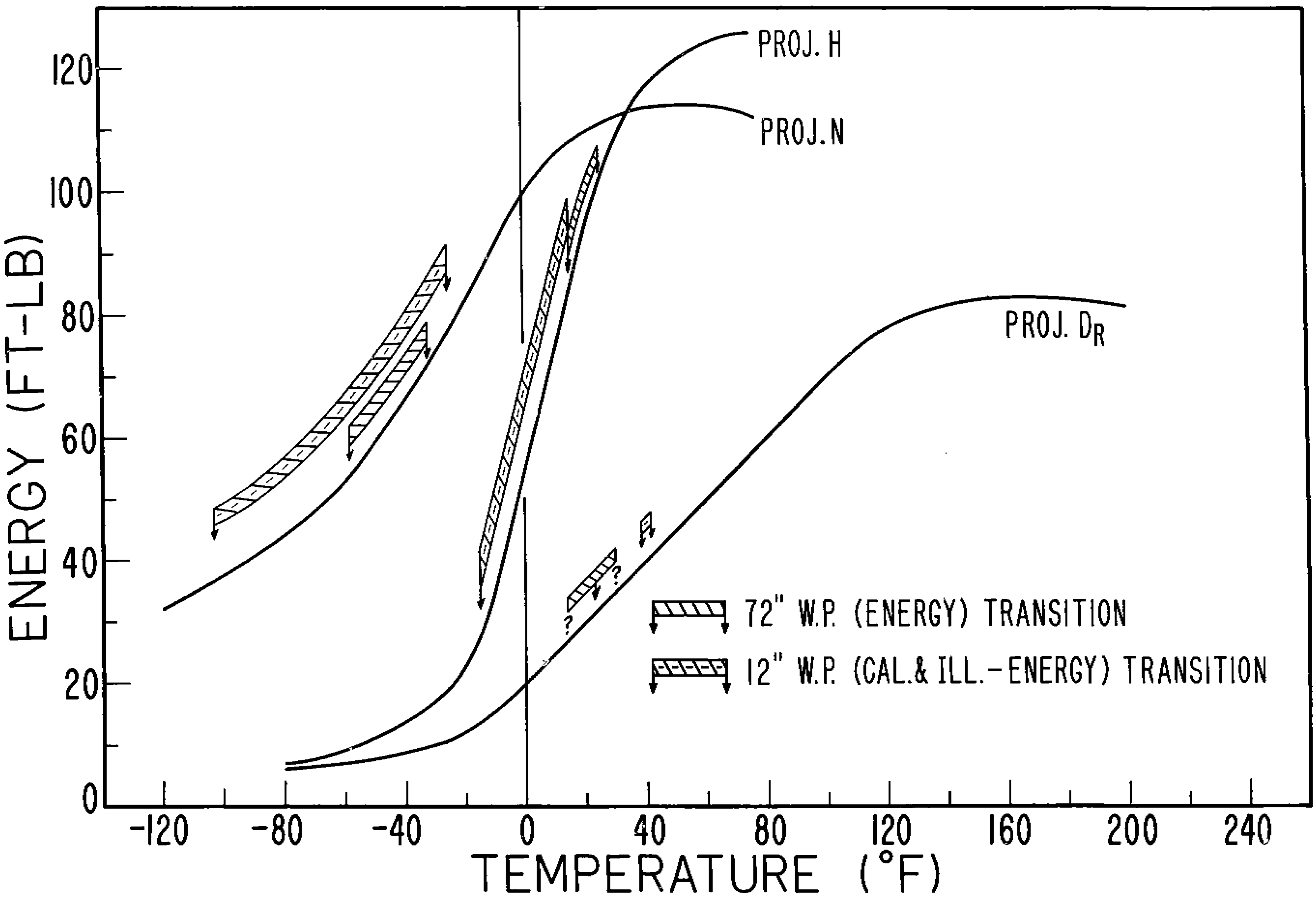

Fig. 17. Relationship of wide plate fracture transitions to Charpy V energy transitions for various fully killed steels.

essentially identical Charpy V energy transitions have been reported in the literature[15]. In this respect it is of interest to review all available data which serve to indicate the uniformity of quality for the various plates of the project steel heats.

In Figure 18 the original Charpy V data for six project steels[16] are compared to those obtained at this laboratory. Essentially equivalent curves are obtained for E, A, B_n and D_n. For steel B_r the two sets of data indicate significant differences between plates within the same heat. The correlations shown in Figure 16 are poor for B_r, which fact may be explained on the basis of plates of different quality.

The various Charpy V curves reported for project C steel are shown in Figure 19. Of the curves reported[16] for the 3/4-in. plates, the one chosen for subsequent correlation studies apparently does coincide with the Charpy V curve for project A steel, but it does not represent the average curve for the various C steel plates. Hence, any conclusions regarding the inadequacies of Charpy V tests based on A and C comparisons are questionable. In the case of the NRL tests, Charpy V curves were obtained for A and C steels adjacent to the material which was tested by the crack-starter method. The same relative differences were indicated by the Charpy curves as well as by the fracture tests (C at approximately 20°F inferior to A).

