SSC-80

AN INTERPRETIVE REPORT ON THE METALLURGICAL AND ECONOMIC ASPECTS OF SHIP STEELS AND THEIR RELATION TO SHIP FAILURES

by

William J. Harris, Jr. and Clyde Williams

SHIP STRUCTURE COMMITTEE

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:

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

August 15, 1956

Dear Sir:

As part of its program to improve hull structures of ships, the Ship Structure Committee has sponsored an interpretive study of the quality, availability, and possibilities for improvement of steels currently used for ship construction. Herewith is the Final Report, SSC-80, of this study, entitled "An Interpretive Report on the Metallurgical and Economic Aspects of Ship Steels and their Relation to Ship Failures," by William J. Harris, Jr., and Clyde Williams.

This project has been conducted under the advisory guidance of the Committee on Ship Steel of the National Academy of Sciences-National Research Council.

Any comments regarding this report should be addressed to the Secretary, Ship Structure Committee.

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

Yours sincerely,

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

Serial No. SSC-80

Final Report
of
Project SR-135

to the

Ship Structure Committee

on

AN INTERPRETIVE REPORT ON THE METALLURGICAL AND ECONOMIC ASPECTS OF SHIP STEELS AND THEIR RELATION TO SHIP FAILURES

by

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transmitted through

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AN INTERPRETIVE REPORT ON THE METALLURGICAL AND ECONOMIC ASPECTS OF SHIP STEELS AND THEIR RELATION TO SHIP FAILURES

INTRODUCTION

Catastrophic failures of all-welded merchant ships and tankers occurred unexpectedly during World War II. In retrospect it can be seen that a long series of earlier brittle failures of steel structures gave notice of the difficulties that might be encountered in all-welded ships. In 1942, however, no summary of previous failures was available.

The failure of a ship on the ways and of others tied up in port caused concern and even doubt as to whether the welded ship program should be continued.

Urgent engineering studies were initiated by a Board of Investigation appointed by the Secretary of the Navy. In 1946 the Board completed its work and recommended a continuing study of the problem of brittle fracture in ships. Its successor was the Ship Structure Committee convened by the Secretary of the Treasury. Advisory services on the metallurgical aspects of ship failures were requested from the National Academy of Sciences-National Research Council. Accordingly, the latter organization formed the Committee on Ship Steel to assist the Ship Structure Committee in planning and maintaining a research program in the field of ship steel metallurgy.

These groups have made possible continuous attention to the brittle fracture problem in ships since 1942. As a result of their very effective coordination of a variety of programs, more is known about the category of ship failures than about any other involving large structures. Under the Ship Structure Committee, studies have been made of the properties of plate taken from failed ships. Investigations of the properties of ship steel now being produced are continuing. Many research projects on the metallurgical and mechanical factors which influence the brittleness of steel have been completed. Others are still being prosecuted.

Much progress has been made toward an engineering solution of the problem of brittle fracture in ships. Design and fabrication practices that can reduce brittle fracture are now incorporated into new ship construction. Improved steels under American Bureau of Shipping specifications have been in use since 1947 and further improvements are now being made. Completed research projects have pointed the way toward control of the notch toughness of ship plate. It therefore seems an appropriate time to establish the current status of research and of shipbuilding practice relating to the reduction of brittle behavior of plating in ships.

This interpretive report will consider several aspects of the brittle fracturing problem in ships:

1. The factors that affect the brittle fracturing of ships.
2. The feasibility of eliminating the tendency toward brittle fracture in ships.

3. The relationship between the brittle fracturing of ships built during a future emergency and the notch toughness of the steel used, considering the use of World War II, current, and proposed alternative steels.

4. The economic and technical factors that affect the production of ship steel of adequate notch toughness to eliminate brittle fractures.

This report is a presentation of the salient findings, conclusions, and recommendations. Appended to the report are Exhibits in which more detailed accounts of the supporting information are presented.

This report was prepared under the sponsorship of the Ship Structure Committee and with the direct advisory guidance of the National Academy of Sciences-National Research Council's Committee on Ship Steel.

A. CONCLUSIONS

1. The consequences of ship failures during World War II due to brittle failures were so grave that every practical step should be taken to eliminate the possibility of their recurrence at present and during any future emergency.

2. A combination of three conditions is required for brittle fractures of ships in service:

a. The existence of stresses from all sources probably in excess of about 10,000 psi.*

b. The presence of a severe notch introduced by unsatisfactory design details or poor welding practices.

c. The use of ship steel with low notch toughness at the operating temperature.

3. It is not feasible to operate ships at stress levels from all sources that are low enough to eliminate failures.

4. A substantial reduction in failure rate has been achieved through elimination of severe notches by improvements in design details and in fabrication practice, but complete elimination of failures by flawless design and construction does not appear to be feasible.

5. It appears that brittle fractures in ships would be virtually eliminated by utilizing steel with a mean Charpy V-notch 15 ft-lb transition temperature of 10 F and, at the same time, using good designs and fabrication techniques.

6. Ships built of plate with the low notch toughness of World War II steel will almost certainly be subject to failure due to brittle behavior (particularly if operated in a future emergency) unless there is extensive use of steel of greater

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*It has not been possible to establish the actual stress levels existing in ships at the time of failure. "Where failures have occurred under nearly static conditions, the calculated stresses resulting from weight and buoyancy distribution have been much lower than 10,000 psi, but we have never been able to determine whether there were any thermal stresses or locked-up stresses, or if so, their magnitude." (Ref. 21) notch toughness for the plating in critical locations or operational use of the ships only in tropic waters.

7. Ships built of steel made to American Bureau of Shipping specifications ABS-A, ABS-B* and ABS-C should be virtually free from service failure due to brittle behavior, even if operated in a future emergency involving a 10 F lower operating temperature than during World War II, except that some fractures may occur in the sections made of the ABS-B grade produced from 1947 to 1/31/56*.

8. Under conditions of a future emergency involving large-scale ship construction programs, ship steel will probably be restricted to semikilled grades. This will necessitate using a semikilled alternative for plates over one inch in thickness where killed steel made in conformance with ABS-C now applies.

9. A semikilled grade containing 0.20% max carbon and 1.00% to 1.35% manganese appears to be a satisfactory alternate for ABS-C steel in plates over 1 in. and at least up to 1 1/2 in. in thickness. This steel has about the greatest notch toughness that can be achieved in an as-rolled, semikilled grade made to current practice and to strength levels now specified.

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*On November 9, 1955, the American Bureau of Shipping adopted a change in the chemical composition of ABS-B steel to be effective January 31, 1956, as follows:

	Carbon	Manganese
Old requirement	0.23% max	0.60% to 0.90%
New requirement	0.21% max	0.80% to 1.10%

This change should substantially improve the notch toughness of ABS-B steel. A change in the carbon content of C steel from 0.25% max to 0.24% max was also made.

10. Although completed research points to a solution to the brittle failure problem in ship steels at current strength levels, there are important investigations in progress that should be continued. Consideration of the relation between mill practice and notch toughness may suggest other ways of achieving improvements. Basic studies of the influence of metallurgical structures on the mechanics of fracture can be expected to contribute valuable information. Studies of the notch toughness of ship steels at other levels of strength than now in use may be necessary in anticipation of the use of such materials.

B. RECOMMENDATIONS

1. A program aimed at gaining production experience with a proposed semikilled alternative for ABS-C steel should be pursued in preparation for emergency need.

2. Every effort should be made to insure an adequate supply of manganese for the production of semikilled ship steel of adequate notch toughness during a possible future emergency.

3. A continuing study should be made of the composition and notch toughness of production heats of ship steel and their relationship to mill practice in order to establish that the notch toughness of ship steel is kept under control as technological change occurs in the steel industry.

C. DISCUSSION OF SHIP FAILURES IN SHIPS BUILT DURING WORLD WAR II

Ship failures obviously involve a wide variety of incidents, including collisions, groundings, and severe storms. In World War II the catastrophic failures of welded ships associated with brittle behavior of the steel, often under what seemed to be rather normal conditions, caused widespread concern. Brittle fractures had been observed in riveted ships but, in most cases the crack progressed through not more than one plate, in many cases stopping in rivet holes or at riveted seams. In the welded ships the much more continuous structure allowed the crack to propagate through many plates until the crack was stopped by lack of energy for propagation or by some barrier such as tough steel or a structural discontinuity.

Failures due to brittle behavior in these ships were classified according to the length and severity of the fracture. Two of these classes* will be considered in this summary:

1. A Group I casualty, defined as "a ship with one or more fractures which have weakened the hull so that the vessel is lost or in a dangerous condition."
2. A Group II casualty, defined as "a ship having one or more fractures which are generally less than 10 feet long...that involve the main hull structure and are potentially dangerous."

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*The third class of failure, the Group III, includes those fractures which do not fall in Group I or Group II.

The rates of failures for various classes of ships have been reviewed in detail(2,11). In this report illustrative data are given in Table 1 for two classes of dry cargo ships, the Liberty ships and the Victory ships, and one class of tanker, the T-2 tanker. Table 1 indicates separately the Group I and II failure rates, but the discussion refers only to the combined rate.

The Liberty ships represent a design that was intended for large-scale production. Welding was necessary if the schedules were to be met. The first all-welded Liberty ships suffered Group I and Group II casualties at a rate of about 200 per 1000 ship years of service. By redesigning the hatch corners and other critical locations to reduce local stress concentrations and by improving the quality of the welds, this failure rate was reduced to about 35 per 1000 ship years of service.

The Victory ships represented a later design and a faster type of dry cargo vessel. They were also nearly all-welded; but since they were designed after the initial Liberty ship failures, they incorporated improved details and fabrication practices from the beginning. As shown in Table 1, they had a Group I and Group II casualty of failure rate of about 7 per 1000 ship years of service.

The all-welded T-2 tankers built in large quantities during the war incurred about 65 Group I and Group II casualties per 1000 ship years of service early in the war, as shown in Table 1.

TABLE 1. RECORD OF STRUCTURAL PERFORMANCE OF VARIOUS TYPES OF WELDED SHIPS (FROM START* TO MARCH 31, 1953)

Type	Ship Years of Service	Group I Casualties	Group I Casualties per 1000 Ship Years	Group II Casualties	Group II Casualties per 1000 Ship Years	Combined Group I and II Casualty Rate
EC-2 (Liberty Ship) 1. All-welded with original details	2100	88	41.8	320	153.7	195.5
2. All-welded Seams, improved details and some riveting	7303	40	5.5	214	29.3	34.8
VC-2 (Victory Ships)	2695	4	1.5	16	5.9	7.4
T-2 (Tanker) 1. All welded	1483	28	18.9	69	46.4	65.3
2. All-welded with riveted straps	2064	25	12.1	94	45.5	57.6

*Records cover service performance from date at which first vessel of each group was placed in service.

Some modifications were then introduced, including the addition of riveted straps that interrupted the continuity of the structure and were expected to serve as crack arrestors. Group I and II casualties in the modified ships fell only slightly--to about 58 per 1000 ship years of service. However, the severity of cracking was somewhat reduced by the crack arrestor.

It is important to note that the failure rates of the two classes of dry cargo ships were reduced drastically without resorting to improvements in steel toughness. Much less success was achieved in treating the tanker failure problem.

The over-all cost of the failures due to brittle behavior and the corrective measures taken to reduce the rate of failure was nearly $100,000,000 expressed principally in World War II dollars, as shown in Table 2.

None of the intangible factors, such as loss of life, loss of cargo, interruptions in the supply line, and lowering of the morale of operating personnel can be expressed in dollars, but their net effect was of great importance. Brittle fractures in dry cargo ships and tankers were not eliminated during World War II.

D. DISCUSSION OF THE COMPLETE ELIMINATION OF BRITTLE FRACTURES IN SHIPS DURING A FUTURE EMERGENCY

There is much justification for the adoption of practices and materials that will eliminate the service failure of ships due to brittle fracture under the usual conditions of service that could be anticipated in a future emergency. A recurrence

TABLE 2. SUMMARY OF COST OF SHIP FAILURES

1943 to 1954

Casualties - Group I	$ 40,000,000
Casualties - Group II	5,000,000
Casualties - Group III	1,000,000
Improvement in Design Details and Reinforcement of Ships	46,000,000
Research Program	4,000,000
Total	$ 96,000,000

of failures which would result in lost lives, lost ships, lost cargoes, and delays in meeting logistic schedules could have a very serious impact on morale since there has been enough time since World War II for development of a solution. The need for corrective action in the face of an outbreak of failures would demand the attention of many responsible people whose efforts could be used to better advantage.

The seriousness of the ship failure problem was enhanced by the impact of the combined Group I and II casualty rate. Even if the rate of failure of ships in any future emergency were quite low or limited to Group II casualties, any recurrence would raise apprehensions about all ships in the light of past experience. To insure against a repetition of loses, expenditures for repairs, and the many delays and other detrimental effects, action should be taken to insure against a repetition of ship failures in a future emergency, particularly in the Group I and Group II categories.

E. GENERAL DISCUSSION OF CIRCUMSTANCES SURROUNDING BRITTLE FRACTURES OF SHIPS

It is now clear that brittle fractures in ships occur when three conditions exist[6]:

1. First, a sufficiently high stress must be present. The rate of failure in World War II was many times as great under the stresses imposed in heavy seas than under the lower stresses in port. However, even in port the low applied stresses, perhaps in combination with thermal stresses resulting from differential air and water temperatures, solar heating, or other causes, and residual* stresses introduced during fabrication, were great enough to cause some failures.**
2. Second, a notch serving to concentrate the stresses must be present[23]. Notches that gave trouble took the form of design features such as square corners in hull openings, and fabrication defects such as cracks or voids in poor welds. Some failures were associated with a defective weldment or an arc strike, often act-

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*Residual stresses are stresses which exist in a structure at uniform temperature when no outside force is acting.

**See Exhibit I.

ing in conjunction with a structural discontinuity.

3. Third, the steel must have low notch toughness at the operating temperatures. To avoid failure, the steel must be able to deform rather than to crack at the root of the notch at service temperatures[9,10,19]. A measure of this ability of steels to deform rather than to crack is often indicated by the term "notch toughness". The level of notch toughness of ship steels* that failed in service is known with a good degree of precision.

The Feasibility of Eliminating Brittle Fractures in Ships by Lowering Stresses. To design a ship for operation at a stress level lower than the level required for brittle fracturing appears to be impractical.** It would be necessary to increase the thickness of structural plates in order to reduce the design stress level below this value. Special attention would be required to compensate for the effects of structural discontinuities and residual stresses. Thicker plates would increase the tonnage of plate required for ships and reduce the pay load. Furthermore, the possibility of exceeding the design stresses would always exist. From experience in World War II,

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*Merchant ships and tankers used during World War II were constructed of ship steels in the range of below 1/2 in. up to 1 1/2 in. in thickness, with the majority in the range of 3/4 in. to 1 in.

**See Exhibit I.

it is evident that wartime operations can lead to unusual stresses from heavy deck loads, poor ballasting, and other circumstances beyond the control of the designer.

Reducing the stress level below the value at which brittle cracks will propagate does not appear to be an acceptable solution to the ship failure problem.

The Feasibility of Eliminating Brittle Failures in Ships by Eliminating Notches. Brittle failures generally require the presence of sharp notches.* In ships two kinds of notches--those introduced by design and those resulting from poor welding--often are superimposed. The design of the original hatch corner in the Liberty ship was undesirable from the standpoint of stress concentrations. It also was difficult to weld so as to avoid defects.

After critical study, the hatch corners were redesigned by rounding the corners, adding doubler plates, and making other improvements. As soon as it was found that a cut-out in the sheer strake was a source of many failures, a design change was made in production. These changes and others were incorporated in service as soon as possible.

In an over-all investigation of the failed ships, many examples of poor welding were found. Fractures in welds that were examined at the National Bureau of Standards occurred only where very evident welding defects were present[23]. In the rapid expansion of facilities for ship construction, inadequate

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*For a comprehensive review, see Ref. 19.

attention had been given in some cases to the training of welders and to the welding practices. Full appreciation of the importance of strict adherence to certain fundamentals of good welding practices had not been acquired. To overcome these difficulties, additional instruction was provided for welders and inspectors. Efforts were exerted to raise the standards in qualifying tests. Inspection procedures were made more rigorous; and, as time went on, the quality of welds improved.

Despite the improvements in design and in fabrication practices, it is not likely that ships can ever be entirely free of notches. Even if the original design and fabrication are perfect, alterations and maintenance work may introduce notches. Attachments added for cargo storage or plate handling are welded and removed without particular concern about their possible role as crack initiation points. Many ship failures can be traced to repair work[23].

The incidence of brittle failures in service has been reduced by improvement in design and fabrication practices. However, complete elimination of notches is virtually impossible in original construction, and ships are often modified and altered while in service. Reliance on flawless designs and fabrication practices as a complete solution to the ship fracture problem in the future does not appear to be warranted.

The Feasibility of Eliminating Brittle Fractures in Ships by Improving the Notch Toughness of Ship Steel.

a. The Notch Toughness of World War II Ship Steel.

When ship failures due to brittle behavior first occurred, it was generally assumed that the steel had ductility properties below the specification values. However, samples of the failed plates conformed in every respect to the applicable specifications. They had an average yield strength of 35,000 psi, a tensile strength of 62,000 psi, and an elongation in 2 in. of 35 per cent in a standard tensile test. Inspection of the fractured plates revealed that very little plastic deformation had occurred and that failures were brittle. This brittle behavior did not seem compatible with the good ductility of the plate material in the tensile test.

