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EVALUATION OF FRACTURE CRITERIA FOR SHIP STEELS AND WELDMENTS

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1981

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An Interagency Advisory Committee
Dedicated to Improving the Structure of Ships

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The Ship Structure Committee in recent years has funded a number of research projects in the areas of fatigue, fracture control, and crack resistance of steels and weldments. Fracture toughness criteria have been proposed. However, there are questions and assumptions that have not been resolved. The Ship Structure Committee was, therefore, very appreciative and accepted the offer of the American Iron and Steel Institute to fund a review and analysis. The Committee is grateful to the Institute for permission to publish the results of the study.

This report presents the state-of-the-art interpretation on the correlation of fracture toughness in ships steels and weldments to proposed criteria for adequate fracture resistance in service.

Clyde T. Lusk, Jr.
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

The purpose of this report is to review in the light of currently existing data the fracture-toughness guidelines for welded ship hull steels first proposed in 1974 by Rolfe and his co-workers and published in Ship Structure Committee Report 244 "Fracture-Control Guidelines for Welded Steel Ship Hulls." The essence of the guidelines was an NDT temperature requirement of 0°F for steel used in primary load-carrying members and an NDT temperature requirement of 20°F for steels used in secondary load carrying members. A subsidiary requirement for primary members was a dynamic tear energy in 5/8 in. specimens, depending on steel strength, of 250 to 500 ft-lb. at 75°F. Crack-arrest materials would be required to have a dynamic tear energy in 5/8 in. specimens, again depending on steel strength, of 600 to 800 ft-lb. at 32°F.

Subsequent to this report, a number of research investigations were undertaken by the Ship Research Committee and others to determine what the characteristic toughnesses of currently used ship plate were with respect to the proposed guidelines. At the same time, research on loads and loading rates in ships and on the effects of strain rates and on the fracture toughness of ship steels produced data that could be used to test some of the assumptions underlying the guidelines.

(Continued)

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16. Abstract (Continued)

Review of this research indicates that ship hull steels currently used with general success will not meet the proposed toughness criteria for primary load-carrying main stress members and that the crack-arrest criteria can be met by only a very few of the steels currently used for this purpose. Moreover, many of the common ship steel weldments will not provide the toughness specified in the guidelines. The research work demonstrates that strain rates experienced by ships in service are not as high as assumed in the guidelines and that the crack-toughness levels available in ship hull steels during dynamic crack initiation, propagation and arrest are higher than those implied in the impact tests proposed for fracture control in the service temperature range.

On this basis, modifications to the proposed guidelines are necessary to recognize the toughness reserve available in the steels currently used in ship service in primary and secondary load-carrying members in main stress regions of the ship hull. It is also shown that few, if any, steels can provide assurance of arresting large running cracks utilizing only the toughness resident in the steel. It is recommended the crack-arrest be treated as a problem in which the design, the location, and the material of the crack arresting system work together to affect fracture control.

Proposed areas of future research included in this report are the developing of a greater data base with respect to the behavior of ship hull weldments and the fracture-toughness characterization of ship steels over a range of loading rates in the NDT temperature range. Crack arrest test development and a better understanding of crack arrester systems are another needed research area. Finally, there is still a need to develop a simple fracture-toughness test that can be used to assess K_{Id}/σ_{yd} ratios in ship steels at the loading rates similar to those experienced in service.

CONTENTS

I. Introduction

A. Historical Background

The problem of developing adequate fracture-toughness criteria for ship plate steels is one of long standing. Starting with World War II, there have been a series of research investigations which have had as their focus insuring that ship plate materials will have sufficient resistance to brittle fracture. The initial investigations are long since documented and now well known in the engineering community. These investigations made the Charpy impact test the fracture-toughness standard that it has been for the last thirty years and gave the 15 ft-lb. energy level in the Charpy test the significance that it has today. The contribution of these studies, and the use of a transition temperature based on the Charpy impact test to control fracture cannot be over estimated. It was perhaps one of the most important steps in the chain of fracture-control development that has been seen in the past fifty years. However, in the period of time since those test studies were completed, many changes have taken place in the materials and in the types of service that are required of ship plate. In general, strength levels and plate thicknesses have tended to increase over the time period between 1945 and today, and it is natural that criteria used to control the fracture toughness of the plates that were used in ships in the past may now have to be re-examined in the light of the compositions and thicknesses employed today.