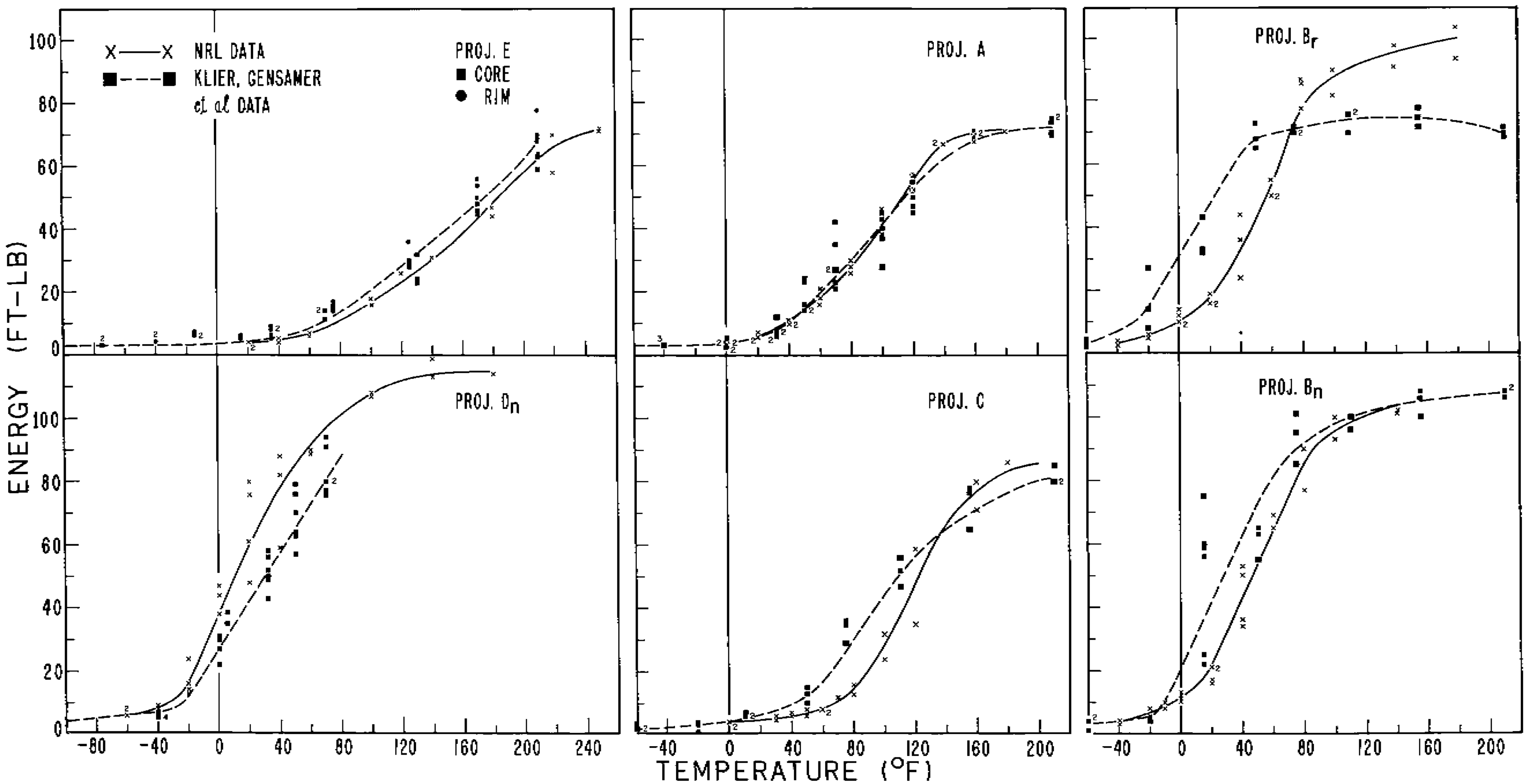

Fig. 18. Comparison of Charpy V data for six project steels.

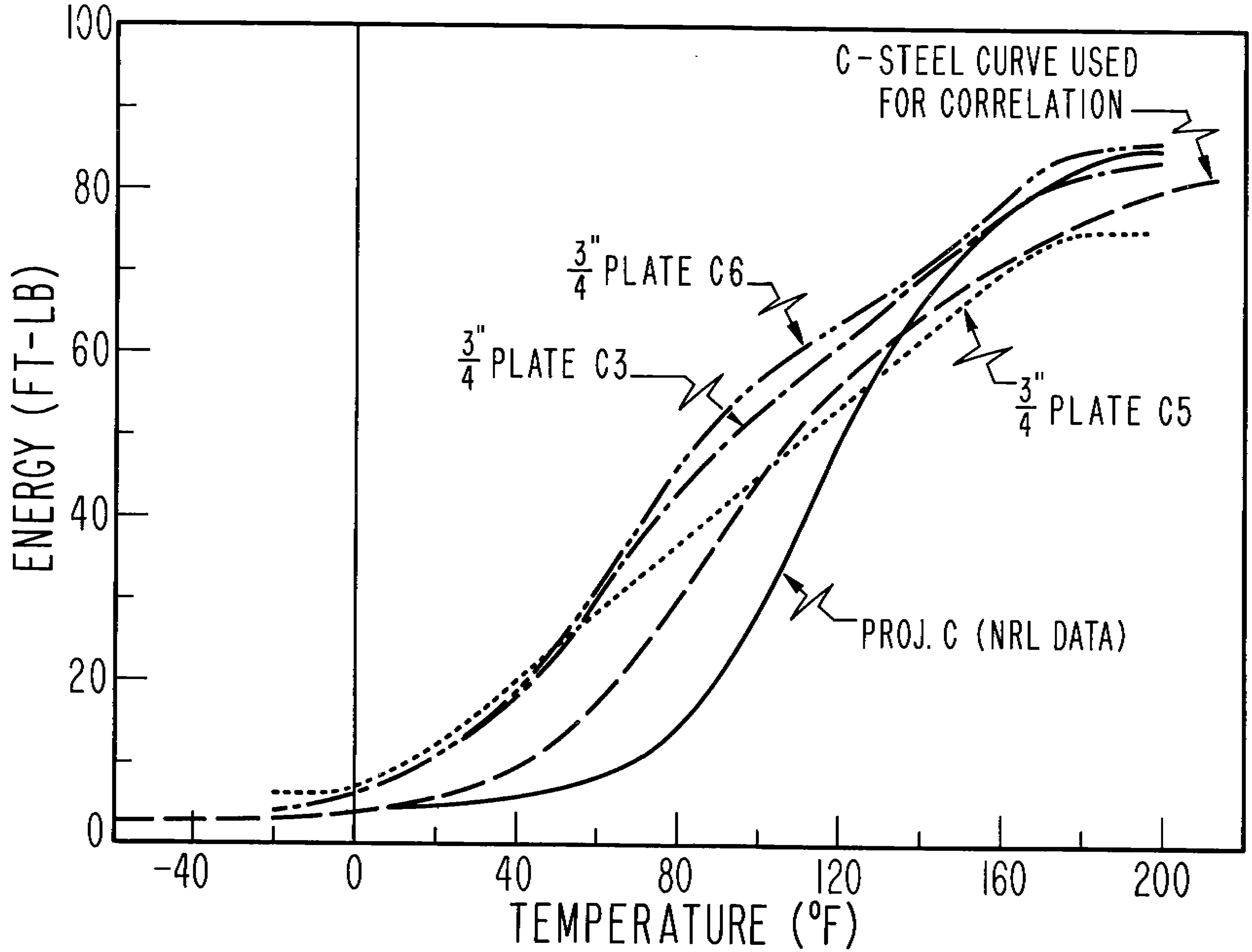

Fig. 19. Various Charpy V energy transition curves reported for project C (3/4-in.) steel.

Differences in tear test transitions for A and C served as another basis of argument against the Charpy V test[17]. It should be noted that for the C steel the tear test correlates with 60 ft-lb, and what is more important this is very near the top of the transition range. In no other case is the tear test correlation so high on the Charpy V curve. Explosion crack-starter tests conducted at temperatures related to the upper portion of the Charpy V transition range have demonstrated <u>without exception</u> a near refusal to crack, see Figure 2.

SUMMARY DISCUSSION

The quest for an ideal specimen for the evaluation of the performance to be expected of a steel in a welded structure such as a ship had led to the development of a great variety of specimens and test procedures. The ideal will probably never be found, for even the closest of all possible duplication of the structure (other ships for example) does not always give the same result in service.

Based on Naval Research Laboratory test results, it is now apparent that service performance is a question of probabilities--a sharp crack defect at a position of yielding in a steel of inadequate properties at the service temperature involved provides for a high probability for the initiation of failure. If the design is such that yielding is not developed at any position or if the steel is not sensitive to crack-like defects to the lowest service temperature, failure should not be possible. Design based on the elimination of yield positions should permit the use of steels susceptible to brittle fracture and, similarly, the use of steels which are resistant to brittle fracture should permit the use of designs in which local yielding is anticipated.