In the course of the study, tests were made of the notch toughness of the steels, a property not covered by specifications.* The notch toughness was evaluated over a range of temperatures by the Charpy V-notch impact test.** The energy required to break the bar decreased markedly as the testing temperature was lowered. This drop in energy was a result of the change of mode of fracturing from shear (ductile behavior) to cleavage (brittle behavior). It is now known that this is characteristic of all ferritic steels[19]. However, there can be considerable difference in the temperature range where the brittle behavior is

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*See Exhibit II.

**This test is made on a carefully machined specimen about 0.4 in. square and 2 in. long. A V-notch is machined in one face. The specimen is supported at both ends and broken by a swinging pendulum which strikes opposite the notch.

observed. To facilitate analysis of the results, the temperature at which the bar absorbed 15 ft-lb of energy while fracturing was found for each plate tested. The 15 ft-lb Charpy V-notch transition temperature of steel from failed ships ranged from about 0°F to about 140 F with an average value of 70 F. Typical transition curves are shown in Fig. 1.

The fractured plates were divided into three groups: plates containing the source of the fracture, those fractured through, and those containing the end of the fracture*[7,8]. A comparison of the distribution of transition temperatures estimated for all World War II ship steels and those of the source plates is shown in Fig. 2.**

All plates which contained the source of fracture had transition temperatures of 60 F or higher. No plate containing the source of fracture absorbed more than 11.4 ft-lb at the failure temperature, while most of the end plates containing the end of the fracture had higher notch toughness at the failure temperature.

Williams[20] has made a very detailed analysis of the reported conditions under which the ship fractures occurred. It has been possible to subdivide the general source, through, and end categories by taking account of special circumstances. This refinement has indicated that a brittle crack can be

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*See Exhibit III

**See Exhibit II

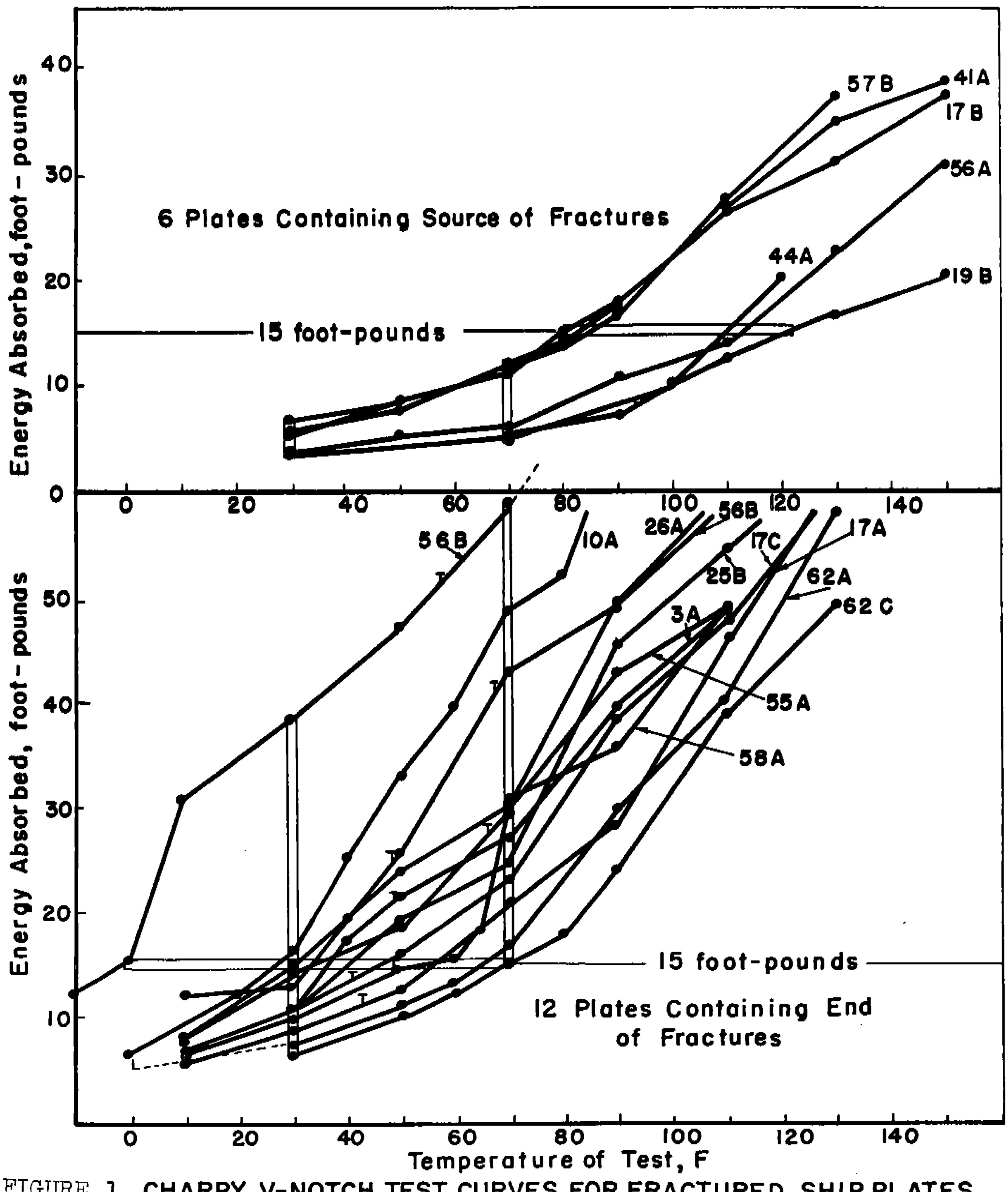

FIGURE 1. CHARPY V-NOTCH TEST CURVES FOR FRACTURED SHIP PLATES, 0.44-0.69 INCH THICKNESS

Horizontal bars indicate ranges of 15 ft-lb transition temperatures. Vertical bars indicate range of energy absorbed in tests at 30 F and 70 F. Temperatures at the time of the ship failures are indicated by the letter "T" on the curves(7)

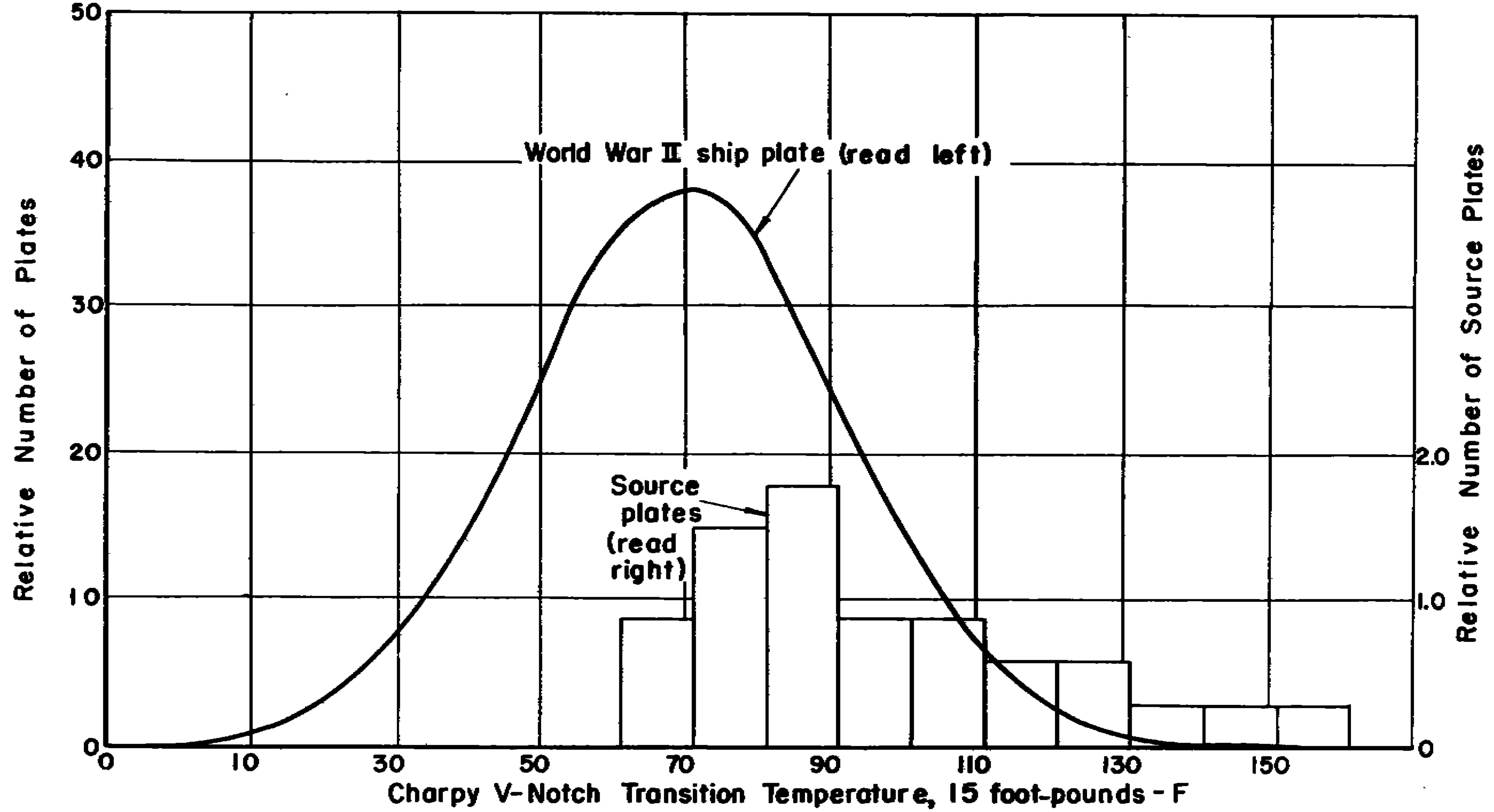

FIGURE 2. DISTRIBUTION OF TRANSITION TEMPERATURE OF WORLD WAR II SHIP PLATE AND SOURCE PLATES
Note that scale for source plate distribution is 10 fold that of the distribution of all plates

initiated only in plate of quite low notch toughness. However, if a crack initiates in a flaw and runs for a very short distance, it will then propagate through plates of greater notch toughness. In ships brittle fractures were stopped by plates of still greater notch toughness, although many cracks stopped because of structural factors or favorable stress conditions. These observations are consistent with studies made by Pellini and Puzak[9,10].

For purposes of the present study, the subcategories used by Williams have been recognized. However, all the source plates have been considered in the statistical analyses, including both the subcategory for fracture under normal conditions and the subcategory for fracture under severe conditions. Ships may be operated under severe conditions. It is therefore not realistic to be concerned only with what appears to be a "normal" circumstance.

The significance of notch toughness in relation to brittle fracture is substantiated by an analysis of those ten cases in which fracture source* and fracture end** plates were available from the same casualty[20]. In all cases the source plate had the higher transition temperature as shown in Fig. 3.

Based on all of these observations, a statistically significant correlation was established relating the notch toughness of plates measured in the laboratory to their brittle behavior in service.

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*Plate in which the fracture started.

**Plate in which the fracture stopped.

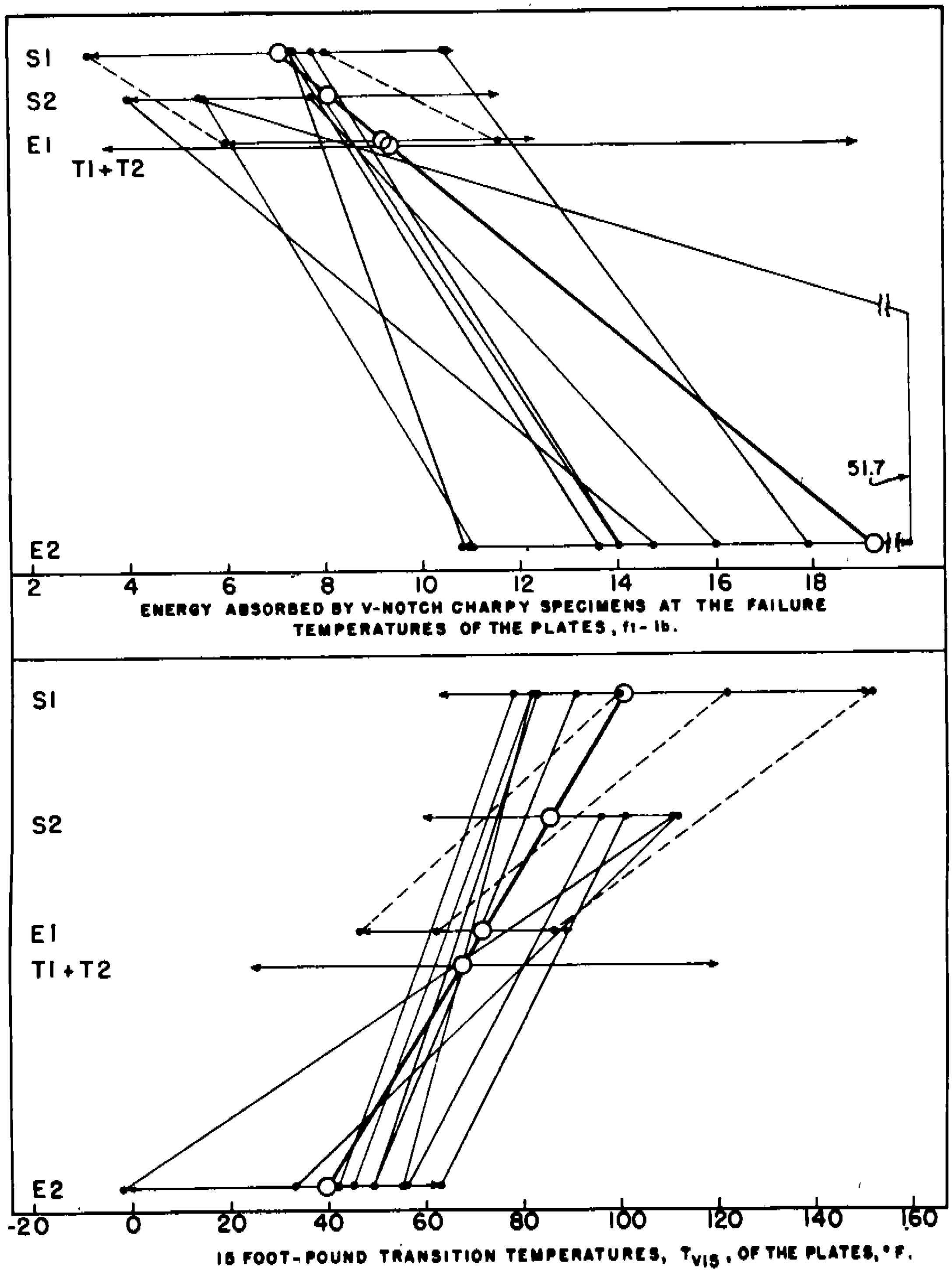

Fig. 3. **Notch sensitivity of source and end plates from same ship, compared to ranges and average values for the different fracture categories.** The fracture categories are spaced vertically so that the average values (large circles) fall on the heavy line. Other diagonal lines indicate relative values for pairs of source (S1 or S2) and end (E1 or E2) plates from the same ship. Horizontpl arrows show the range of values for all plates in each category.

b. Estimate of the Effect on Ship Fracture of using Steel of Lower Transition Temperature.

Since brittle failures in ships have been shown to occur only in plate that has low notch toughness at the operating temperatures, it is reasonable to assume that use of steel with greater notch toughness would reduce failure rates. Such steel represents material of a lower transition temperature. The extent of reduction necessary to eliminate brittle fractures in service can be estimated by certain rather straightforward statistical analyses described in Exhibit IV.

The reasoning behind this approach is illustrated in Fig. 4, which shows the distribution of transition temperature values for World War II ship steel, for World War II source plates, and for ABS-B steel, a post-war ship steel of improved notch toughness.

The ratio of the number of actual source plates to total plates of a given transition temperature decreased from quite a high value at 130 F to 0 at 59 F as can be seen in Figs. 2 and 4. A very small percentage of all of the ABS-B steel would have been potential source plate material under World War II conditions, as shown by the small shaded overlap in Fig. 4. All of these potential source plates in the post-war steel population are in the region of a low ratio of actual failures to total number of plates.