It may be expected that re-examination of the brittle fracture control plan for ships, as with other large structures, will be a continuous discipline. As the decades have passed since those first engineering studies, a significant number of new fracture-control concepts have been developed and applied. Some of these concepts have not been developed within the context of ordinary ship plate material and may not necessarily be useful in transport ships. Ship plates developed for naval applications in which both high strength and high toughness are required led to the development of a series of new fracture-control tests beginning with the drop weight test[1] in the mid-1950's through to the dynamic tear test[2] which was developed in the 1960's. The intent of these two tests was to assess the toughness of ship plate material using larger specimens than the standard Charpy impact test, and, therefore, simulating more directly the behavior of higher strength and greater thickness ship plate. It is not surprising that the tests developed for these ship structure applications would eventually influence the testing techniques applied to more ordinary ship plate.

B. Development of Fracture Mechanics

Parallel development with high-strength steels in the same time period led to a series of fracture-control concepts which we refer to today as

Linear Elastic Fracture Mechanics. Indeed, the study of the behavior of high-strength materials under conditions of high constraint has had an important influence on the concepts of fracture control as they are applied to low strength, low constraint ship structures. For example, there has been a strong tendency in the last five years to reinterpret the older more established toughness tests, and to attempt to utilize the data that have been generated from them over a period of thirty years by giving them new interpretations. Indeed, there have been substantial efforts to modify such tests as the Charpy impact test to enable them to provide the kind of information that can be directly utilized in fracture-toughness-based fracture-control plans.

The initial studies of Linear Elastic Fracture Mechanics suggested that small-sized tests, such as the Charpy test, could not provide the fracture-behavior information necessary for fracture control in engineering structures. There are studies that dispute the accuracy of this position.[3] Moreover, subsequent studies of the behavior of large structures have shown that, while brittle fracture under plane strain can occur, the most common service loadings for many structures produce conditions between the plane strain and plane stress. On this basis, the conditions of the Charpy test, while far from ideal from a theoretical viewpoint, may be useful in establishing adequate empirical relationships. Indeed, it was found that older fracture-control plans based primarily on the Charpy test could be shown to have incorporated fracture-toughness concepts even if their original basis was primarily empirical.

C. Ship Structure Committee Studies

A major review of fracture-control plans for steel ship hulls was undertaken by Rolfe, Rhea and Kuzmanovic under the sponsorship of the Ship Structure Committee in 1972 and was published in 1974.[4] This significant work undertook to examine not only the material performance characteristics required for ship hull service but also to develop criteria for design factors what would interact with material behavior to provide assurance that brittle fracture would not occur in welded steel ship hulls. It is not surprising that this work would suggest many areas of future research and, beginning in 1975, a subsequent series of research programs were undertaken under Ship Structure Committee sponsorship. It was the purpose of these studies to clarify points raised in the report of Rolfe et al. and to provide data on ship plate material to establish whether the criteria developed were practical and applicable to ship materials used today. These research programs eventually resulted in additional Ship Structure Committee reports. Notable among these studies was a material toughness study entitled "Fracture Toughness Characterization of Shipbuilding Steels," a research investigation performed at the Naval Research Laboratory by Hawthorne and Loss.[5] A follow-up study entitled, "Fracture-Behavior Characterization of Ship Steels and Weldments," by Frances, Cook and Nagy[6] was completed with a study of strain-rate effects using the same steels entitled "The Effect of Strain Rate on the Toughness of Ship Steels," also by Frances, Cook and Nagy.[7] Both of these latter studies were done at Southwest Research Institute. The subsequent reports, combined with the report of Rolfe et al., were designed to include information on the range of the materials used in ship plate and how they related to the criteria proposed. They were also to determine what further research information would be required to fully implement the suggestions.