The various test procedures which have been developed for the evaluation of the susceptibility of the steel to fracture fall in three groupings:

1. Tests of conventional small specimens, such as the Charpy V type, for which correlation to service is expected to be empirical.
2. Tests of full thickness specimens, such as wide plate tests utilizing arbitrary machined notches, which are expected to correlate directly to service on a basis of fracture appearance (propagation aspects of fracture).
3. Tests of full thickness specimens utilizing ultra sharp cracks considered to be the equivalent to the natural type. For these tests, such as the crack-starter type, it is expected that a direct correlation to service may be attained with respect to ductility and fracture transitions (initiation and propagation aspects of fracture).

The only reliable correlation to service performance now available is in terms of an empirical correlation of Charpy V tests to ship fracture plates obtained by the NBS studies. It is considered significant that the ultra sharp notch, full thickness tests described as the crack-starter tests show the same correlation with Charpy V test data as the NBS studies with respect to both initiation and propagation limits.

On the basis of these findings the crack-starter tests should be considered of value for the investigation of improved steels for which no service data are available. The findings that crack-starter tests of fully killed steels, such as the ABS-C type, do not correlate with the Charpy V curve in the same manner that the semikilled and rimmed steels do present a real problem. While no service data relating to failures of fully killed steel are available, it is difficult to ignore the indications of crack-starter tests that the NBS correlation cannot be extended to other types of steels. The fact remains that in the drop-weight test the ABS-A steels may be severely deformed without fracture at temperatures of Charpy V 15 to 20 ft-lb, while at the same Charpy levels the ABS-C steels fracture with the application of barely measurable deformation, Figure 20. The presence of a sharp crack is a realistic assumption for a large welded structure, and the development of small amounts of deformation at positions of unfavorable design is also realistic. At 15-20 ft-lb temperatures the ABS-A steel shown in Figure 20 has a very large ductility reserve, but the

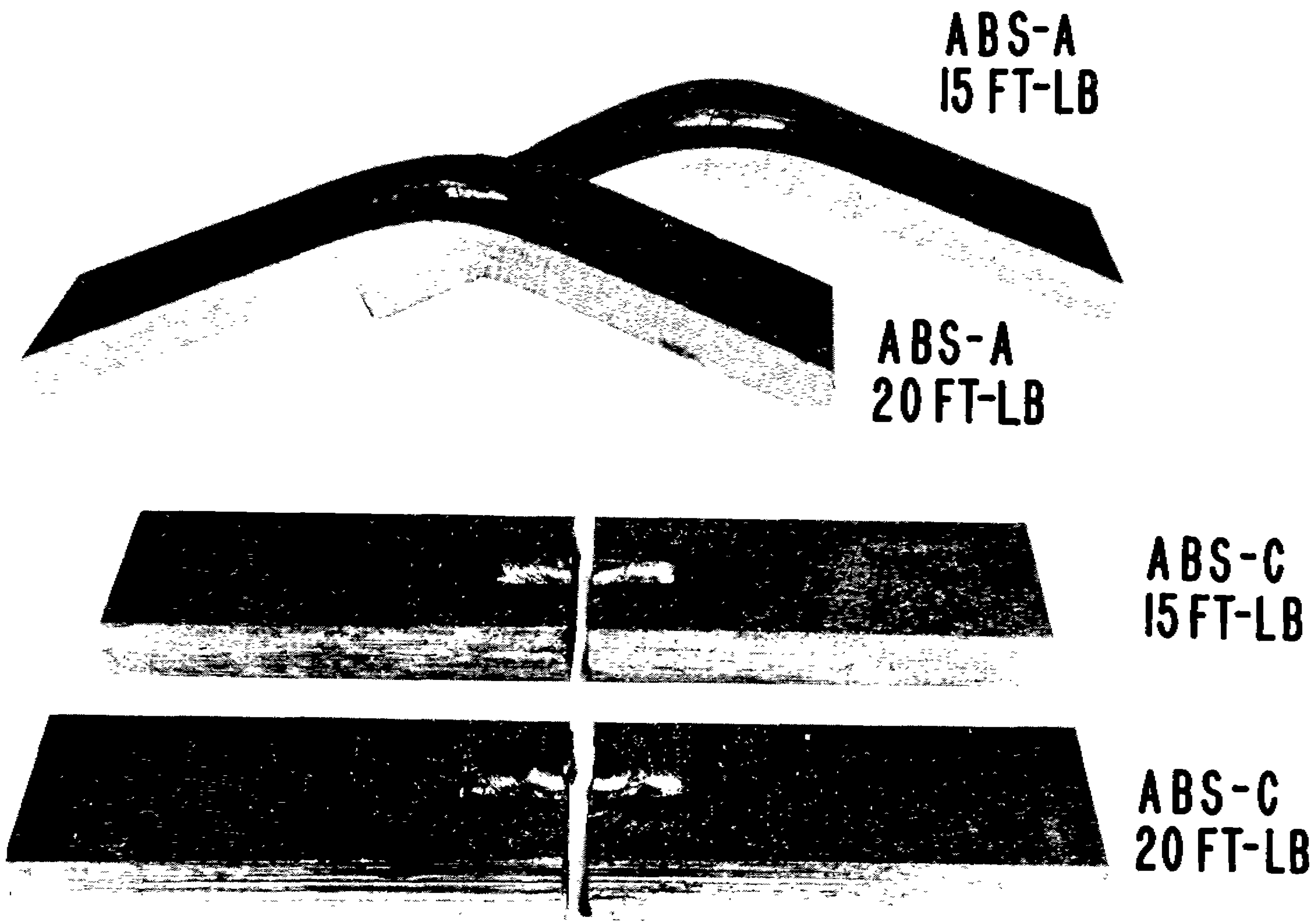

Fig. 20. Drop-weight tests of ABS-A and ABS-C steels at temperatures equivalent to Charpy 15 and 20 ft-lb. Note large ductility reserve in A steel but not in C steel. In order to develop extensive deformation in the ABS-C steel, it is necessary to test at Charpy V 30 ft-lb temperatures.

ABS-C does not.

Additional evidence of differences between semikilled and rimmed steels and fully killed steels is demonstrated by the wide plate tests. The fracture transition of the wide plate tests corresponds to the fracture transition T--S of the explosion tests. Like the T--S transitions, wide plate transitions of fully killed steels occur at temperatures equivalent to higher Charpy V energy than observed for the semikilled and rimmed steels.

REFERENCES

1. Hartbower, C. E., and Pellini, W. S. "Investigation of Factors Which Determine the Performance of Weldments," THE WELDING JOURNAL, Res. Suppl., October 1951, pp. 499-s--511-s.

2. Pellini, W. S., and Eschbacher, E. W. "Part II: Investigation of the Performance of Weldments and Prime Plate of ABS-B Steel," Final Report, Ship Structure Committee Report, Serial No. SSC-78, June 18, 1954.