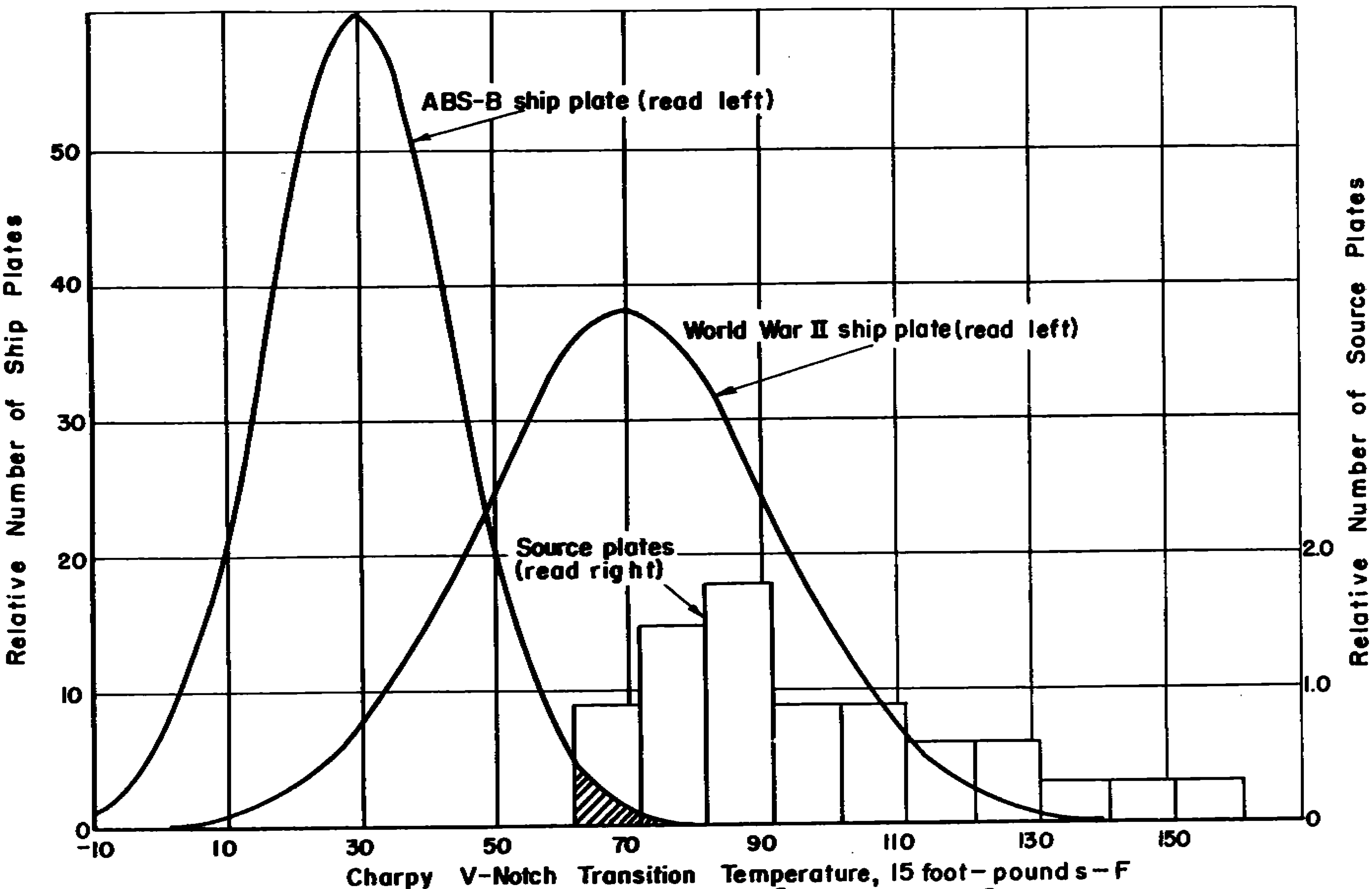

FIGURE 4. DISTRIBUTION OF TRANSITION TEMPERATURES OF $\frac{3}{4}$-INCH ABS-B, $\frac{3}{4}$-INCH WORLD WAR II PLATES AND WORLD WAR II SOURCE PLATES
Note that scale for source-plate distribution is 10 fold that of the distribution of all plates

From these considerations, as shown in Exhibit IV, the ABS-B steel would have had only about 5 per cent of the failure rate of World War II steel. This procedure of analysis can easily be used to estimate the failure rate with steels of other mean transition temperatures. While experience in World War II was largely with steels in the range of 1/2 to 1 in. in thickness, it appears reasonable to extend this estimate up to at least 1 1/2-in. plate. Fig. 5 shows that the failure rate would fall to a negligible percentage of the World War II rate if steel of a sufficiently low transition temperature were used. Some care must be taken in the application of this observation. Puzak and Pellini[9] have demonstrated that the N.R.L. crack starter test may reflect severe service more accurately than the Charpy V-notch test. This test indicates that for various classes of steel there is a different Charpy value that corresponds to brittle behavior in service. However, within the grades of semikilled steel of interest in cargo ship construction, it appears that a mean 15 ft-lb Charpy V-notch transition temperature of 10 F offers good assurance of freedom from brittle behavior. <u>On this basis, it appears that service failures can be virtually eliminated by use of steel with a mean Charpy V-notch 15 ft-lb transition temperature of 10 F or lower. However, as indicated previously, there is good reason to continue efforts to reduce the number and severity of notches</u>

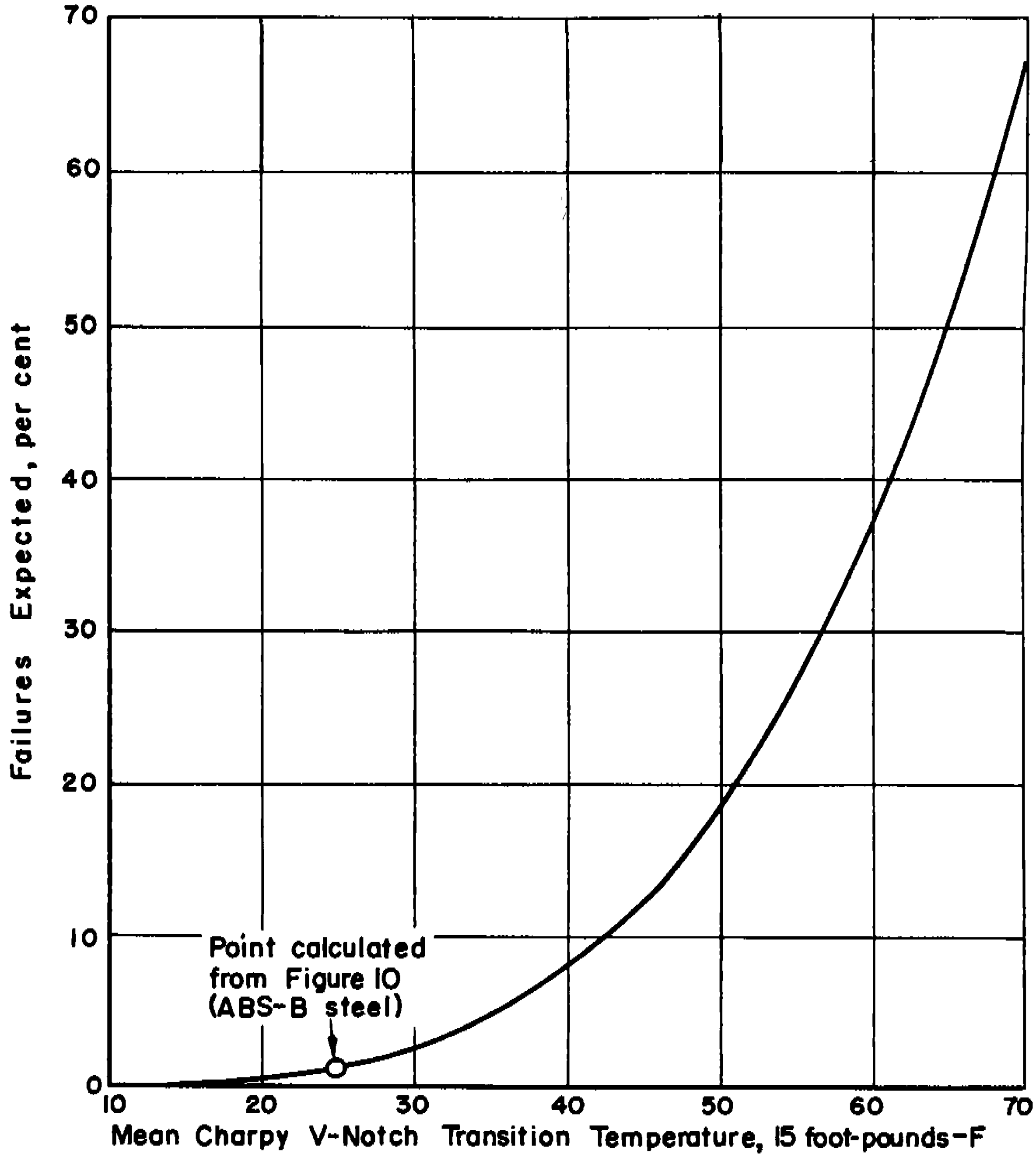

FIGURE 5. FAILURE EXPECTED WITH HULL PLATE HAVING MEAN TRANSITION TEMPERATURE BELOW THAT OF WORLD WAR II HULL PLATE, EXPRESSED IN TERMS OF PERCENTAGES OF WORLD WAR II FAILURES (See Exhibit IV)

as well as to improve the notch toughness of the ship steel in arriving at the desired goal of complete elimination of brittle fractures of ships.

F. IMPROVEMENT IN NOTCH TOUGHNESS OBTAINABLE BY CHANGING GRAIN SIZE OR SHIP STEEL COMPOSITION

There have been many comprehensive studies of the relationship of metallurgical variables and transition temperature of steels suitable for ship plate that suggest ways of achieving the desired level of transition temperature.

It is possible to reduce transition temperature of steel by achieving a finer ferrite grain size as shown in Table 3. Such a reduction in grain size can be attained by subjecting the plate to heat treatment after it is rolled. A simple treatment which will effect such a change in grain size is called normalizing and involves heating a plate to a suitable temperature and air cooling it. However, the ferrite grain size of ship steels as now produced is quite small, and the average improvement by normalizing is limited to a transition temperature reduction of 20 to 45 F.

Another means of reducing the grain size and perhaps effecting other useful changes in structure involves lowering the temperature of final rolling. This practice necessitates special control over the temperature of the original billet and the rate of rolling. Some foreign mills are being specially adapted for this practice. In the United States, no mill is now in a position

TABLE 3. RELATION BETWEEN COMPOSITION AND GRAIN SIZE AND TRANSITION TEMPERATURE OF STEEL

Factor	Change in 15 ft-lb Charpy V-Notch Transition Temperature Per Unit Change in Factor
Carbon Content	+300 F per increase of 1 per cent
Manganese Content	-100 F per increase of 1 per cent
Phosphorus Content	+1000 F per increase of 1 per cent
Silicon Content	-300 F* per increase of 1 per cent
Grain Size	-22 F** per increase of 1 ASTM grain size number

*Up to about 0.2 per cent silicon. Above this level, the effect may be reversed

**Based on Charpy keyhole, mid-span transition temperature.

to control finishing temperature in order to reduce transition temperature under conditions of high output as would be anticipated during an emergency.

It has been found that within the ranges of composition applicable to ship steels the 15 ft-lb Charpy transition temperature is altered by composition changes as follows:

(a) Raised by increasing carbon content

(b) Lowered by increasing manganese content

(c) Lowered by increasing silicon content in the range of interest in ship steels.

(d) Raised by increasing phosphorus content

These effects are summarized in Table 3.*

There are practical limits on the extent of variation in composition that can be introduced. Ship steel is required to have tensile strength between 58,000 psi and 71,000 psi. If the steel falls below this strength, plates may be subject to buckling failures in service; if it goes over, fabrication problems may be encountered. The specified range of strengths can be achieved in ship steel by maintaining a balance between carbon and manganese, since an increase in either will raise strength. For greatest notch toughness the manganese is raised, and the carbon is lowered. The upper limit of the manganese content imposed by welding considerations is about 1.35%. This value is also about the upper limit that can be accepted in semikilled steels with acceptable production yields. For satisfactory production a corresponding manganese range should be from about 1.00% to 1.35%.

The carbon content should not exceed about 0.20% for acceptable notch toughness, and the range necessary for production control is provided by specifying an acceptable maximum value.

Two 25-ton heats of a semikilled grade in the range of 0.20% max carbon and 1.00% to 1.35% manganese were made. The transition temperatures were at the values predicted as shown in

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*See also Exhibit V.

Table 4, and other characteristics were satisfactory.[1]

The phosphorus content of ship steel is kept at low levels and cannot be lowered significantly. Therefore, it is not a useful element to consider in adjusting transition temperatures.

In semikilled steels of maximum manganese content, the silicon content must be kept to a minimum and cannot be raised significantly as a means of lowering transition temperature. The increased silicon content in killed steels helps to contribute to their lower transition temperature range.

Recently Williams[23] has confirmed the fact that additions of manganese lower transition temperature. However, he finds that manganese has very little effect on the probability that a plate will be a source of fracture in a ship. Williams concludes that the effect of manganese on fractures in service is "much smaller than its effect on the V-notch transition temperature". He points to the findings of Pellini and Pellini and Puzak[9,10] for confirmation of these results. Their results suggest that the Charpy V-notch transition temperature may be lower than the drop-weight transition temperature for plates of higher manganese contents. As applied to probable service behavior, their results could be interpreted to suggest that manganese has a smaller effect on service performance than on Charpy V-notch transition temperature. Nevertheless, consideration must be given to the validity of arguments in this report based on the relation between composition and service behavior. It appears that the observations need be tempered only slightly by Williams' findings. There is complete agreement that the carbon content of ship steel should be at the lowest practical level. At present there is no serious move under way to alter the strength characteristics of ship steel; consequently, the manganese must be raised proportionately as the carbon is lowered to maintain the strength. The semikilled grade in the range of 0.20% max carbon and 1.00% to 1.35% manganese not only has a low Charpy V-notch transition temperature but also has drop-weight transitions in the range of 0 to 10 F. According to the information reviewed in Figure IX-1 of Appendix IX, ship operations in this temperature range were quite infrequent. In ships of good design and made with good fabrication practices, it appears that the proposed alternate semikilled steel has adequate fracture resistance, even though the manganese effect on V-notch transition temperature may not be fully realized in terms of service performance.

Within a range of steels that have the same strength and fabricating characteristics as World War II steel, it is possible to make a maximum change of about 100 F in transition temperatures by changing only carbon and manganese content. Steel with a maximum of 0.20 per cent carbon, a range of 1.00 per cent to 1.35 per cent manganese, and a maximum of about 0.04 per cent silicon has a transition temperature of -15 F, well below the level needed to eliminate failure.

G. REVIEW OF ECONOMIC AND TECHNOLOGICAL ASPECTS OF PRODUCING SHIP STEEL DURING A POSSIBLE FUTURE EMERGENCY

1. Steel-making practice.* It is convenient to describe three classes of steel as currently made. One of these is called rimmed steel**, another semikilled steel†, and a third killed steel†† with a modification of the latter designated as made to fine-grained practice‡. These three categories of steel refer to the practice followed in deoxidizing the steel. As the amount of oxygen dissolved in the steel is decreased to a minimum through the addition of such agents as silicon and aluminum, the shrinkage of the steel during solidification increases and leaves a large void or pipe toward the top of the ingot.

In order to minimize the extent of the pipe, killed steel is generally made in big-end-up ingots with hot tops. The

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*See Exhibit VI.

**An incompletely deoxidized steel normally containing less than 0.25 per cent carbon and having a rim somewhat purer than the average composition, a core containing scattered blowholes, and a minimum amount of pipe. Rimmed steel is not used for ship plate over 1/2 in. under current specifications.

†Steel incompletely deoxidized to permit evolution of sufficient carbon monoxide to offset solidification shrinkage.

††Steel deoxidized with a strong deoxidizing agent such as silicon or aluminum in order to reduce the oxygen content to a minimum so that no reaction occurs between carbon and oxygen during solidification.

‡Killed steel to which aluminum is added is designated as made to fine-grained practice.

special handling necessary for the hot tops and the big-end-up mold not only increases the cost of making the steel but also introduces a requirement for special facilities. At present, the capacity of the industry for making steel is over 100,000,000 tons per year, but only about 15,000,000 tons per year of hot-topped steel can be made because of the limited availability of these special facilities. Furthermore, ship plates are rolled from slab ingots, not ingots that are of other configurations. The facilities for making hot-topped slab ingots represent only a fraction of all hot-topping facilities.*

Killed steel generally contains more silicon than semikilled steel and has a lower transition temperature for the same carbon and manganese contents and the same ferrite grain size. Killed steel is now specified and used for ship plate over 1 in. in thickness.

Killed steel is commonly used for products of the highest quality. During World War II, about 15 million tons per year were produced for aircraft, ordnance, ship armor, and other critical uses. Because the large increase in steel-making capacity in the United States since 1945 has not been accompanied by a corresponding increase in facilities for making killed steel, a future emergency would find killed steel in great demand. Every effort should be made to find ways of using semikilled

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*See Exhibit VII.

steel in place of killed steel in ships because of the likelihood that killed steel capacity in a future emergency will be diverted from ship plate.

At least one mill that produces ship plate in the United States is equipped to roll directly from ingots. Semikilled practice requires additional equipment for slabbing and conditioning practices. Under this circumstance, mills that roll directly from the ingot can produce ship plate only of killed or rimmed steel. This factor must be recognized in any overall review of facilities for making ship plate.

2. Normalizing Practice. Plate normalizing capacity in the United States is even more limited than killed steel capacity. Every effort should be directed toward the development of ship steels that have adequate properties without requiring a normalizing treatment. In an emergency it is likely that the normalizing capacity will be completely absorbed by ordnance and other applications.*

3. Control of finishing temperature. The lowering of finishing temperature in order to lower transition temperature would seriously interfere with rolling schedules. Only a few mills with special practices such as continuous rolling from ingot to plate could achieve the desired degree of control. This practice does not appear to be an immediately promising method of reducing transition temperature except in a few special cases.*

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*See Exhibit VII

4. Summary of Economic and Technological Aspects of Ship Steel Production. Considering the economic and technical aspects of ship steel production during a future emergency, it appears that the only feasible solution to the problem of making enough ship steel of adequate notch toughness is through the adoption for all thicknesses of semikilled grades of the proper carbon and manganese levels that are neither normalized nor produced with a specially designated finishing temperature.

H. DISCUSSION OF PRESENT SHIP STEEL AND ALTERNATES FOR USE DURING A POSSIBLE FUTURE EMERGENCY

In 1947 the American Bureau of Shipping introduced a new specification* for ship steels with three grades of steel as follows:

ABS-A for plates up to and including 1/2 in.