3. Puzak, P. P., Eschbacher, E. W., and Pellini, W. S. "Initiation and Propagation of Brittle Fracture in Structural Steels," THE WELDING JOURNAL, Res. Suppl., December 1952, pp. 561-s--581-s.

4. Pellini, W. S. "Evaluation of the Significance of Charpy Tests," A. S. T. M. Symposium on Metallic Materials at Low Temperatures, Atlantic City, June 28--30, 1953. (To be issued as a symposium booklet by the A. S. T. M.).

5. Williams, M. L. "Investigation of Fractured Steel Plates Removed from Welded Ships," Ship Structure Committee Report, Serial No. NBS-3, June 1951.

6. Williams, M. L., and Ellinger, G. A. "Investigation of Structural Failures of Welded Ships," THE WELDING JOURNAL, Res. Suppl., October 1953, pp. 498-s--527-s.

7. Puzak, P. P., Schuster, M. E., and Pellini, W. S. "Applicability of Charpy Test Data," (Submitted March 1954 to THE WELDING JOURNAL).

8. Boodberg, A., Davis, H. E., Parker, E. R., and Troxell, G. E. "Causes of Cleavage Fracture in Ship Plate--Tests of Wide Notched Plates," THE WELDING JOURNAL, Res. Suppl., April 1948, pp. 186-s--199-s.

9. Wilson, W. M., Hechtman, R. A., and Bruckner, W. H. "Cleavage Fracture of Ship Plates as Influenced by Size Effect," Final Report, Ship Structure Committee Report, Serial No. SSC-10, June 12, 1947.

10. Carpenter, S. T., and Roop, W. P. "Tensile Tests of Internally Notched Plate Specimens," THE WELDING JOURNAL, Res. Suppl., April 1950, pp. 161-s--182-s.

11. MacCutcheon, E. M., Pittiglio, C. L., and Raring, R. H. "Transition Temperature of Ship Plate in Notch-Tensile Tests," THE WELDING JOURNAL, Res. Suppl., April 1950, pp. 184-s--194-s.

12. Klier, E. P., and Gensamer, M. "Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests," Final Report, Ship Structure Committee Report, Serial No. SSC-30, January 30, 1953.

13. Kahn, N. A., and Imbembo, E. A. "Further Study of Navy Tear Test," THE WELDING JOURNAL, Res. Suppl., February 1950, pp. 84-s--96-s.

14. New York Naval Shipyard, Material Laboratory, Final Report on Laboratory Project 5208-1, April 6, 1951. (Not available for general distribution).

15. Klier, E. P., Wagner, F. C., and Gensamer, M. "The Correlation of Laboratory Tests with Full Scale Ship Plate Fracture Tests," THE WELDING JOURNAL, Res. Suppl., February 1948, pp. 71-s--96-s.

16. Gensamer, M., Klier, E. P., Prater, T. A., Wagner, F. C., Mack, J. O., and Fisher, J. L. "Correlation of Laboratory Tests with Full Scale Plate Fracture Tests," Progress Report, Ship Structure Committee Report, Serial No. SSC-9, March 19, 1947.

17. Kahn, N. A., and Imbembo, E. A. "Notch-Sensitivity of Ship Plate--Correlation of Laboratory-Scale Tests with Large-Scale Plate Tests," A. S. T. M. Special Technical Publication No. 87, Symposium on Deformation of Metals as Related to Forming and Service, June 22, 1948.

A P P E N D I X

APPENDIX

The drop-weight test was developed to determine the temperature at which a given steel loses its ability to deform in the presence of a sharp crack-like defect (the worst type to be expected). Figure A-1 illustrates the specimen and test equipment. The condition of a sharp crack-like flaw is synthesized by the use of a brittle, hard-surfacing type weld. On loading by drop-weight, this weld cracks in a brittle manner thus developing a sharp crack-like defect. As noted (Figure A-1) 3° of bend is required to fracture the weld. By the use of a stop, the total bend is restricted to 5°; if the additional 2° of bend is not permitted, the steel fractures.

THE DROP-WEIGHT EQUIPMENT

The drop-weight equipment is of simple design based on the use of readily available rolled steel shapes. Figure A-2 illustrates the complete assembly. The weight release mechanism is illustrated in Figures A-3 and A-4. The weight is raised by the use of an electric hoist or alternately by the use of a hand crank.

PREPARATION OF THE DROP-WEIGHT SPECIMEN

The drop-weight specimen which is T-in. by 3 1/2-in by 14-in. (T being any thickness up to and including 1 inch) can be either flame or saw cut from plate material. Figure A-5,