ABS-B for plates over 1/2 in., up to and including 1 in.

ABS-C for plates over 1 in.

The transition temperatures for World War II, ABS-B and ABS-C steel are shown in Fig. 6.

Plates up to and including 1/2 in. in thickness, with one exception, were not represented in the material taken from failed World War II ships and examined at the National Bureau of Standards. However, failures of these thinner plates have been reported. A lower transition temperature in these thin plates is attributed both to metallurgical factors relating to the degree of

*See Exhibit IV

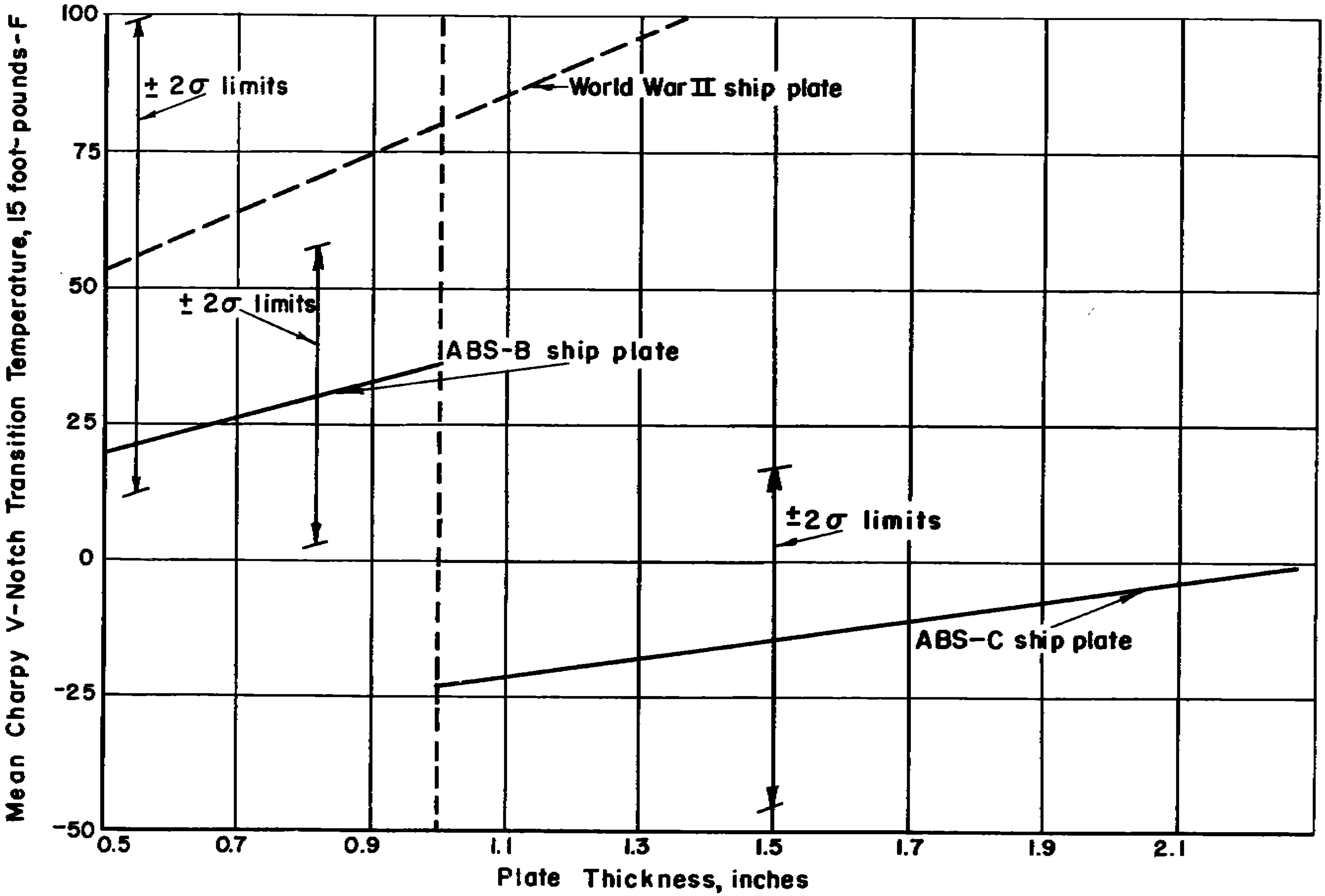

FIGURE 6. RELATION OF THICKNESS OF PLATE TO TRANSITION TEMPERATURE OF SHIP STEEL PRODUCED IN WORLD WAR II AND UNDER ABS-B AND ABS-C SPECIFICATIONS

hot working of the plates and to factors involving the mechanics of fracture(19). In the new specification it was not thought necessary to improve the notch toughness of plates in this range of thickness in part since structural design requirements rule out their use in the main ship structure. Plates up to and including 1/2 in. in thickness may have the same composition as World War II steel. It is possible that, under severe conditions and exceptionally low temperatures, some brittle fractures may be found in plates made to ABS-A.

Plates over 1/2 in. up to and including 1 in. in thickness, did crack extensively during World War II. Therefore, the new specification governing this range, ABS-B, provides for a lower carbon content and a higher manganese content that World War II ship steel. The 0.23 per cent maximum carbon content and the 0.60 to 0.90 percent manganese content have lowered the transition temperatures to about 30 F. Although this is not sufficient to eliminate the possibility of failure, there have been no failures to date in ships that incorporate ABS-B steel. Presumably the post-war ships represent a combination of good design, good fabrication practices, and reasonably tough steel that has had the effect of eliminating failures. Nevertheless, two failures of foreign ships during recent years in steels falling only slightly outside the ABS-B specification ranges suggest that steel under ABS-B made before 1/31/56 may be subject to brittle fractures in service, particularly under severe operating conditions if notches or cracks are present.

Under the ABS-B specification applicable after 1/31/56 the steel in the 1/2 to 1 in. thickness range should have a transition temperature of about 5 F, sufficiently low for virtual elimination of failures due to brittle behavior.

Plates over 1 in. in thickness are made to comply with ABS-C. This specification provides for a maximum carbon content of 0.25 per cent* and a manganese content of from 0.60% to to 0.90% and specifies that the steel shall be made to fine-grained practice. The result of these changes is to lower the 15 ft-lb Charpy V-notch transition temperature to about -20F, well below the 10 F required for virtual elimination of failure due to brittle behavior, even when the observations of Pellini and Puzak[9,10] are taken into account.

Plates 1 3/8 in. in thickness and over may be required under ABS-C to be given additional treatment. Such treatment may be normalizing which further reduces transition temperature.

While killed steel made to fine-grained practice under ABS-C has a satisfactory transition temperature, it probably would not be available for use during an emergency for the reasons stated above. A semikilled grade with about the same transition temperature has been made on a 25-ton basis as described previously and should be a fully satisfactory alternative material.

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*A revised ABS-C specification that will apply after 1/31/56 limits the carbon content to a maximum of 0.24%.

The transition temperatures of the World War II ship steel, ABS-A, -B, and -C steels, and the alternative grade are given in Table 4. Good agreement exists between the measured values and the values calculated from the factors of Table 3 and the composition differences. This agreement could be altered inadvertently at some future time by a change in steel mill practice. Until the relation between mill practice and notch toughness is established, a continuous check on the transition temperature of production heats of ship plate will be necessary to demonstrate that the expected level of notch toughness is actually being obtained.

The use of the semikilled grade has the effect of increasing manganese usage.* During World War II there was a shortage of all alloying elements used in steel, including manganese. However, with a level of ship plate production comparable to that of World War II, the manganese required for ABS-B steel and an improved semikilled grade would be less than 5 per cent of the current annual consumption. It would appear that such a requirement could be satisfied by special measures including stockpiling to ensure an adequate supply of manganese for ship plate of this type.

While this grade is similar to other steels now in production, early action should be taken to gain manufacturing experience and to establish production yields in preparation for its possible use.

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*See Exhibit VII

A semikilled grade of ship steel now under development appears to be an acceptable alternative material for ABS-C steel, particularly for use in an emergency when the facilities for making killed steel would be too limited to meet shipbuilding requirements for plate.

TABLE 4. COMPOSITION AND TRANSITION TEMPERATURE OF VARIOUS GRADES OF SHIP STEEL WITH YIELD STRENGTH OF ABOUT 35,000 PSI

Steel Designation	Average Composition			15 ft-lb* Charpy V-Notch Transition Temperature of 1-inch Plate	
	C	Mn	Si	Calculated	Measured
1. World War II Ship Steel (semikilled)	0.24	0.43	0.04	-	78
2. ABS-B (semikilled)	0.19	0.71	0.04	35	33
3. ABS-B (after 1/31/56)	0.17	0.95	0.04	5	- †
4. ABS-C (made to fine-grained practice)	0.19	0.73	0.21	-18	-23**
5. Alternate for** ABS-C (semikilled)	0.17	1.15	0.04	-15	-10

*As discussed in the appendices, the correlation between the temperature of possible service failure and the transition temperature is not the same for all classes of steels.

**Extrapolated from measured values at several thickness levels.

†No measurements yet available.

I. ESTIMATED RATES OF SERVICE FAILURE DUE TO BRITTLE BEHAVIOR DURING A POSSIBLE FUTURE EMERGENCY

During a future emergency it is possible that heavy deck loadings and inadequate ballasting practice will be necessary as during World War II and probable that operating temperatures will be lower. Therefore, this discussion of service failures during a possible future emergency is based on an estimate that the average operating temperature will be about 10 F below the average of 65 F experienced during World War II and the distribution of values the same.* As calculated in Exhibit IX, such a reduction in temperature would about double the rate of failure.

The failure rate due to brittle behavior in ships has been estimated according to differences in their design, the fabrication practices, and the level of notch toughness of the steel and is given Table 5. In view of the near impossibility of building and maintaining ships without flaws, it appears that ships built of World War II steel will incur a substantial number of Group I and II failures if operated during a future emergency. Utilization of improved plate in critical locations or limitation of their service to tropical waters would be required in order to reduce or eliminate failures in ships built of plates of the notch toughness of World War II ship steel.

Under the conditions that are anticipated in a future emergency, a small number of failures may be observed in ships

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*See Exhibit IX

Table 5. ESTIMATED GROUP I AND II SHIP FAILURE RATES DURING A FUTURE EMERGENCY* FOR VARIOUS TYPES OF STEEL--NUMBER OF CASUALTIES PER THOUSAND SHIP YEARS

	TYPE OF STEEL			
Class of Ship	World War II	ABS-A,B,C** used until 1/31/56	ABS-A,B,C** used after 1/31/56	ABS-A,B and proposed‡ semikilled class
Liberty Ship	70†	--	--	--
Victory Ship	14†	--	--	--
Ships Built from 1947--1956	--	0.3 or less	--	--
Ships Built 1956 and after	--	--	less than 0.1	--
Ships Built early†† in a future emergency	28	--	less than 0.1	less than 0.1
Ships Built late†† in a future emergency	14	--	less than 0.1	less than 0.1

*Mean operating temperature assumed to be 10 F below that of operations during World War II.

**ABS-B chemical composition requirements changed after 1/31/56 from 0.23% max C and 0.60--0.90% Mn to 0.21% max C and 0.80--1.10% Mn and ABS-C from 0.25% max C to 0.24% max C.

‡Proposed semikilled grade containing 0.20% max C and 1.00--1.35% Mn suggested as replacement for killed ABS-C grade.

†Higher than World War II rate because of assumed lower mean operating temperature.

††Assuming fair fabrication practices and good design in early stage and good fabrication and good design in late stage of a future emergency.

built from 1947 to 1956 in the sections incorporating ABS-B steel. There should be no brittle fractures of ships built after 1956 incorporating ABS-A, B* and C steels except under conditions where fracture is forced as might occur during collisions, explosions, or similar unusual circumstances beyond the control of the designer and ship builder. Ships built during a future emergency will probably be as free from troublesome design details as Victory ships. It is likely, however, that there will be an initial period of construction during which the quality of welding will be low. Ships built during this period will have a tendency to fail unless they incorporate steel with adequate notch toughness that could be produced during the emergency. ABS-A and B* steels will be satisfactory for plates up to 1/2 in. and up to 1 in. in thickness, respectively. Plates over 1-in., at least up to 1 1/2-in. in thickness should be satisfactory if made of a semikilled grade containing a maximum of 0.20% carbon and from 1.00% to 1.35% manganese. Given a satisfactory manganese supply, it appears that this semi-killed steel could be produced during the emergency.

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*As made to specifications applicable after 1/31/56.

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EXHIBIT I

INFLUENCE OF STRESS ON FRACTURING

One of the three conditions required for brittle fracturing is an applied stress. Recently Robertson(3) determined that brittle cracks can propagate in plate at stresses of a fraction of the yield strength. In tests conducted by Feely et al.(4) a critical temperature was established below which brittle cracks run at one-third or less of the yield stress and above which they run at levels approaching the yield stress.

In a ship the design reflects the stresses introduced by loading and by the movement of the ship at sea. In addition, these stressed members of the ship are also subjected to residual stress. These are introduced by welding or by joining members that are brought together by force. Residual stresses are quite variable and difficult to measure with precision. Their role in fractures has been controversial. There is no doubt but that they must be taken into account in any study involving the precise stress level required for fracturing. For purposes of this study, it suffices to indicate that residual stresses do exist and that "in general, residual stresses of the same sign as those arising from the applied load are to be avoided, particularly at points of stress concentration."(16)

Another category of stresses includes those introduced by thermal gradients. These arise from the differential heating by solar radiation, by the heating or cooling of certain cargo spaces of the ship, or by the differential between water and air temperatures.

Stresses applied in service act in conjunction with residual stresses and thermal stresses. The stress system and the magnitude of the stresses existing at the time of any particular fracture are very difficult to establish, but they may often be well above the level required for brittle crack propagation.

EXHIBIT II

TENSILE AND IMPACT PROPERTIES OF WORLD WAR II SHIP STEELS

The general properties of World War II ship plate were established in studies at the National Bureau of Standards of samples of plate which cracked in service[7,8]. The composition of World War II ship plate estimated from these samples is shown in Table II. 1. Tensile tests were also conducted on these plates, and the available values are shown in Table 1. It should be noted that the plates were acceptable under the specifications then in force.

Charpy V-notch tests were conducted over a range of temperatures as shown in Fig. 1 on samples taken from locations as close to the path of fracture as was feasible. Care was taken not to test plates which might have been damaged by welding or deformation. The results of typical Charpy V-notch tests on plate from fractured ships are shown in Fig. 1. A horizontal line at a level of 15 ft-lb is drawn through the curves relating the energy absorbed in the test and the test temperature, and the intersection of the line and the curve is called the 15 ft-lb transition temperature. The temperature at which the ship failed is also indicated where known in order to establish the Charpy V-notch energy at failure temperature. As shown in Table II.2, a sample of failed plates of all ship types has been tested at the National Bureau of Standards. The transition temperature varied from plate to plate in a behavior typical of measurements made on a large number of samples of any kind. A statistical treatment was helpful in analyzing the data. From test results(7) on samples of plates tested at the National Bureau of Standards, estimates from two different approaches were made of the notch toughness of ship steel made during World War II.

TABLE II.1. AVERAGE PROPERTIES OF WORLD WAR II SHIP PLATE

	Yield Point, psi	Tensile Strength, psi	Elongation, per cent	Reduction of Area, per cent
Tensile Properties	35,000	62,000	35	58

AVERAGE COMPOSITION OF WORLD WAR II SHIP PLATE

	C %	Mn %	Si %	P %	S %
Composition	0.24	0.43	0.04	0.010	0.030

Table II.2. Summary of Casualties Reported, Tests Completed to December 31, 1954, Percent of Casualties Tested, and Samples not Tested, for Various Vessel Types

Vessel Type	EC2	T2	VC1	C1	C2	C3	C4	Tkr	ET1	Riv	Other	Total
Casualties Reported to March 31, 1953 [a]												
Group 1	145	53	4	10	13[b]	7	2	11	5	1	9[c]	260
Groups 1 & 2	839	216	20	56	79[b]	67	13	-	-	-	-	1290
Tests Completed at NBS to December 31, 1954												
Group 1	12	17	2	0	5[b]	3	1	5	3	1	2[c]	51
Group 2	5	5	1	0	0	1	0	0	2	1	1	16
Subtotal	17	22	3	0	5	4	1	5	5	2	3	67
Group 3	3	1	0	0	0	0	0	0	0	1	1	6
Other	2	0	2	0	0	0	0	0	0	0	0	4
Total	22	23	5	0	5	4	1	5	5	3	4	77
Percent of Casualties Reported on which Tests are Completed (Sample ratio)												
Group 1	8	32	50	0	38	43	50	45	60	100	22	20
Group 1 & 2	2	10	15	0	6	6	8	-	-	-	-	-
Samples Not Suitable for Tests of Plate Material												
Group 1	1	-	-	-	-	-	-	-	-	-	-	1
Group 2	2	-	-	-	4[c]	-	-	-	-	-	-	6
Group 3	4	-	-	-	-	-	-	-	-	1	1	6
Total	7	-	-	-	4	-	-	-	-	1	1	13
Samples Not Tested to Date [c]												
Group 1	2	5	-	-	3	3	-	1	1	-	3	18
Group 2	-	-	1	1	5	1	-	-	-	-	-	8
Total	2	5	1	1	8	4	-	1	1	-	3	26
Total Samples Received												
All Groups	31	28	6	1	17	8	1	6	6	3	7	116

(a) Adapted from Board Report and SSC Technical Progress Reports 1, 2, and 3.

(b) Includes Navy operated C2 not listed in References (a)

(c) Includes casualties since date of Third Technical Progress Report.

One approach was developed by Dr. W. J. Youden of the National Bureau of Standards as follows: about 100 plates of World War II steel taken from failed ships have been tested at the National Bureau of Standards. The 15 ft-lb Charpy V-notch transition temperature of these plates varied from 2 F to 151 F. From a random sample of this size, it is possible to make an estimate of the notch toughness of all ship plate produced during World War II. Such an estimate can be made by assuming the shape of the frequency curve of these values. It has been assumed that these data would follow a normal distribution curve. Under this circumstance, two values establish the curve representing population. The first is the center of the population or the average transition temperature of all plates. The second is the standard deviation which indicates the width of the distribution curve.

In estimating the position of the center of the distribution or the average transition temperature, the following data from the National Bureau of Standards may be considered:

Plates	Average Transition Temperature F
28 source plates	96.4
45 through plates	66.1
32 end plates	51.5

The average for the combined start and end plates is about 74 F. It may be argued that this average is somewhat above the population average because a source plate is always a plate of high transition temperature; but an end plate may have an especially low transition temperature, depending on whether the crack stopped because the plate was tough or because a drop in stress or a structural discontinuity was operative.

The thru plates, with an average transition temperature of about 66 F, probably have a lower transition temperature than that of the population because they specifically exclude source plates and end plates. As mentioned earlier, the source plates necessarily have a higher transition temperature average than the other plates. End plates, on the other hand, should not deviate from the average to the same extent as source plates because, while some end plates have particularly low transition temperatures, others may be only of average quality, with the crack stopping for reasons other than good toughness of the plates.

A reasonable compromise might be made by averaging the values of the mean thru-plate transition temperature, 66 F, and the mean of the source- and end-plate transition temperatures, 74 F. Thus, the average transition temperature of the population would be about 70 F.

Some data on World War II plates taken at random from shipyards are available from the Naval Research Laboratory. The average 15 ft-lb Charpy V-notch transition temperatures of these plates is about 69 F. The 70 F value for plates from failed ships and the 69 F for unfailed plates are in quite good agreement.

Another approach in estimating the transition temperature of World War II ship steel by Messrs. Hulbert and Chase of Battelle Memorial Institute is as follows: In estimating the standard deviation of the transition temperature of World War II ship steels, a more formal method of analysis may be introduced. The sample of World War II ship plate obtained from failed ships had a wide variation in thickness. If plate thickness were to have any effect on transition temperature, this effect should be removed in computing the standard deviation of the ship steels.

Therefore, as a first step, the regression of transition temperature on thickness of plate was computed. This operation essentially consists of plotting the transition temperature values against the thickness of the plate, drawing the best straight line through the data, and determining the equation representing the line. This gave the regression equation:

$$T.T = 42.95\ W + 36.99$$

where W is the thickness in inches.

The values of transition temperatures are scattered around this line. From the distance of the individual points from the line, the standard error of estimate was calculated to be 26.4. This can be thought of as an upper limit for the standard deviation of the World War II hull steels.

The sample of World War II plates was not chosen at random because source plates and end plates were selected more frequently than through plates. The consequences of the selection were that particularly bad and particularly good plates were represented in high proportion through the emphasis on tests of source and end plates. In other words, the 100 plates tested showed a greater amount of scatter than would have been expected in a random sample of 100 plates.

Since the sample was known to be weighted to give a standard deviation higher than that of the population, the five extreme points with deviations from the regression line of more than twice the standard error were arbitrarily discarded.

A new regression line was calculated, based on the remaining points, giving the equation:

$$\overline{TT} = 54.80\ W + 25.75$$

The standard error of estimate for this line is 21.9 and this value was taken to be a more representative estimate of the standard deviation of the population.

Similar analyses were made on the values of transition temperature versus thickness for post-war steels. Regression lines of transition temperature on plate thickness were fitted to samples of steel manufactured under ABS-B and ABS-C specifications and selected for test at random. The equations representing these lines were:

(a) for ABS-B

$$\overline{TT} = 31.64\ W + 3.60$$
(Standard error = 13.8)

(b) for ABS-C

$$\overline{TT} = 17.45\ W - 40.91$$
(Standard error = 16.1)

On this basis, the standard deviation of ship steel made under ABS-B was taken to be 14 F, and under ABS-C, about 16 F.

The standard deviation of the 15 ft-lb Charpy V-notch transition temperature of 15 heats of carefully made laboratory steels was 8.5 F. It is not surprising to find a larger amount of scatter in production heats, particularly in view of variations of composition from heat to heat and processing variables from mill to mill that may be expected.

EXHIBIT III

ANALYSIS OF BEHAVIOR OF PLATES FROM FAILED SHIPS

In order to facilitate analysis, plates from failed ships were classified in three categories:[7]

"(1) Source plates: Plates which contained the starting point of a fracture which occurred in service. This category includes some plates which contained both the starting point and the end or ends of a short fracture, and a few plates in which secondary fractures originated and propagated to meet the main fracture. A number of the fractures originated near welds, which usually involved both a structural or geometrical notch and the metallurgical effect on the plate metal resulting from the welding operation. However, if the fracture originated in a weld due to insufficient weld metal, poor fusion, or slag inclusions, the adjoining plates were not included in this category.

"(2) Thru plates: Plates which were fractured in the ship failures, but which contained neither a fracture source nor a fracture end.

"(3) End plates: Plates in which the ship fractures ended and which did not contain a fracture source. This category includes three plates which showed definite evidence that the fracture had stopped in the plate, but which were broken completely by a secondary fracture which propagated from another plate, or by increased stresses resulting from failures of other plates as the vessel broke in two. Plates in which the fractures ended by running out at an edge of the plate (as at a crack arrestor slot) are not included in this category, but are considered as 'fracture thru' plates."

A detailed analysis of these three categories of plates has been completed[20]. The source, thru and end plates have been subdivided as follows:

"S1. Plates containing the source of a primary or independent fracture which occurred under normal operating conditions.

"S2. Plates in which secondary fracture started ahead of the main fracture or plates in which fractures started under unusually severe conditions.

"T1. Primary thru plates that were the first to propagate a fracture; that is, where the fracture originated in an adjoining weld and turned or ran directly into the plate.

"T2. Secondary thru plates that fracture after the crack had propagated a foot or more in another plate.

"E1. Plates in which fractures ended, but where there appeared to be structural failure or stress conditions that may have influenced the ending of the fracture.

"E2. Fracture end plates where there was no apparent structural factor or stress condition involved in the stopping of the fracture.

"NF. (No fracture) Plates that did not contain a fracture, but were adjacent to a fractured plate."

The 10, 15, and 25 ft-lb Charpy V-notch transition temperatures have been given by Williams[20] for source plates, thru plates, and end plates. An analysis of the data is indicated in Fig. III.1. The source plates definitely have higher transition temperatures than the plates in the other two categories. Fig. III.2 shows the energy absorbed by other specimens tested at the failure temperatures and indicates that only three of the source plates have an energy at failure temperature above 10 ft-lb, with no values above 11.4 ft-lb. Plates

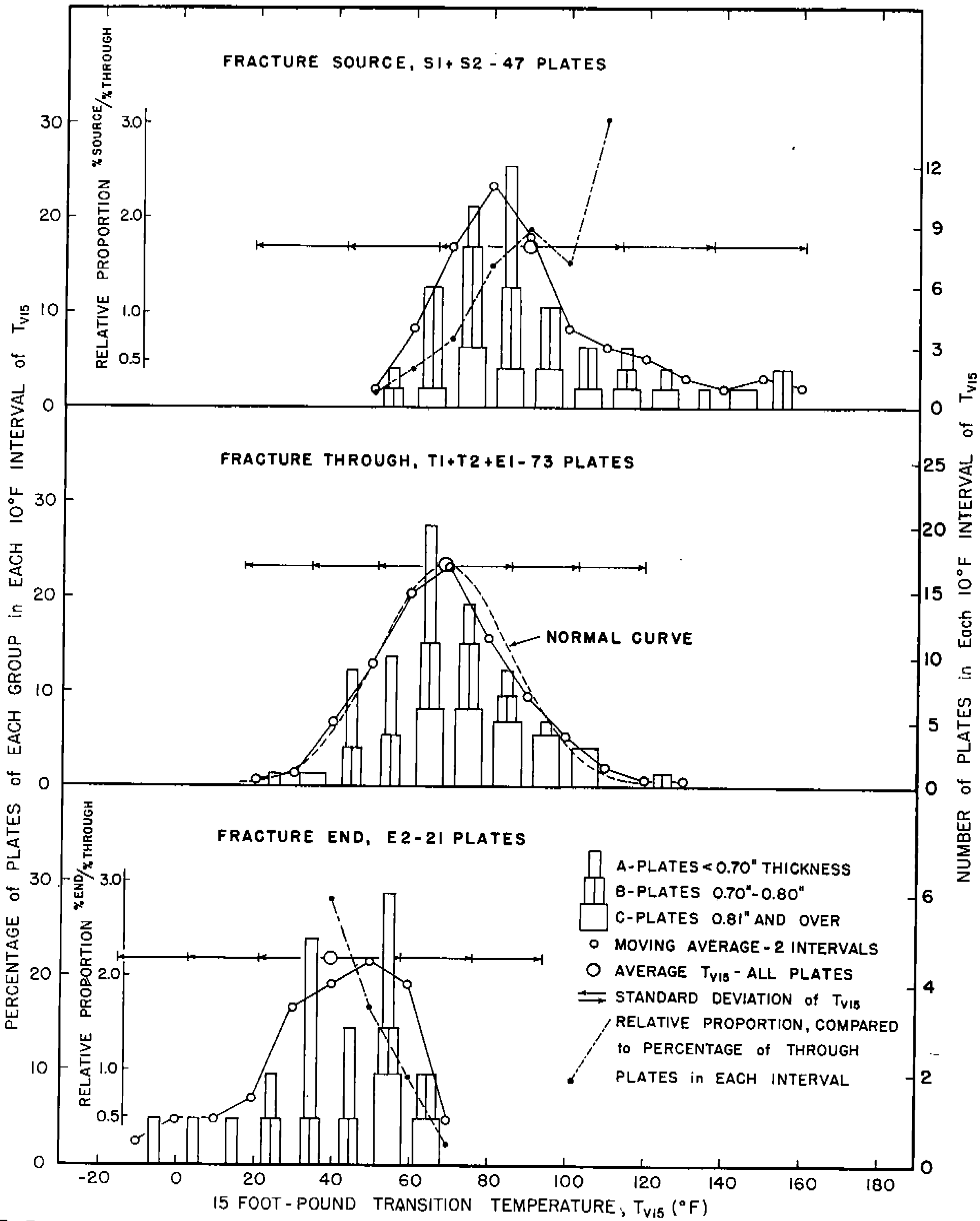

Fig. III.1. Frequency distributions of T_{V15} for revised grouping of the plates. Plates of the E1 sub-category are placed with the "Fracture Through" group.

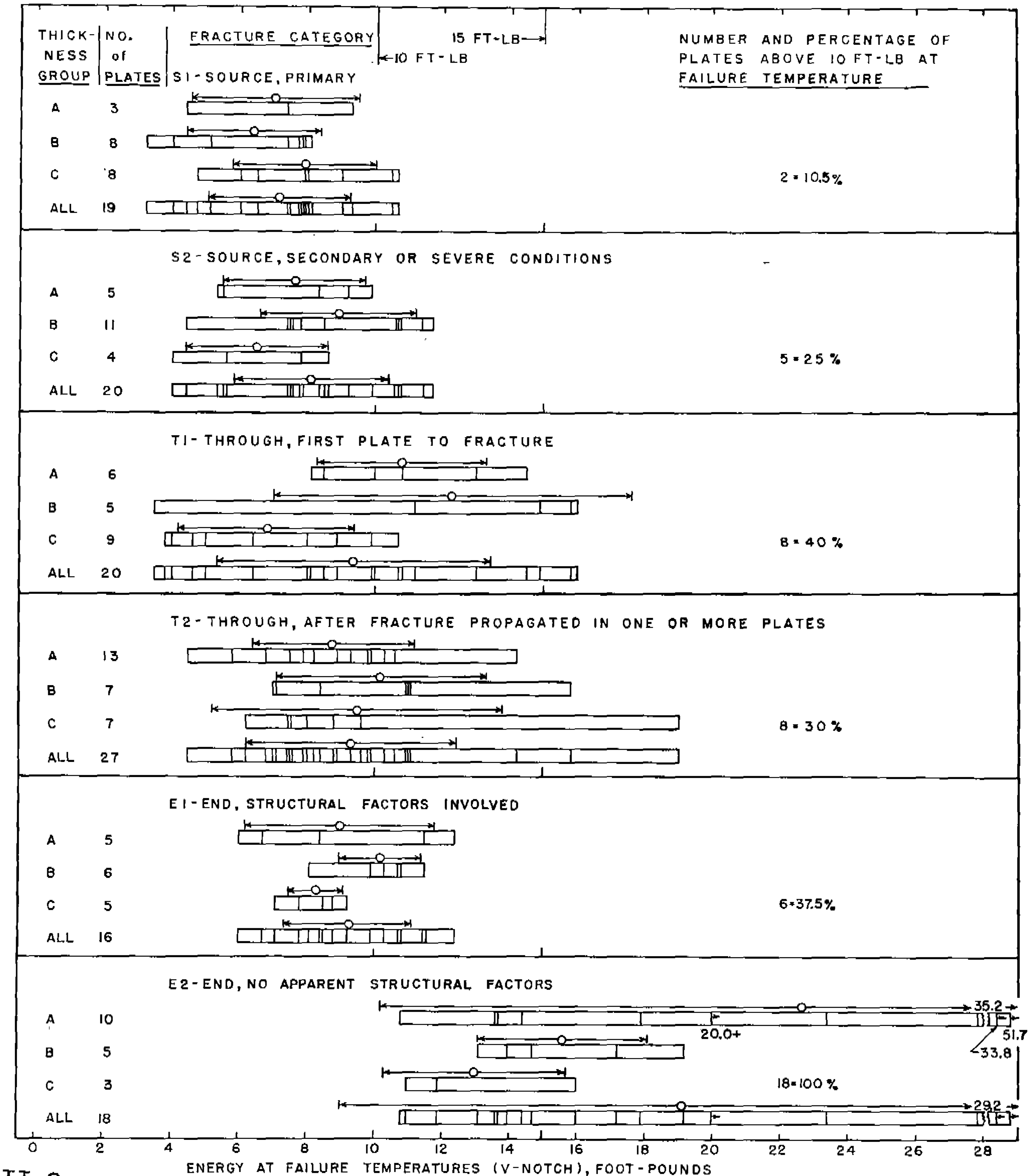

Fig. III.2. Energy Absorbed By V-notch Charpy Specimens at the Failure Temperature of the Plates. Circles indicate average, and arrows show standard deviation (±1σ) for each group.

fracturing through may have energies at failure temperature up to 19 ft-lb while plates containing the end of fracture may have higher energies at failure temperature.

There is one exception to this conclusion which may be mentioned. A few examples of a special situation require some consideration. The source plate category represents plates containing the starting point of the fracture. In most cases thru plates received a fracture from an adjacent plate. However, in a very few cases the thru plates received a fracture which had run for a short distance in the weld, and then entered the plate. Under these circumstances, the thru plate was the first to fracture. This means that if a crack can get up to speed in a bad weld defect, it will propagate into plates which absorb as much as 19 ft-lb on the Charpy V-notch impact test at the failure temperature. To keep from having brittle failures in ships with long and serious weld flaws, it would have been necessary to have plates of World War II steel with a minimum Charpy V-notch impact energy of 19 ft-lb or more at the operating temperature, which is higher than the 11.4 ft-lb for the source plates. Therefore, in order to reduce the rate of brittle fracturing to a negligible level, it is necessary not only to eliminate all source plates but also to eliminate long flaws in which a crack can begin and run for several inches.

It is evident that a correlation exists between certain criteria of the notch toughness of steel and its propensity to crack in service. In view of the number of conditions which must be satisfied for brittle cracking, it is not surprising that the impact properties of plates containing the source of fracture overlap the properties of plates cracking through. However, Fig. III.3 shows that in those ships from which samples of both the source and end plates are available for the same fracture, the fracture source plate, without exception, has significantly less notch toughness than the plate containing the end of fracture. Over a range of severity of conditions, a crack may start in plates which absorb from 3 to 11 ft-lb at failure temperature. However, where the crack is stopped, this occurs in a plate that is always relatively tougher than the source plate.

A number of laboratory tests can be correlated with the observation that no fracture source plate taken from World War II ships absorbed more than 11.4 ft-lb in the Charpy V-notch impact test conducted at failure temperature. At this energy level a specimen and presumably a plate of semikilled steel cannot deform even slightly to adjust to the loads at notches which are regions of stress concentration(9). The material cracks in a brittle fashion instead.