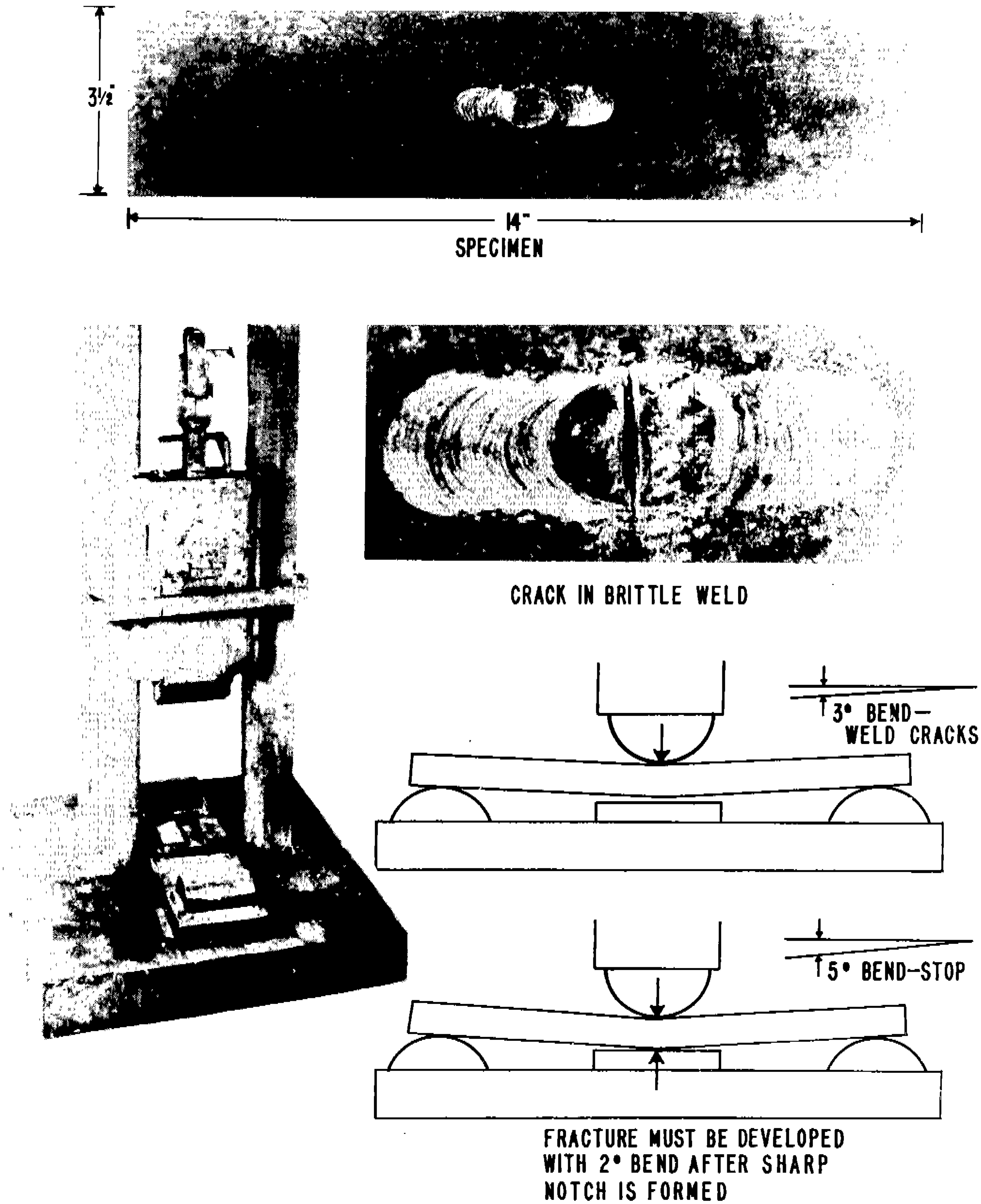

Fig. A-1. Drop-weight test method.

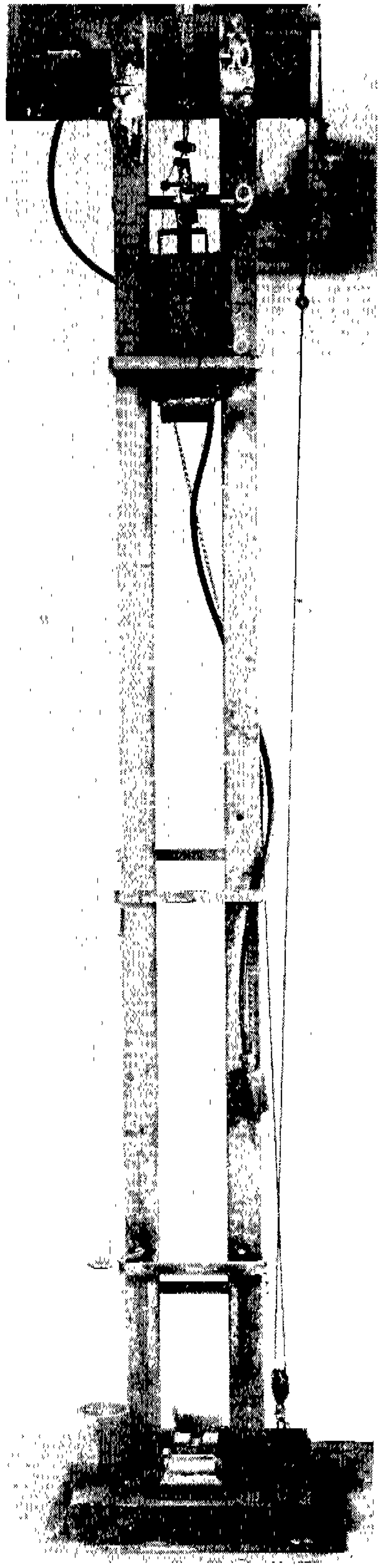

Fig. A-2. General view of drop-weight test frame.

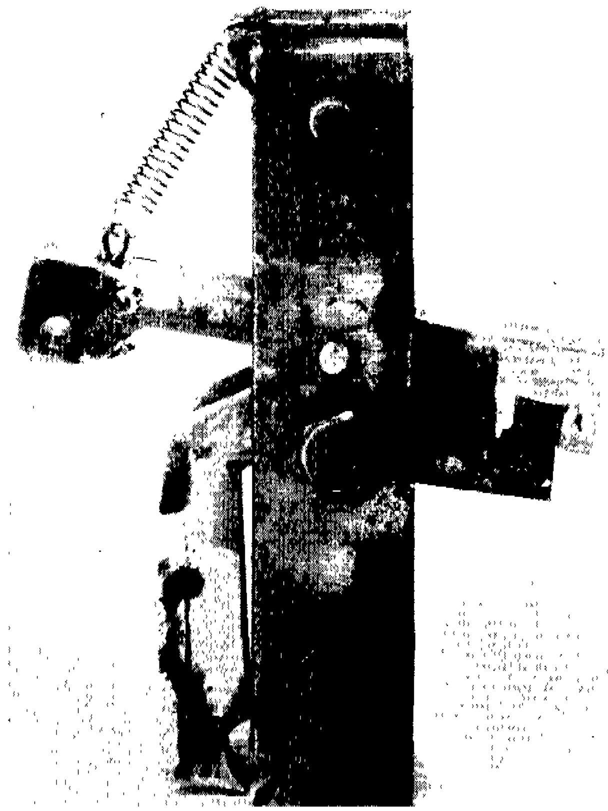

Fig. A-3. Quick release mechanism.