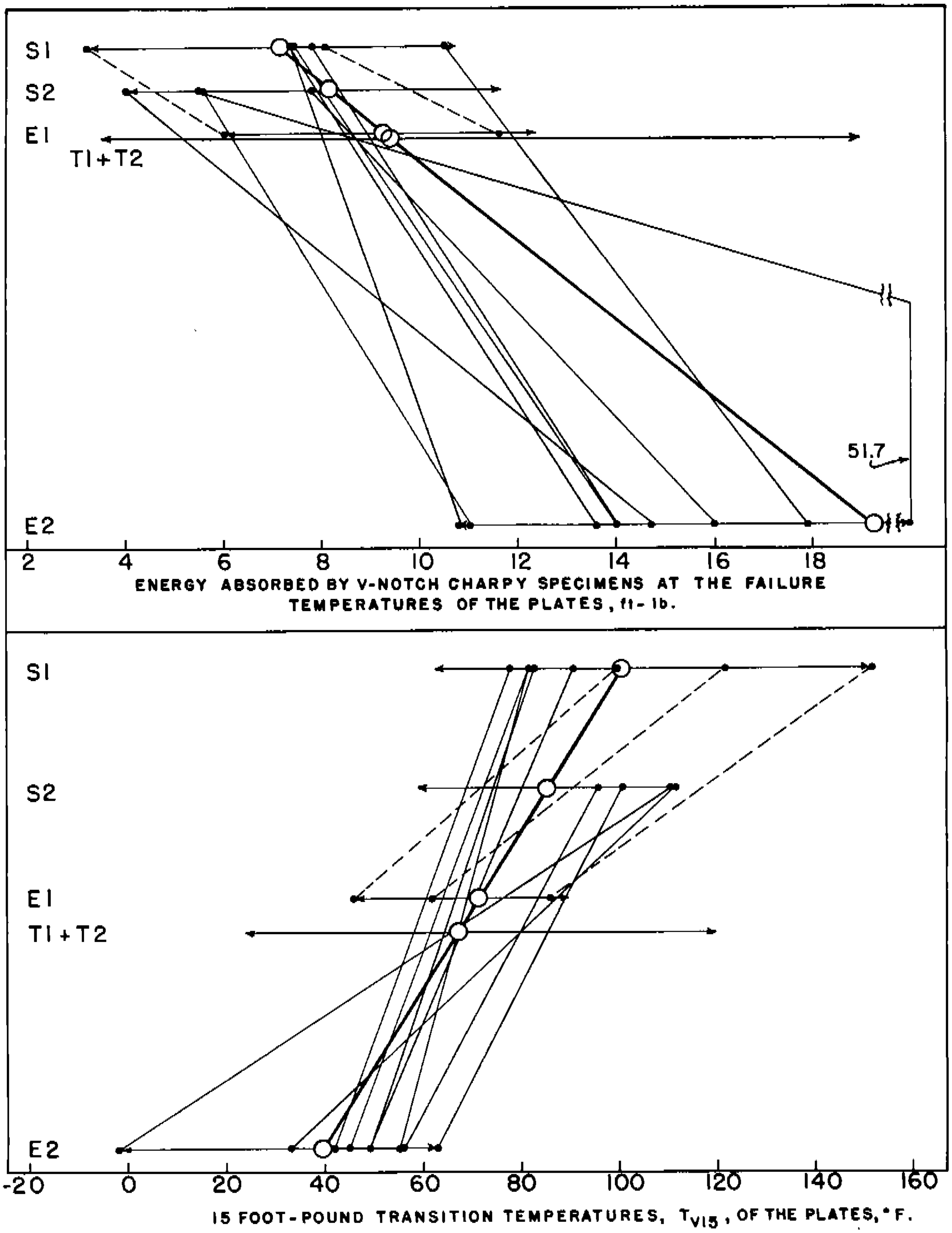

Fig. III.3. **Notch sensitivity of source and end plates from same ship, compared to ranges and average values for the different fracture categories.** The fracture categories are spaced vertically so that the average values (large circles) fall on the heavy line. Other diagonal lines indicate relative values for pairs of source (S1 or S2) and end (E1 or E2) plates from the same ship. Horizontal arrows show the range of values for all plates in each category.

EXHIBIT IV

CALCULATION OF THE PERCENTAGE OF FAILURE OF SHIPS OF STEEL OF LOWER TRANSITION TEMPERATURE

Hulbert, Chase, and Bell--Battelle Memorial Institute

Derivation of Results. In reviewing the effect of notch toughness of plates on service failures due to brittle behavior, it is evident that source plates have less notch toughness on the average than the remainder of the plates in the World War II ship steel population. It is well known that increasing notch toughness (lowering transition temperature) of a plate lowers the probability that it will fail under a given stress at a given temperature and in the presence of a notch. In order to determine the probability of fracture of a given ship plate at a given time, it would be necessary to know the stresses and operating temperatures encountered by the plate as well as its transition temperature and its proximity to a sharp crack or structural discontinuity. However, of these factors, only the general range of operating temperatures and transition temperatures are known for the period of World War II.

Therefore, the problem of estimating the effect of lower transition temperature of the ship plate on the probability of failures can only be treated statistically in the aggregate by making some reasonable assumptions in regard to the distribution of all of the variables affecting fracture rate.

The distribution of transition temperatures for World War II ship plate here is assumed to be normal. In Exhibit II an attempt was made to determine its mean and standard deviation. The mean was estimated to be about 70 F, but the standard deviation varied according to the method chosen for analysis. Because of this, three standard deviations (14 F, 18 F, 22 F) are used here in the calculations.

A number of source plates from failed World War II ships were tested for transition temperature at the National Bureau of Standards, and data from these were available in May, 1955, when these calculations were made. From the results of the tests, a distribution of transition temperature for source plates was obtained that was assumed to apply to all source plates.

The distribution of the transition temperatures of all World War II ship plates, that of the source plates, and the distribution of transition temperatures for any new steel are sufficient to estimate the reduction in fracture rate that is obtained by using this new steel. However, in deriving the expression for this reduction, several other quantities are needed that require definition. The following is a list of definitions for all quantities used in the derivation.

p_i = the probability that a steel plate with a transition temperature in the i-th interval will fracture if it is included in a test exactly like that given World War II ship plates.

u_i = number of World War II steel plates used in this test that had transition temperatures in the i-th interval.

$$\sum u_i = U$$

e_i = expected number of failures among plates with transition temperatures in the i-th interval during a test exactly like that given the World War II ship plate.

$$\sum e_i = E$$

ω_i = observed number of failures among plates with transition temperatures in the i-th interval during the test given the World War II ship plate.

$$\sum \omega_i = \Omega$$

u_i' = number of plates with transition temperatures in the i-th interval for plates made from some new steel.

$$\sum u_i' = U'$$

e_i' = expected number of failures among plates of this new steel if they were given the same test as was given the World War II ship plate.

$$\sum e_i' = E'$$

We have first that:

$$e_i = p_i \, u_i .$$

We assume

$$\frac{e_i}{E} = \frac{\omega_i}{\Omega}$$

and that

E = total of all failures in the test of World War II ship plate. Then

$$p_i = \frac{e_i}{u_i} = \frac{\omega_i}{u_i} \frac{E}{\Omega} .$$

Assume that p_i would be the same if another test were performed exactly like that in World War II, except that a new steel is used with a new set of u_i, namely, u_i'. Then

$$e_i' = p_i \; u_i'$$

and

$$e_i' = \omega_i \; \frac{u_i'}{u_i} \, \frac{E}{\Omega}.$$

Thus

$$\frac{E'}{E} = \frac{\sum \omega_i \frac{u_i'}{u_i}}{\Omega} .$$

Since the two tests were identical, we have that $\sum u_i' = U = \sum u_i$ whence

$$\frac{E'}{E} = \frac{\sum \omega_i \frac{u_i'/U}{u_i/U}}{\Omega} = \sum \frac{\omega_i/\Omega}{u_i/U} \cdot \frac{u_i'}{U} .$$

The fraction E'/E is the relative rate of ship failures which is obtained when a new steel is used for ship plate.

The fraction $f_i = \frac{\omega_i}{\Omega} \Big/ \frac{u_i}{U}$ is a measure of the relative fracturability of a steel plate with transition temperature in the i-th interval. From the above it follows that $E'/E = \sum f_i \, \frac{u_i'}{U}$. Thus the relative fracture rate, using a new steel, is simply the sum over all temperature intervals of the product of the relative fracturability of a plate in the i-th interval and the probability that the transition temperature of a plate of the new steel is in the i-th interval.

Tables IV.1, IV.2, and IV.3 give values of ω_i, $\frac{\omega_i}{\Omega}$, $\frac{u_i}{U}$, and f_i for the three standard deviations mentioned above. The values f_i^*, given in the last column of each of these tables, are obtained by drawing a smooth curve through a plot of f_i against transition temperature and adjusting the smoothed values by requiring $\sum f_i^* \frac{u_i}{U} = 1$. Then the relation fracture rate F which is finally obtained is given by $F = \sum f_i^* \frac{u_i'}{U}$. The values u_i'/U were not tabulated but were obtained from a normal distribution with mean m and standard deviation of 14 F.

<u>Discussion of the Results</u>. It is to be noted here that the results given in Table IV.4 apply only to the relative fracture rates to be expected if a new steel were to be put to the same test as the World War II steels. In applying these results to a test that differs markedly from the World War II situation, all that can be said is that steels with a lower transition temperature would probably reduce the over-all fracture rate. Quantitative statements made concerning the amount of reduction to be expected under this very different situation would have a low degree of precision.

TABLE IV.1. COMPUTATION OF RELATIVE FRACTURABILITY, f_i, OF SHIP PLATE ASSUMING $\sigma = 14$ F FOR WORLD WAR II STEEL

TT Interval	ω_i	ω_i/Ω	u_i/U	f_i	f_{i*}
41.5-- 51.5	0	0	0.07229	0	0
51.5-- 61.5	0	0	0.17870	0	0.098
61.5-- 71.5	3	0.1111	0.27078	0.410	0.293
71.5-- 81.5	5	0.1852	0.25164	0.736	0.687
81.5-- 91.5	6	0.2222	0.14340	1.550	1.449
91.5--101.5	3	0.1111	0.05008	2.219	3.534
101.5--111.5	3	0.1111	0.01071	10.373	9.574
111.5--121.5	2	0.0741	0.00140	52.929	49.479
121.5--131.5	2	0.0741	0.00011$_6$	673.6	632.5
131.5--141.5	1	0.0370	5×10^{-6}	7.4×10^3	7273.6
141.5--151.5	1	0.0370	1.6×10^{-7}	2.3×10^5	2.066×10^5
151.5--161.5	1	0.0370	3×10^{-9}	1.2×10^7	1.2×10^7

TABLE IV.2. COMPUTATION OF RELATIVE FRACTURABILITY, f_i, OF SHIP PLATE ASSUMING $\sigma = 18$ F FOR WORLD WAR II STEEL

TT Interval	ω_i	ω_i/Ω	u_i/U	f_i	f_{i*}
41.5-- 51.5	0	0	0.0935	0	0
51.5-- 61.5	0	0	0.16636	0	0.141
61.5-- 71.5	3	0.1111	0.21482	0.517	0.470
71.5--81.5	5	0.1852	0.20535	0.902	0.823
81.5-- 91.5	6	0.2222	0.14528	1.530	1.363
91.5--101.5	3	0.1111	0.08438	1.317	2.093
101.5--111.5	3	0.1111	0.02949	3.768	3.386
111.5--121.5	2	0.0741	0.00849	8.725	7.806
121.5--131.5	2	0.0741	0.00177	41.850	37.382
131.5--141.5	1	0.0370	0.00028	132.3	118.03
141.5--151.5	1	0.0370	0.00003$_6$	1235	1161
151.5--161.5	1	0.0370	5×10^{-6}	7400	6967

TABLE IV.3. COMPUTATION OF RELATIVE FRACTURABILITY, f_i, OF SHIP PLATE ASSUMING σ= 22 F FOR WORLD WAR II STEEL

TT Interval	ω_i	ω_i/Ω	u_i/U	f_i	f_{i*}
31.5-- 41.5	0	0	0.03366	0	0
41.5-- 51.5	0	0	0.10262	0	0.053
51.5-- 61.5	0	0	0.14942	0	0.237
61.5-- 71.5	3	0.111	0.17756	0.626	0.448
71.5-- 81.5	5	0.1852	0.17224	1.075	0.791
81.5-- 91.5	6	0.2222	0.13636	1.630	1.318
91.5--101.5	3	0.1111	0.08812	1.261	2.029
101.5--111.5	3	0.1111	0.04648	2.391	3.031
111.5--121.5	2	0.0741	0.02000	3.704	5.060
121.5--131.5	2	0.0741	0.00703	10.541	9.356
131.5--141.5	1	0.0370	0.00202	18.317	18.422
141.5--151.5	1	0.0370	0.00047	78.72	79.07
151.5--161.5	1	0.0370	0.00009	411.11	411.14

TABLE IV.4. RELATIVE FRACTURE RATES FOR STEELS WITH TRANSITION TEMPERATURE DISTRIBUTIONS HAVING VARIOUS MEANS

Mean, F New Steels	Relative Fracture Rate F, %		
	σ = 14 F†	σ = 18 F†	σ = 22 F†
70	100.0	70.6	67.4
60	33.4	37.0	37.9
50	12.4	16.2	18.8
40	3.8	5.5	7.7
30	1.0	1.4	2.5
20	0.1	0.2	0.6

†These are standard deviations assumed for World War II steels (Tables IV.1, 2, 3). Standard deviation for new steels was 14 F.

EXHIBIT V

EFFECT OF CHANGES IN COMPOSITION AND GRAIN SIZE ON NOTCH TOUGHNESS

Results of a number of investigations now make it possible to estimate quite accurately the effect of changes in chemical composition on notch toughness. Table V.1 summarizes the effect of carbon, manganese, phosphorus, and silicon observed by various investigators[7,8,12,13,14]. While other elements change transition temperature, they are present in small amounts in ship steel and do not play an important part in changing notch toughness. While phosphorus has a profound effect on transition temperature, it has remained at about the same level in World War II and post war steels and therefore has not played a significant role in changing transition temperature.

Many studies have been made of the effect of grain size on transition temperature, and the results are summarized in Table V.2. There is fair agreement between the various observations. It is interesting to note, however, that various studies[18,22,23] suggest a different effect of grain size on transition temperature for various techniques of obtaining the same range of grain sizes; finishing temperature changes are nearly twice as effective as annealing temperature changes. These results suggest that the practice adopted for altering grain size also introduces other changes not understood at present. Until the relationship between the fine structure of the steel and notch toughness is established, great care must be exercised in making use of the data shown in Table V.2.

Data on the effect of changes in practice on grain size are quite limited. However, it has been suggested that "optimum finishing temperatures of normalizing of the steel can only be expected to reduce the ferrite grain size about one ASTM number for 1-in. plate. For 1/2-in. thickness, perhaps little or no reduction would be obtained"(17). A series of special studies made at Battelle Memorial Institute has likewise shown that a mean change of one ASTM grain size number in the ferrite grain size of 1-in. plate is about all that can be expected by changing finishing temperature or normalizing. It is probable that "the main benefit of normalizing would be obtained in those plates that were finished at the highest temperatures and hence had the coarsest grain size...The net effect would be to reduce the width of the distribution curve and to lower slightly the mean transition temperature"(17). These observations apply particularly to semikilled steel. There is some evidence that normalizing will reduce the grain size of aluminum killed steel by as much as two ASTM grain size numbers. If a semikilled and an aluminum killed grade had the same as rolled grain size, normalizing would result in a smaller grain size in the aluminum killed steel with a difference of up to one ASTM grain-size number.

TABLE V.1. EFFECTS OF CHANGES IN COMPOSITION ON CHARPY V-NOTCH TRANSITION TEMPERATURE

Element	National Bureau of Standards‡ (6,7) (Plates from Fractured Ships) F	Battelle Memorial Institute‡‡ (12) (Semikilled Steels) F	Naval Research Laboratory‡ (13) (Al-Killed Steels) F: Ductility Transition	Naval Research Laboratory‡ (13) (Al-Killed Steels) F: 15 ft-lb T.T.
	Change in T.T. per 1% Addition	Change in T.T. per 1% Addition	Change in Transition Temperature per 1% Addition	
C	+300	+360	+160	+240
Mn	-100	- 95	-100	-100
P	+1000	+850	+1000	+1000
Si	-300	-200*	- 70**	0***

*Data available up to 0.15% Si. Over this value, the effect may be reversed.
**Data available up to 0.9% Si. Over this value, the effect may be reversed.
***Data available up to 0.2% Si. Over this value, the effect may be reversed.
‡V-Notch Charpy - 15 ft-lb T.T.
‡‡Keyhole Charpy - 20 ft-lb T.T.

TABLE V.2. EFFECT OF CHANGES IN GRAIN SIZE ON TRANSITION TEMPERATURES

Reporting Laboratory	Shift in Transition Temperature per Increase of 1 ASTM Grain Size Number--Ferrite Grain Size		Note
	Shift in T.T. F	Transition Temperature Definition	
National Bureau of Standards (7)	-14	15 ft-lb V-Notch	Hull plate from failed ships
U. S. Steel Corp. (15)	-22	Mid-Span Keyhole Notch	AISI-1020-Semikilled
Battelle Memorial Institute (6)	-30*	20 ft-lb Keyhole	Semikilled
	-25**	20 ft-lb Keyhole	Semikilled
	-18***	20-ft-lb Keyhole	Semikilled

Fracture grain size reported.

*Grain size changed by changing Finishing Temperature.
**Grain size changed by changing Normalizing Temperature.
***Grain size changed by changing Annealing Temperature.

EXHIBIT VI

PROBLEMS ANTICIPATED IN THE PRODUCTION OF SEMIKILLED STEEL OF ADEQUATE NOTCH TOUGHNESS TO ELIMINATE SERVICE FAILURES

The semikilled grade of ship steel produced with an average carbon content not greater than 0.20 per cent and a manganese content from 1.00 to 1.35 per cent appears to be an acceptable alternative to ABS-C for emergency use(1). From the standpoint of production during an emergency, the most important difference between the proposed grade and World War II ship steel is the difference in manganese level. The change in the grade proposed to replace ABS-C steel is from an average of 0.44 per cent manganese to an average of 1.15 per cent, an increase of 0.71 per cent.

The increase in consumption of ferromanganese can be readily calculated by making the following assumptions:

1. The efficiency of ferromanganese ladle additions is about 85 per cent; that is, roughly one-sixth of the ferromanganese added in the ladle is oxidized and is lost in the slag.
2. The blooming mill and plate mill losses through cropping roughly approximate 20 per cent of the weight of the ingot. This is an important consideration because when the scrap is recirculated through the open hearth, practically all of its manganese is oxidized and lost in the slag.

The difference in manganese between World War II and the proposed semikilled plate amounts to $\frac{2000 \times 0.71}{100}$ or 14.2 pounds of manganese per ton of ship plate. However, in order to compensate for the 15 per cent oxidation loss in the ladle and for the 20 per cent scrap loss in the mills, it is necessary to boost the estimated manganese requirements as follows:

$\frac{14.2}{.85 \times .80} = 20.9$ pounds of metallic manganese,

equivalent to $\frac{20.9}{0.80}$ or 26.1 pounds of ferromanganese (80 per cent manganese) per ton of ingots.

At the current market quotation (June 1, 1954) of 12.5 cents per pound of contained manganese in 80 per cent ferromanganese, the alloy cost of raising the manganese content is approximately $2.61 per ton of plate. Answers to questionnaires sent to producers of ship plate gave $3.00 per ton of ship plate as the quoted (June 1, 1954) extra for producing steel under ABS-B, which has an average manganese content of 0.71 per cent. The proposed semikilled steel with its higher manganese content would carry a somewhat higher extra.

The increased consumption of ferromanganese depends on the level of production. For each one million tons of annual production of the proposed grades, the additional ferromanganese consumption would amount to $\frac{26.1 \times 1 \times 10^6}{2000}$ or 13,050 tons. If there were four million tons of this grade of ship plate produced, the additional manganese requirements could reach 52,200 tons.

This is a quantity which seems modest in comparison with the one million tons of ferromanganese consumed in peak years of post-war steel production. However, during World War II, the pressure on available manganese was very great. In any future emergency, the same situation might again prevail. It appears essential to call this prospective need for manganese to the attention of the groups now concerned with emergency requirements. Other similarly hidden demands may be brought to light. It may be essential to make special provisions for reserving the necessary quantity of manganese for the improved semikilled ship plate steels.

ABS-B and -C require more manganese than World War II ship steel but less than the alternate for ABS-C steel. If the four million tons of plate were divided between ABS-B and the new grade, the manganese requirement would be reduced accordingly.

EXHIBIT VII

ECONOMIC ASPECTS OF THE PRODUCTION AND UTILIZATION OF VARIOUS TYPES OF STEEL PLATES

INTRODUCTION

Barrett and Mahin(15) considered all phases of research on the ship steel problem in their evaluation of the progress to date in this field. In their discussion, they pointed out that there were a number of approaches to the production of ship steel with adequate notch toughness to reduce the service failure rate of ships due to brittle behavior. They urged that an analysis be made of the relative feasibility of the various practices.

This exhibit will discuss the problems involved in the production of killed steel and the manufacturing problems involved in the production of normalized plates and of plates rolled at a low finishing temperature.

The information on production of ship steel used in this exhibit of the report is based in part on answers to a questionnaire sent to the leading producers of ship plate in this country. It has been supplemented by discussions with some of the makers of normalizing furnaces.

PROBLEMS ANTICIPATED IN THE PRODUCTION OF ALUMINUM KILLED STEEL OF ADEQUATE NOTCH TOUGHNESS TO ELIMINATE SERVICE FAILURES

The production of killed steel made to fine-grain practice is more costly than the production of semikilled steels. It involves the use of hot tops; but, even so, there is about a ten per cent greater crop loss than in semikilled steels. Aluminum additions of roughly two pounds per ton of ingots are made. This is equivalent to an aluminum consumption of about three pounds per ton of ship plate. Holding time in the molds is increased, since solidification time of the metal in the hot top is much longer than that of a semikilled ingot cast in an open-top mold. This is a significant economic item because (1) the longer residence of the ingot in the mold reduces the mold life and (2) the delays in the stripping yard slow down production when the mills are operating at full capacity.

According to published information and replies to the questionnaire, all aluminum killed, fine-grained ship steel is cast in hot-topped, big-end-up molds. However, unconfirmed reports indicate that this grade of steel may be successfully cast in big-end-down, open-top molds without hot tops. If this practice proves to be feasible, it may be an important factor because it will prevent the stripping yard from becoming a bottleneck when operations are at full capacity.

The June 1, 1954 published extra for the change in deoxidation practice from semikilled to aluminum killed steel was $10.00 per ton of plates.

The capacity of the steel industry to produce killed steel is limited to about 15 million tons per year. However, not all this capacity could be used for ship plate because of the fact that plates are rolled from slab ingots. Despite a large increase in steel-making capacity since 1945, there has been little increase in capacity to produce killed steel in hot-topped slab ingots. The need for such steel was consistently underestimated early in World War II. In any future emergency, the need for aluminum killed steel for aircraft, ordnance, armor, and other applications will undoubtedly exceed the available capacity. It will not be possible to make enough aluminum killed ship plate steel to meet the needs of a large ship building program. If there is a marked increase in killed steel production capacity or future development of techniques which avoid the use of hot tops, a fraction of the ship plate might be rolled from killed steel ingots. The pressure for killed steel in applications other than ships will probably be so great that every effort should be made to develop semikilled steels with adequate notch toughness.

Information on the cost of additional facilities for making killed steel in hot-topped ingots is not available.

PROBLEMS ANTICIPATED IN THE PRODUCTION OF NORMALIZED PLATES OF ADEQUATE TOUGHNESS TO ELIMINATE SERVICE FAILURES

The normalizing process involves putting a plate of rolled steel into a heating furnace, raising its temperature to about 1650 F, soaking the plate until it has a uniform temperature, and then removing it from the furnace and permitting it to cool in air. In many mills the facilities for normalizing involve handling of plates on a batch basis. Some new types of equipment would permit continuous operation. These new methods are not in general use.

The only advantage of normalizing is that it would permit production of steel of equivalent notch toughness and a reduction in manganese content of semikilled steel by about 0.2 per cent and of killed steel by about 0.4 per cent or steel of greater notch toughness. The facilities for normalizing are relatively limited. It appears that there is substantially less normalizing capacity than capacity to produce killed steel. Planning for the use of a large quantity of steel for ship plate would undoubtedly necessitate the building of additional facilities. In answer to the questionnaire, one steel producer estimated that normalizing facilities to treat 70,000 tons of steel a year in plates 46 in. by 360 in. would cost about $6,500,000. The published extra for normalizing was $20 per ton in 1954. Whether this cost would remain as high if production were at a substantially greater level is difficult to estimate.

PROBLEMS ANTICIPATED IN THE PRODUCTION OF SHIP PLATE ROLLED WITH A LOWER FINISHING TEMPERATURE

Although research carried on at Battelle and elsewhere has clearly indicated that a lower finishing temperature in the plate mill lowers the transition temperature of ship steel, the lowering of finishing temperature under regular production conditions is one step upon which steel producers look askance. The main reason for this is the fact that except in continuous-rolling plants, where the ingot is rolled directly into plate without intermediate slabbing, a finishing temperature of 1650 F is a difficult goal to attain. To do so would substantially reduce the tonnage output during a period of presumed national emergency.

It is also difficult to arrive at a realistic figure of the extra costs imposed by such a practice. As one steel producer expressed it in replying to the questionnaire:

> "To develop such an estimate would be an extremely complex undertaking. It would be necessary to develop specific plate sizes and relate them to our individual plate-producing facilities. Such a survey would vary so much as to make an answer to this question impractical and thus of little value."

EXHIBIT VIII

NOTCH TOUGHNESS OF SHIP STEELS MADE UNDER CURRENT AMERICAN BUREAU OF SHIPPING SPECIFICATIONS

In 1947 the American Bureau of Shipping introduced specifications for hull plate of various thicknesses. A revision to that specification that applied after 1/31/56 is covered by the following important announcement issued by the American Bureau of Shipping.

> "At a meeting of the Technical Committee on November 9, 1955 there were adopted changes to the Bureau's requirements for hull steel plates of greater than 1/2" thickness as recommended by the Special Subcommittee--Materials and the Committee on Naval Architecture. These changes result in the substitution of the following for the present paragraph (10) of Section 39 of the 1955 edition of the Rules for Building and Classing Steel Vessels.
>
> (10) Chemical Composition--Ladle Analysis--
>
> (a) Except as specified in paragraph (b) and (c), the material shall conform to the requirements of Class A as to chemical composition.
>
> (b) Material for plates over 1/2" up to 1" inclusive shall conform to the requirements of Class B as to chemical composition. (Material conforming to the requirements of Class C will be accepted.)
>
> (c) Material for plates over 1" and not exceeding 2" in thickness shall conform to the requirements of Class C as to chemical composition. Where plates of over 1 3/8" thickness are used in important structural parts, it may be required that such plates be produced to special specifications. Plates over 2" in thickness are to be produced to specially agreed upon specifications. In both of these cases the purchaser shall indicate on the orders a notation indicating the agreed upon specification.

"

	Class A	Class B[3]	Class C[1]
Carbon, max. per cent	---	.21	.24
Manganese, per cent	---	.80 to 1.10	.60 to .90
Phosphorus, max. per cent[2]	.04	.04	.04
Sulphur, max. per cent	.05	.05	.05
Silicon, per cent	---	---	.15 to .30

Note[1]--Plate steels produced to the requirements of Class C shall be made with fine grain practice.

Note[2]--Where steel is made by the acid process the maximum per cent phosphorus permitted may be .06

Note[3]--Where the use of material of cold flanging quality has been specially approved (see Sec. 3, Par. 1) the manganese content may be reduced to the range of .60 to .90.

The changes from the present requirements are as follows:

The application of the Rules for Class C material has been limited to plates not exceeding 2" in thickness and the optional clause for special requirements for plates over 1 3/8" in thickness has been transferred from the preamble just preceding Par. (8) of Sec. 39 to new sub-paragraph (c) of Par. 10.

Class B
Carbon max. per cent is now .21 (formerly .23)
Manganese per cent is now .80 to 1.10 (formerly .60 to .90)
Note # 3 has been added

Class C
Carbon max. per cent is now .24 (formerly .25)

These revised requirements are to be made applicable to material for new vessels for which contracts are placed after January 31, 1956 and for all orders for stock or repairs to existing vessels placed after that date. Existing stocks conforming to the previous requirements may be used for repairs or alterations and to some limited extent for new construction, where specially approved, until exhausted."

The tensile properties covered in the specification are as follows:

(a) The material, except as specified in Paragraph (b), shall conform to the following requirements as to tensile properties:

	Structural Steel	Rivet Steel and Steel for Cold Flanging
Tensile Strength, psi	58,000--71,000	55,000--65,000
Yield Point, min, psi	32,000	30,000
Elongation in 8 in., min, %	21	23
Elongation in 2 in., min, %	22	--

(b) Flat-rolled steel 3/16 in. and under in thickness, shapes less than 1 square in. in cross section, and bars, other than flats, less than 1/2 in. in thickness or diameter, need not be subjected to tension tests.

(c) For material over 3/4 in. in thickness or diameter, a deduction from the percentage of elongation in 8 in. specified in Paragraph (a) of 0.50 per cent shall be made for each increase of 1/8 in. of the specified thickness or diameter above 3/4 in. to a minimum of 18 per cent.

(d) For material under 5/16 in. in thickness or diameter, a deduction from the percentage of elongation in 8 in. specified in Paragraph (a) of 1.25 per cent shall be made for each decrease of 1/32 in. of the specified thickness or diameter below 5/16 in.

Plates up to 1/2 in. in thickness, now covered by ABS-A, showed little tendency to fail in service. The notch toughness of steels under ABS-A is currently being evaluated, but data are not yet available for review.

A few of the data on the transition temperature of steels made in accordance with ABS-B* and ABS-C specifications are shown in Table VIII. 1. It can be seen that the transition temperature of steel made under ABS-C is lower than that under ABS-B. A rather wide scatter in values, as in World War II steels, is apparent. Part of this scatter is due to differences in composition and part to other processing variables. The scatter, expressed in terms of the standard deviation, is about 14 F for ABS-B steel and 16 F for ABS-C steel, both of which are somewhat lower than the 18 to 22 F standard deviation of World War II steel.

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*For ABS-B steel made to the revised specifications, the transition temperature should be substantially lower than the value given in Table VIII. 1.

TABLE VIII.1. **CHARPY V-NOTCH 15 FT-LB TRANSITION TEMPERATURES FOR ABS-B AND -C SHIP STEELS**
(Sources of data are the American Bureau of Shipping and the New York Naval Shipyard)

	ABS-B Ship Steel (Thickness, In.)						ABS-C Ship Steel (Thickness, In.)													
	9/16	5/8	3/4	13/16	7/8	1	1-1/8	1-3/16	1-1/4	1-3/8	1-7/16	1-1/2	1-9/16	1-5/8	1-3/4	1-7/8	1-15/16	2	2-1/16	2-1/4
A – American	–	15	3	–	–	15	-38	-30	-30	-8	-20	-40	-17	-12	-28	–	-4	-40	-22	-8
Bureau of	–	34	20	–	–	28	-33	-26	-24	–	-8	-28	+40	0	-20	–	–	-28	–	–
Shipping	–	38	25	–	–	30	-32	-21	-10	–	–	-26	–	–	–	–	–	-15	–	–
Data	–	–	52	–	–	–	-30	-18	-8	–	–	-23	–	–	–	–	–	-10	–	–
	–	–	–	–	–	–	-20	–	–	–	–	-18	–	–	–	–	–	–	–	–
	–	–	–	–	–	–	-12	–	–	–	–	-16	–	–	–	–	–	–	–	–
	–	–	–	–	–	–	–	–	–	–	–	-10	–	–	–	–	–	–	–	–
	–	–	–	–	–	–	–	–	–	–	–	+4	–	–	–	–	–	–	–	–
	–	–	–	–	–	–	–	–	–	–	–	9	–	–	–	–	–	–	–	–
	–	–	–	–	–	–	–	–	–	–	–	11	–	–	–	–	–	–	–	–
	–	–	–	–	–	–	–	–	–	–	–	16	–	–	–	–	–	–	–	–
B – New York	+45	35	55	31	30	51	-3	–	+10	-23	–	–	–	–	–	–	–	–	–	–
Naval	15	33	41	–	–	47	-16	–	–	–	–	–	–	–	–	–	–	–	–	–
Shipyard	10	26	35	–	–	45	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Data	–	23	28	–	–	39	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	–	20	27	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	–	18	4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	–	16	-4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	–	18	-20	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	–	12	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

EXHIBIT IX

EFFECT OF CHANGES IN SERVICE ON SHIP FRACTURE

All of the three conditions necessary for brittle fracture are affected by the operating circumstances:

1. The stress level in a ship depends on its loading and the sea encountered. Many cases are on record in which a fracture is associated with an exceptionally heavy sea. Table IX.1, taken from the final Board Report (11) of July 15, 1946, shows that the ratio of incidence of fractures occurring while the ship was at sea is five times that of the incidence of fracture of ships in port when the temperature was high and nearly sixteen times the incidence of fracture in port when the temperature was low. "Sea conditions varied from calm to storm; and, undoubtedly, if a more careful study were possible, the incidence of fracture under conditions of heavy sea would be in excess of the (5:1 or 16:1) ratios noted above (11)."

   The increased stress introduced by heavy seas probably raises the stress level in many areas and brings into action sharp notches which by virtue of their distance from structural discontinuities are not generally sources of fracture. The increased stress, then, not only makes for more severe conditions at obvious structural notches, but also makes possible fracturing in many other regions of the ship.

2. The notches which can cause fracture operate in part as stress raisers. Since a minimum stress is required for fracture, it is possible that less severe notches can become fracture sources when the nominal stress is higher. Hence, under extreme loading conditions many notches may start cracks which normally would not.

3. Notch toughness of steel is temperature dependent. This has been clearly shown by the transition curves of Exhibit II. The importance of temperature on fracturing rate is shown in Fig. IX.1, taken from the final Report of the Board of Investigation (11). Note the marked increase in failure rate at temperatures below 40 F.