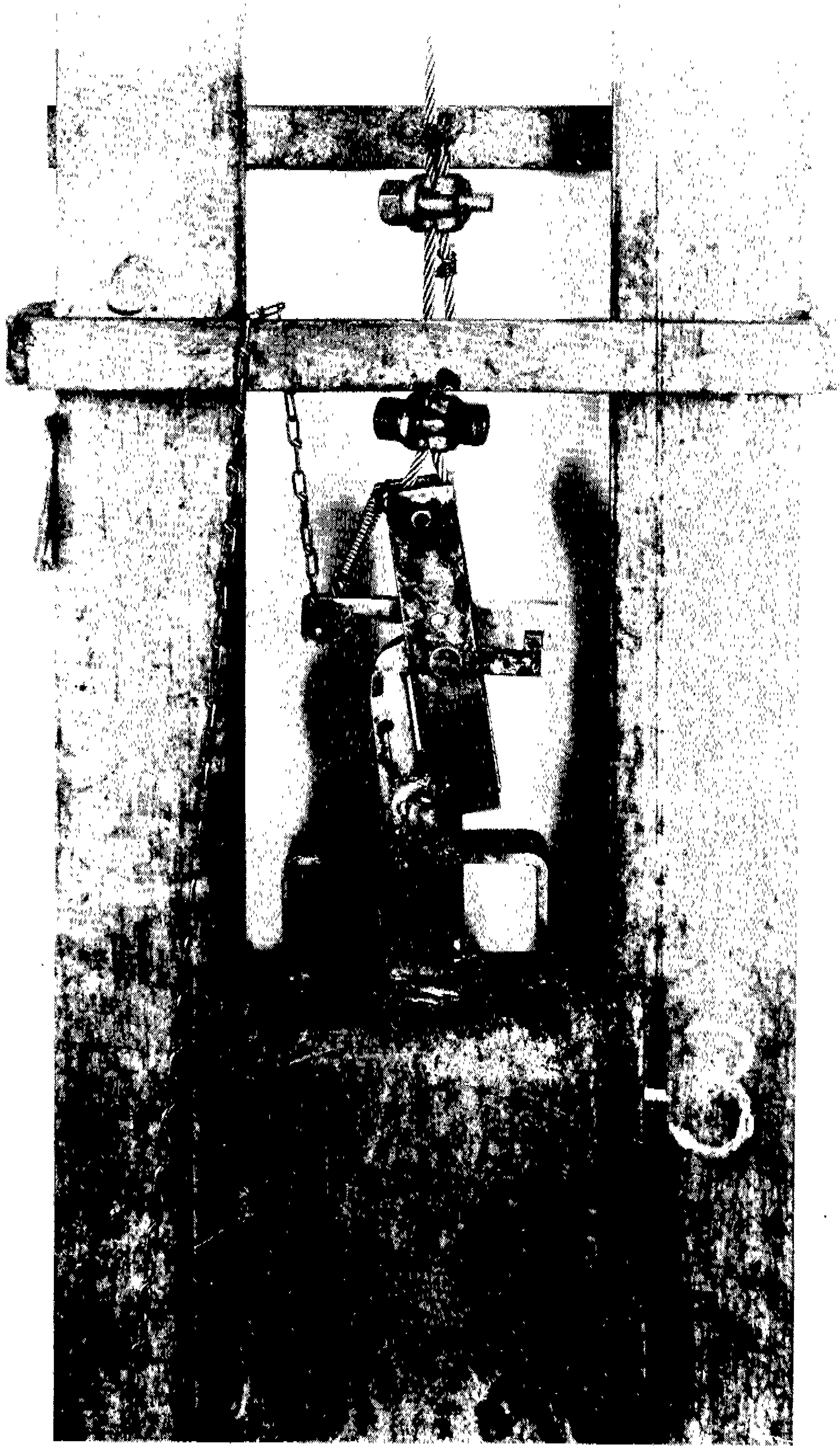

Fig. A-4. Release mechanism in support position; a downward pull on the chain causes release of the weight.

A

B

C

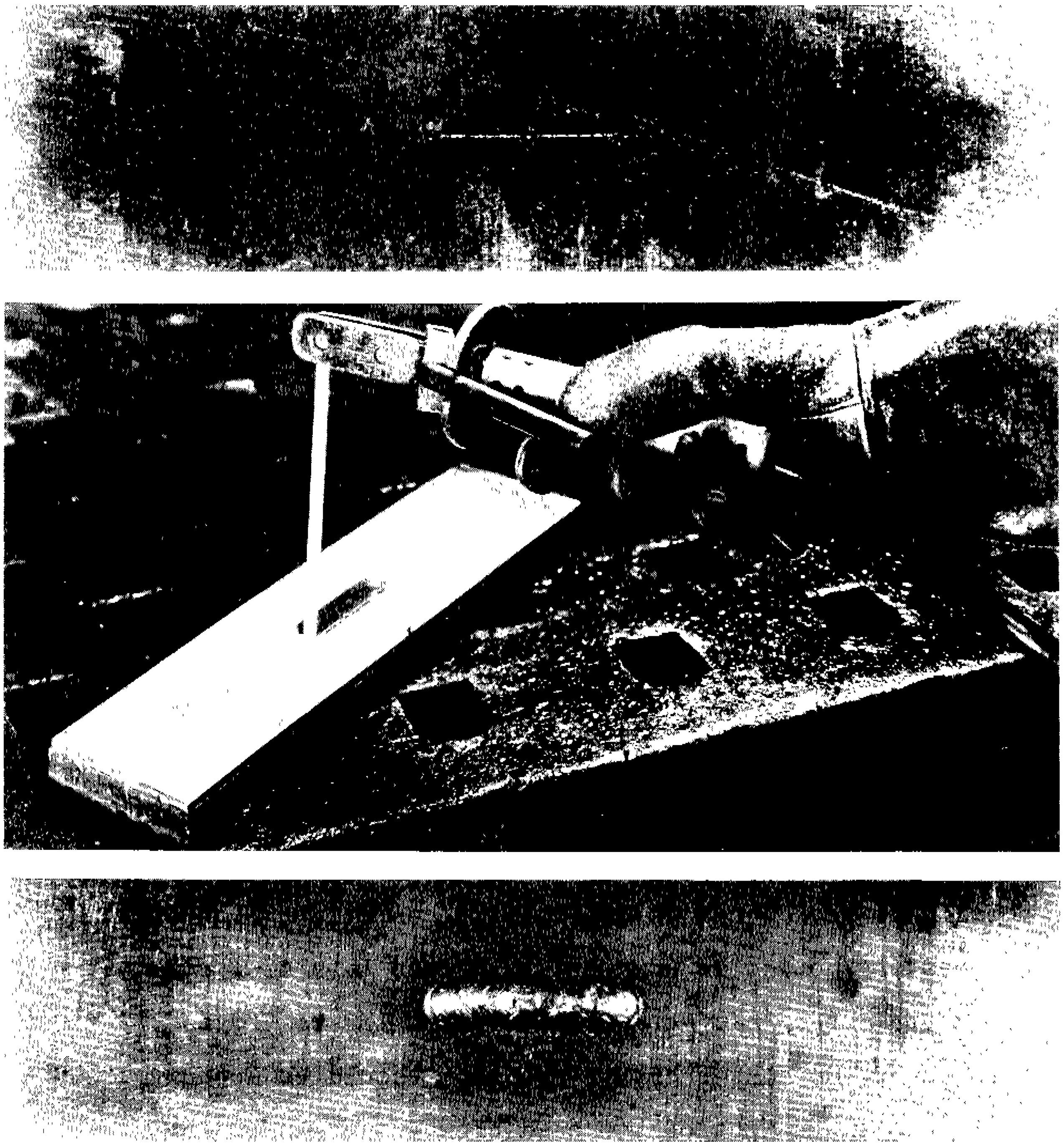

Fig. A-5. Methods of depositing weld bead.

part A shows the layout detail prior to application of the crack-starting weld bead. The three punch marks assist the welding operator in centering the bead properly on the test piece. Points A and D, each of which are 1 1/4 in. from the center point C, are the weld start locations; the terminal point for each half of the weld bead is point C. In lieu of the punch layout method for preparing the specimen, an alternative system which in many respects is more desirable can be used. A copper template, Figure A-5, part B with an elongated slot at the center is used to locate the weld bead; the same welding sequence is employed.

Murex Hardex 25, 3/16-in. diameter electrode, is employed to deposit the weld bead. The deposited weld metal is extremely brittle to temperatures as high as 400°F, which makes this material well suited for the intended purpose of crack initiation. The bead appearance is determined by the amperage, arc-voltage, and speed of travel used; 180 to 200 amperes, a medium arc-length, and a travel speed which will result in a moderately high-crowned bead have been found to be suitable conditions. An oscillating or weaving motion is unnecessary, since this electrode naturally deposits a bead having a width of from 1/2 to 5/8 in. The height of the center crater position should be approximately equal to the height of the bead crown, but any deficiency observed after cleaning the weld can be corrected by adding more metal to the crater depression. The finished crack-starter weld is shown in Figure A-5, part C.

The final preparation of the specimen consists of notching the deposited weld at the center as shown in Figure A-6. A variable speed, flexible-shaft machine is used for this purpose. A thin, 1-in. diameter abrasive disk (Ticonium separation disk) on the extended hand-controlled shaft is used for the grinding operation. To reduce abrasive wheel breakage, it is essential that light pressure and a high rotating speed be maintained during this operation. The shaft extension consists of a 1/4-in. rod approximately 10 in. long revolving in a lubricated brass ferrule which permits a hand-grip for easy control and results in a notch which is normal to the surface of the specimen. The abrasive disk is retained on the end of the shaft by means of a small machine screw.

The depth of the notch is not maintained at a specific dimension. Instead of measuring the depth of the notch referenced from the crown of the weld, the thickness of the remaining weld under the notch has been arbitrarily standardized at .070 in. with a plus .010-in. tolerance. The .070-in. thickness is maintained across the width of the weld. This is easily accomplished by a slight back and forth motion of the cutting disk.

Figure A-7 illustrates the method for measuring the thickness of weld metal at the bottom of the notch. The adjustable dial gauge with bridge support is used in the following manner: (1) the dial is adjusted to the zero setting while resting in

Fig. A-6. Notching of weld bead.

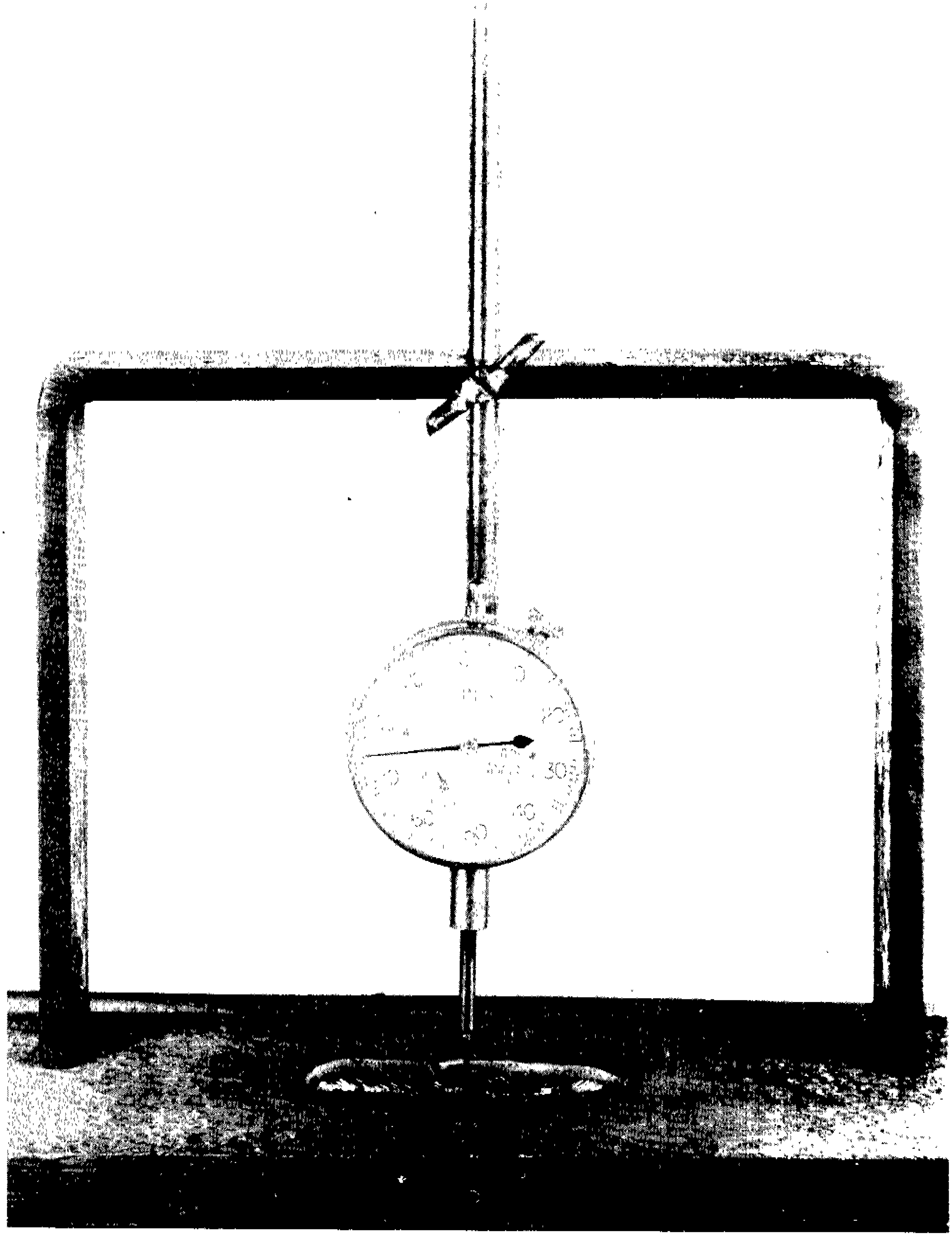

Fig. A-7. Thickness gauge.

position on the specimen so that the pointer contacts the plate surface; (2) the bridge is moved to a location directly over the weld with the pointer resting in the notch; (3) the dial now reads the thickness of weld metal under the notch. With experience in the preparation of a few specimens, the instrument needs only to be used in the final checking of the finished notch. Actually, the height of the remaining weld metal is not critical--all that is necessary is to insure that the notch is not cut so as to contact the plate.

To facilitate the alignment of the specimen on the anvil of the drop-weight machine, a line is scribed (a yellow wax pencil is suitable for this purpose) on the unwelded surface opposite to the notch. When the specimen is placed on the anvil for testing, this scribed line serves as reference mark for aligning the notch directly under the impact point of the tup, Figure A-8. Alternately, a scribed line located and referenced as shown in Figure A-9 may be used.