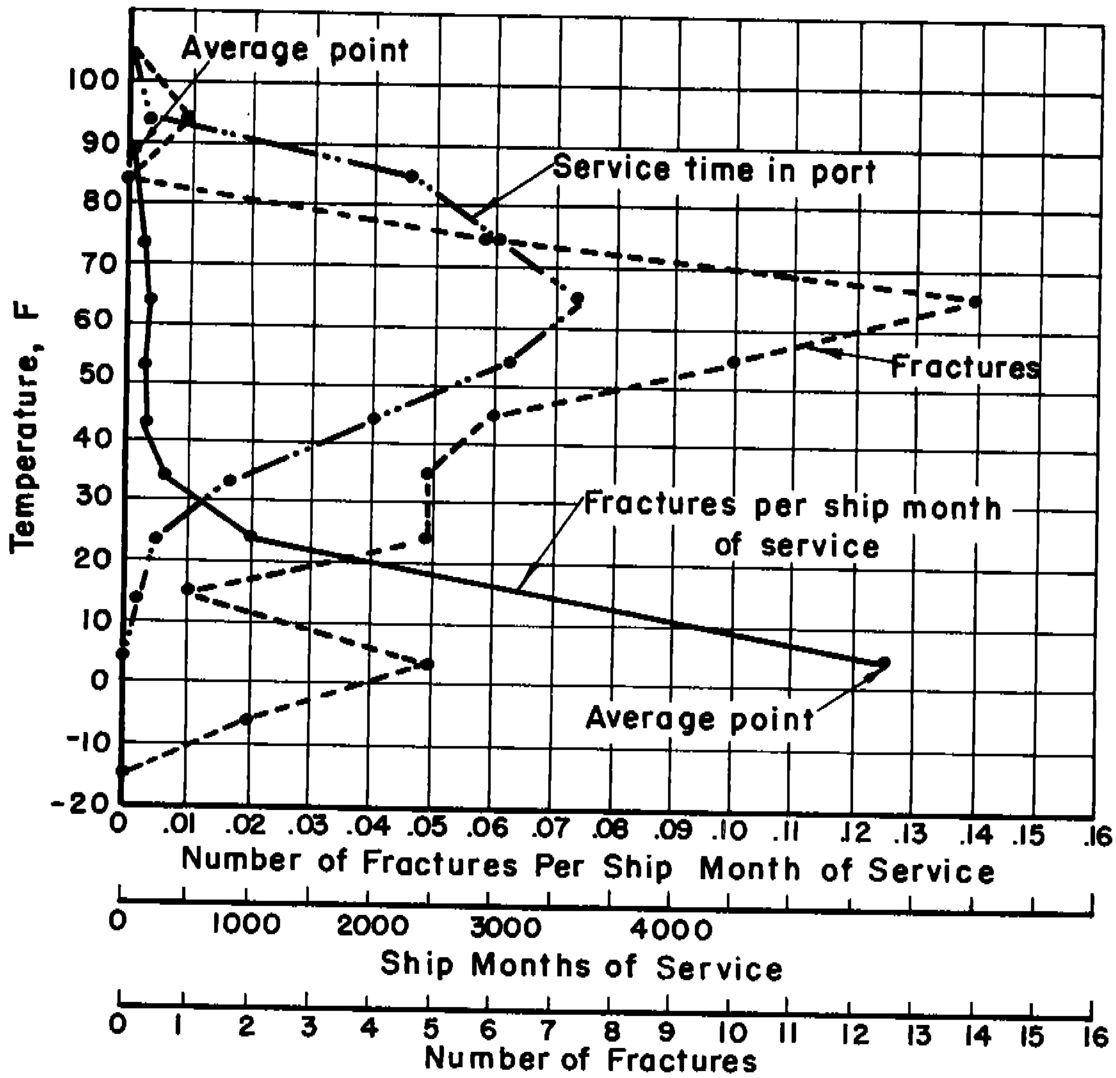

Fig. IX.1. ABOVE WATERLINE FRACTURES VERSUS AIR TEMPERATURE

Based on 55 fractures occuring before 1, August 1945 on 667 selected Liberty Ships (vessels in port only)

All types of fractures(11)

TABLE IX.1. COMPARISON OF NUMBER OF FAILURES AT SEA AND IN PORT*

	Fractures (Groups I, II, and III)	Ratio
Temperature High in Port	11	1
Temperature Low in Port	37	3
Temperature High at Sea**	53	5
Temperature Low at Sea**	519	47

*Taken from page 42,[11] Report of a Board of Investigation-Design and Methods of Construction of Welded Steel Merchant Vessels, 15 July 1946, Washington, D. C. Government Printing Office, 1947.

**It must be realized that two-thirds of the operating time of the 667 Liberty Ships on which this table is based was spent in port; consequently, the service time in the two "at sea" quadrants includes not only time in heavy seas and in normal and calm seas, but also a certain amount of time in port.

> Had substantially more ships been at lower temperatures, it is quite certain that more fracturing would have occurred. It is interesting to note that failures in calm seas or in port occurred at temperatures averaging 15 F below temperatures of fractures in heavy seas (6). This suggests that there is a limiting temperature at sea below which operation is quite uncommon. In port, however, temperatures may be lower. Without these very low temperatures it appears that the failure rate in port or in calm seas would have been reduced by about 25 per cent.

During 1942 and 1943 there were extensive cargo missions in the North Atlantic and the North Pacific. Later in the war the center of merchant ship operations moved to the South Seas.

The World War II period probably included the extremes of temperature which might be anticipated. However, it is generally assumed that operations in any future emergency may include more activity in regions of lower temperature than the average of World War II experience. In considering the effect of lower operating temperature, it appears that within the limits of ambient temperature the state of stress and the severity of the notch will not be altered appreciably. However, a drop in temperature may lead to a significant increase in the percentage of steel which may act as source plates and therefore increase the failure rate.

A general estimate can be made of the effect that lower operating temperatures would have had on World War II ships. It has been shown that source plates have an energy at failure temperature below 11.4 ft-lb with most below 10 ft-lb and the average about 7 ft-lb. The percentage of hull plates with their

10 ft-lb transition temperature below the noted temperature is shown in Fig. IX.2. The distribution of World War II operating temperatures for 667 Liberty ships in port and the rate of fracture of these ships is shown in Fig. IX.1. The fracture rate began to increase very rapidly at about 30 F which, according to Fig. IX.2, is the temperature at which about 85 per cent of the ship plates had energies of 10 ft-lb or less. At 10 F the fracture rate was nearly 10 times the rate at 30 F, and the percentage of plates with an energy of 10 F was about 98 per cent. Below a temperature of 10 F, the fracturing rate might increase very rapidly, as the major effect of temperature is to increase the percentage of plates which serve as potential source plates for brittle fractures. Furthermore, damage from the cracks might also increase because of the chances of finding a plate which can absorb enough energy to stop a crack is also reduced.

The effect of increased operations at low temperatures can be estimated qualitatively from the data already presented in Fig. IX.1 on rate of failure for ships in port as a function of temperature. The rate of failure goes from 0.01 per ship-month at 32 F to 0.02 at 25 F and 0.10 at 10 F. From these data, doubling the time of operation at 10 F would have added three additional fractures out of 55, or an increase of about 5 per cent. Doubling the time of operation below 32 F would have added about 14 failures, an increase of about 20 per cent. A more precise estimate was developed by Hulbert, Chase, and Bell of Battelle as follows:

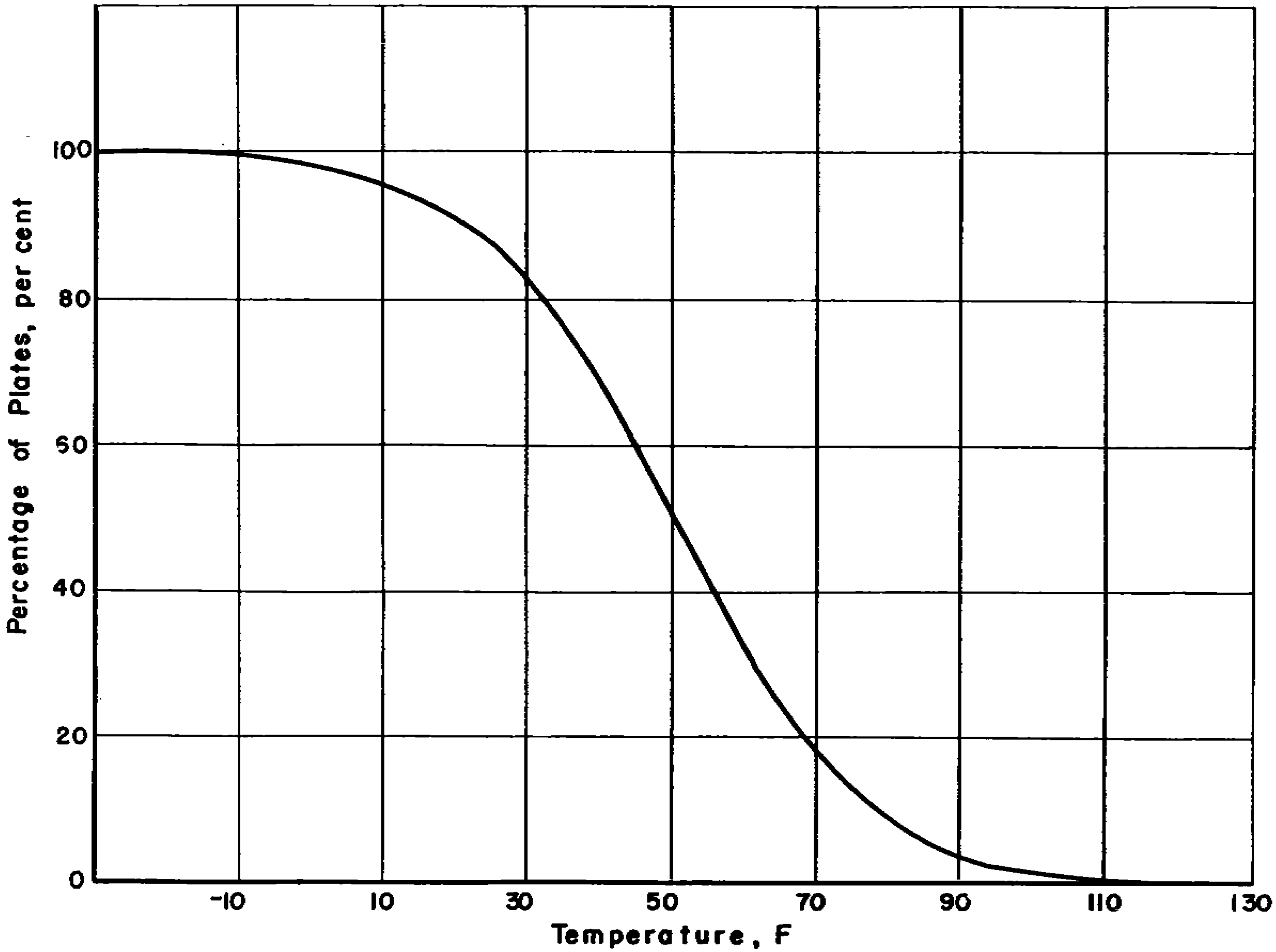

Fig. IX.2. PERCENTAGE OF WORLD WAR II STEELS WITH ENERGIES BELOW 10 FOOT-POUNDS OVER A RANGE OF TEMPERATURES

The estimated fracture rate for changes in mean operating temperature will be obtained in a manner analogous to that of Exhibit IV. To show the extent of the analogy, consider the following. We assume that:

(a) If all other test factors are fixed, the transition temperature x and the operating temperature t influence the probability of failure of a plate only according to some function of the difference of those temperatures.

(b) The relative frequency of plates with transition temperature x is a function solely of x - m, where m is the mean transition temperature of all plates.

(c) The relative frequency of temperatures T at which an arbitrary plate (or ship) can be expected to operate at any time is a function solely of T - n, where n is the mean of all operating temperatures.

We wish to show from these assumptions that the relative fracture rate F, as a function of the mean transition and operating temperatures, is a function of only their difference. That is, $F(m,n) \equiv F(m - n)$.

The operating temperature T, of course, varies with time Θ, so that $T \equiv T(\Theta)$. Now let $P(x - T)$ be the probability of failure per unit time of operation at temperature T for a plate with transition temperature x. Also let $V(T - n)$ be the relative frequency of operating temperatures. Then the probability of fracture per unit time for a plate with transition temperature x is

$$P'(x,n) = \int_{-\infty}^{\infty} P(x - T)\, V(T - n)\, dT$$

$$= \int_{-\infty}^{\infty} P(x - n - \eta)\, V(\eta)\, d\eta.$$

This is a function of only x - n; that is, $P'(x,n) \equiv P'(x - n)$. Since this relation holds at all times, the probability of failure p(x,n) for this plate during the entire test is also a function of only x - n. That is, $p(x,n) \equiv p(x - n)$.

According to the preceding section, the relative fracturability f(x,n) is proportional to the probability of fracture; $p(x,n) \equiv p(x - n)$. Therefore, $f(x,n) \equiv f(x - n)$. According to assumption (b), the relative frequency U(x,m) of plates with transition temperature x is $U(x,m) \equiv U(x - m)$. Then the relative fracture rate is

$$F(m,n) = \int_{-\infty}^{\infty} f(x - n)\, U(x - m)\, dx$$

$$= \int_{-\infty}^{\infty} f(\xi + m - n)\, U(\xi)\, d\xi.$$

Thus $F(m,n) \equiv F(m - n)$, as was asserted.

It is to be noted that assumptions (b) and (c) imply that the shape of the respective distributions are not changed if their means are changed. For instance, if the distributions were normal, this would imply that the means would be changed without changing the standard deviations.

The conclusion reached means that a reduction in mean transition temperature of the steel affects the fracture rate in a manner equivalent to raising the operating temperature by a like amount.

With this in mind an analysis was made of some data collected on the frequency with which ships were at various temperatures in port and the failures that occurred for various ranges of temperatures. These were taken from Fig. 26 of the Final Report of the Board of Investigation[11] which is included in this exhibit as Fig. IX.1.

A. Application to the Original Data. The basic data, read as carefully as possible from the Figure[11], are given in Table IX. 2. Here the failures are recorded per ambient temperature interval. N_i is the service time recorded per temperature interval in terms of ship-months of service. The column headed f_i is simply n_i/N_i. Now, in the previous section, we used $\omega_i/\sum\omega_i$ and $u_i/\sum u_i$ for determining f_i which was the relative fracturability per transition temperature averaged over all operating temperatures. To obtain the relative fracturability per operating temperature averaged over all transition temperatures, one would use the equivalent values $n_i/\sum n_i$ divided by $N_i/\sum N_i$. Therefore, the f_i which is used here is proportional to the fracturability, the proportionality factor being $\sum N_i/\sum n_i$. This factor is canceled in determining the relative fracture rate, so that no attempt was made to evaluate it for this section. No smoothing of the variation of f_i was made in this calculation. Table IX.3 gives the relative fracture rates if the mean operating temperature is shifted by S degrees.

TABLE IX.2. COMPUTATION OF RELATIVE FRACTURABILITY PER OPERATING TEMPERATURE INTERVAL (UNSMOOTHED DATA)

Ambient Temperature Interval	Recorded Failures (n_i)	N_i	f_i
-20 to -10	0	-	-
-10 to 0	2	*	-
0 to 10	5	*	-
10 to 20	1	100	.010
20 to 30	5	250	.020
30 to 40	5	850	.0059
40 to 50	6	2100	.0029
50 to 60	10	3200	.0031
60 to 70	14	3700	.0038
70 to 80	6	3100	.0019
80 to 90	0	2300	0
90 to 100	1	200	.005
100 to 110	0	*	0

*These are values different from zero, but too small to estimate from the graph.

TABLE IX.3. RELATIVE FRACTURE RATES FOR OPERATING TEMPERATURE DISTRIBUTIONS HAVING VARIOUS MEANS

S °F	Relative Fracture Rates, % of World War II
0	100
+10	78
+20	62
+30	49
+40	35
+50	20
+60	7
+70	2

B. Application to the Adjusted Data. It is also possible to use smoothed curves for these calculations instead of the raw data. MacCutcheon and Wright[5] fitted the original curve of ship-months of service per operating temperature with a normal curve, obtaining the relation:

$$f(T) = 379 \exp - \left[0.04(65 - T)\right]^2$$

The N_i obtained from this curve, together with the n_i of Table IX.2 (adjusted as noted), the values $f_i = n_i/N_i$, and values f_i* derived from f_i (which was smoothed in this case) are given in Table IX.4. Table IX.5 again gives the relative fracture rates obtained if the mean operating temperature is shifted S degrees.

TABLE IX.4. COMPUTATION OF RELATIVE FRACTURABILITY PER OPERATING TEMPERATURE INTERVAL (SMOOTHED DATA)

Ambient Temperature Interval	Recorded Failures (n_i)	N_i	f_i	f_i*
-20 to -10	0	0.17	0	0
-10 to 0	2	1.80	1.1129	1.16563
0 to 10	5 (adjusted to 3)	13.67	0.2195	0.22990
10 to 20	1 (adjusted to 3)	75.99	0.03948	0.04137
20 to 30	5	309.94	0.01618	0.01686
30 to 40	5	920.21	0.00543	0.00576
40 to 50	6	2005.54	0.00299	0.00377
50 to 60	10	3200.57	0.00312	0.00304
60 to 70	14	3740.04	0.00374	0.00241
70 to 80	6	3200.57	0.00187	0.00189
80 to 90	0	2005.54	0	0.00136
90 to 100	1	920.21	0.0011	0.00094
100 to 110	0	309.04	0	0.00052
110 to 120	0	75.99	0	0.00021
120 to 130	0	13.67	0	0

TABLE IX.5. RELATIVE FRACTURE RATES FOR OPERATING TEMPERATURE DISTRIBUTIONS HAVING VARIOUS MEANS

Change in Mean Operating Temperature - S °F	Relative Fracture Rates, % of World War II
-20	510.5
-10	199.7
0	100.0
+10	64.4
+20	45.5
+30	31.5
+40	20.2
+50	11.6
+60	6.1

A comparison of Table IX.5 with Table IV.4 shows a somewhat slower reduction in fracture rates with a change in temperature for Table 4. This may be due in part to the lower stresses encountered by ships in port. However, this is only one of the things which could have affected the rate.

In view of the fairly radical differences in the conditions of the two tests, the results agree surprisingly well.