TESTING PROCEDURE

Figure A-10 shows a system for cooling or heating the test specimens to the desired testing temperature. Each plywood box contains a cylindrical, light-gauge metal tank which has been surrounded with 4 in. of vermiculite insulation. The tall, perforated-metal baskets are filled with pieces of dry ice and immersed in and out of the denatured alcohol bath which

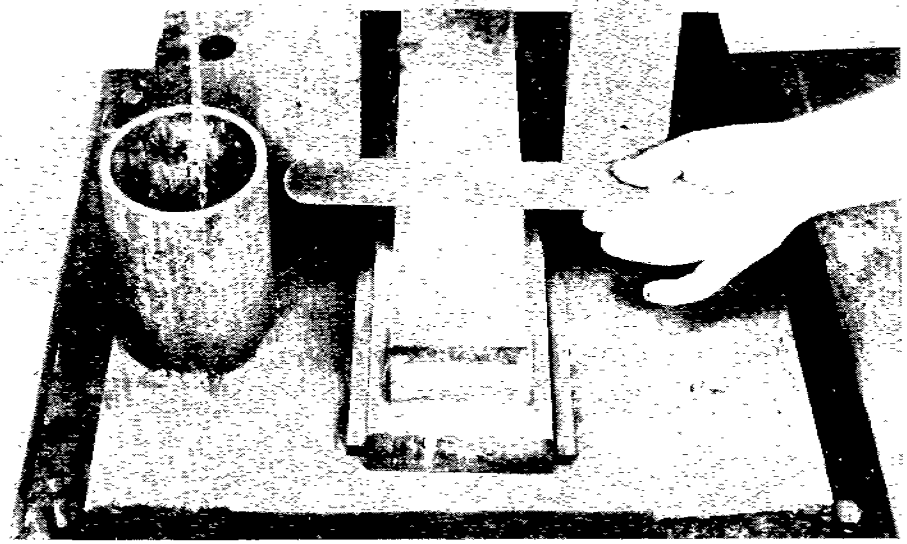

Fig. A-8. Alignment by center-scribed line.

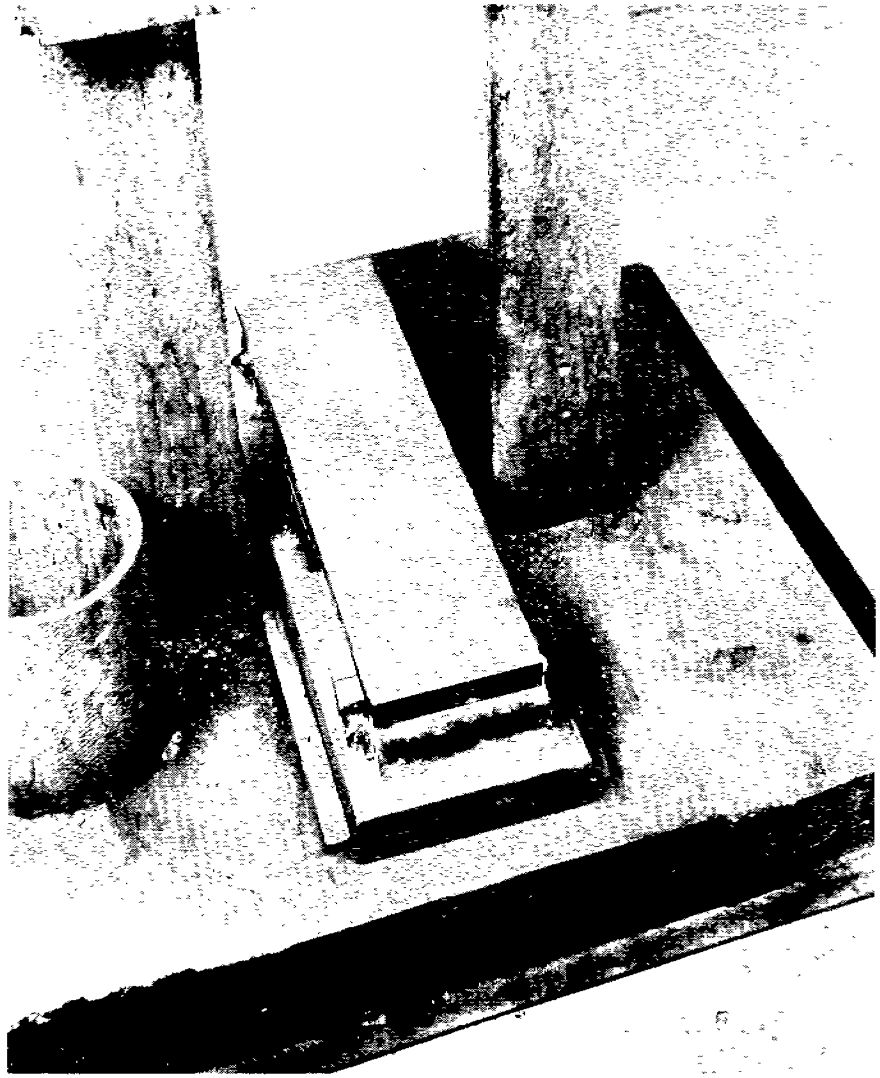

Fig. A-9. Alignment by reference mark at support position.

Fig. A-10. Equipment for cooling or heating test specimens.

covers the specimens (as many as eight to ten specimens of various materials may be cooled at the same time). Adjustment of the temperature may be made during the 30- to 45-minute hold period required for equalization of the specimens. The combination of a multi-point temperature recorder and thermocouples is a convenient and accurate method of temperature recording; however, immersion thermometers may also be employed. Testing temperatures as low as -100°F can be attained with this or similar equipment. Temperatures above the ambient are attained by means of immersion heaters in water or light oil depending on the temperature. Approximately ten seconds elapse between removal of the specimen from the bath and the completion of testing. This delay does not significantly affect the temperature of the specimen.

The usual test sequence is as follows: (1) estimate the approximate fracture temperature, then test in 20°F steps (0°, 20°, 40°F would be a good series for a mild steel). (2) when the approximate fracture temperature is established (assume specimens at 0° and 20°F broke but at 40° did not) test in duplicate in 10°F intervals above the highest fracture temperature, i.e., +30° and +40°F for this example. It will be found that initially six to eight specimens are required; with experience it is possible to cut the number to a minimum of six. If material is not sufficient, ends may be welded to samples as small as 3 1/2- by 4-in., Figure A-11. By this procedure

Fig. A-11. Test of small sample by means of welded ends.

three tests may be made from one 3 1/2- by 14-in. test sample, i.e., after the first test the two halves are assembled as shown in the figure, and two more tests are made.

The design of the machine permits varying the height from which the weight is dropped. This is necessary for testing materials of various thicknesses and tensile strengths. The height at which the weight should be set for a specific material is determined by preliminary room temperature tests using various heights and observing the minimum height which develops full deflection of the specimen as indicated by contact against the stop block of the anvil. After determining the minimum height, an additional one or two feet are added, and this height is used for subsequent tests at all temperatures. Since the height which is necessary to produce contact with the stop is directly related to the tensile strength of the material, it follows that any material of similar strength can be tested in a like manner provided its nominal thickness is the same. It is suggested that a height record of test materials be maintained as a guide for testing similar materials. Table 1-A provides a listing of heights used from various materials.

TABLE 1-A

DROP HEIGHTS (60# WEIGHT) FOR VARIOUS MATERIALS--12-in. SUPPORT SPAN

Materials	Tensile Strength (lb. per sq. in.)	Thickness	Height
Mild Steel	60,000	1/2 in.	6
		3/4 in.	8
		1 in.	10
Alloy Steel	125,000	1/2 in.	8
		3/4 in.	10
		1 in.	14
	150,000	1/2 in.	10

High strength materials in particular often fly outward on breaking. A removable metal guard shown in Figure A-12 serves as protection from flying pieces.

Fig. A-12. Back view of protection guard--the front remains open to the operator.