D. Research by Other Agencies

At the same time as the Ship Structure Committee was sponsoring research, data were also being obtained on similar materials at other agencies. For example, a substantial amount of data on materials of similar composition and mechanical properties were developed under the auspices of the American Association of Highway and Transportation Officials (AAHTO). This organization had undertaken to develop rational fracture-control plans for bridge structures in the early 1970's.[8] In order to do so, they made a series of research investigations to assess aspects of the fracture-control problem that were not included in the Ship Structure Committee work. Moreover, during the same time period, investigations of the fracture behavior of carbon-manganese and carbon-manganese-alloy steels had also been undertaken by the Pressure Vessel Research Committee of the Welding Research Council.

In conjunction with a number of companies, the WRC-PVRC undertook to develop data on the fracture behavior of materials used in nuclear pressure vessels.[9] The intent was to develop a rational fracture-control plan for nuclear reactors based on a fracture-mechanics characterization of the steels. The development of this fracture-control plan, which eventually became part of the ASME Boiler and Pressure Vessel Code Section III, also stimulated a number of research investigations by companies and agencies involved in the nuclear power industry. Notable among these were investigations sponsored by the Electric Power Research Institute and the Heavy Section Steel Technology Program. These were aimed at obtaining a characterization of at least several grades of steels used in nuclear reactors. While these investigations were not of materials that were directly comparable to ship steels, it is apparent from an examination of the compositions, microstructures and general mechanical behavior of these steels that much of the information could be applicable to ship steels as well.

E. Scope of This Evaluation

Thus, it appears reasonable on the basis of the extensive work undertaken since the publication of the fracture-control guidelines for welded steel ship hulls developed by Rolfe et al., that a careful re-evaluation of those guidelines be undertaken in the light of the now existing data. It is the purpose of this report to make such an analysis. Foremost in the evaluation of the guidelines will be the work reported and discussed in Ship Structure

Committee Reports 248, 275 and 276. However, the work performed under the sponsorship of the Pressure Vessel Research Committee and by other agencies will also be considered. In addition, part of the information needed to develop the fracture-control guidelines in more detail, that is, the stresses and strain rates in ship hulls, have been developed over the 6-year period since the publication of SSC Report 244. These data have primarily been from additional Ship Structure Committee research studies and, indeed, are the fruition of a number of years of research on instrumented ship hulls. These data are an important input into an evaluation of any ship fracture-control program and need to be used to evaluate the fracture criteria in the fracture-control guidelines published in 1974.

At the start of this study, the specific charge to the author was to answer three basic questions.

1) Are enough data available to adequately assess the proposed fracture-toughness criteria?

2) Are the fracture-test methods proposed in Ship Structure Committee Report 244 adequate measures of material performance in ship applications?

3) Based on material data and service performance, are modifications to the proposed criteria needed?

It is the purpose of this report to try to answer these questions and to determine what research, if any, is needed to provide answers to those questions for which current information is inadequate.

II. Current American Bureau of Shipping Ship Hull Steel Requirements

The current ship steels included in the American Bureau of Shipping specifications are indicated in Tables 1 and 2. The basic requirements for the purchase, inspection, testing, repairing and application of these steels, as well as their method of manufacture and heat treatment, are found in Section 43 of the American Bureau of Shipping Rules for Building and Classing Steel Vessels[10] from which Tables 1 and 2 are derived. The general division of steels is into "Ordinary-strength Hull Structural Steel," including Grades A, B, D, E, DS and CS, and "Higher-strength Hull Structural Steel," including Grades AH32, DH32, EH32, AH36, DH36 and EH36. Section 43 also includes "Low Temperature Materials" which are steels for cargo tanks and secondary barriers for carrying liquified low-temperature cargos, and sections on hull steel castings and forgings.

A. Ordinary and Higher Strength Steels

Considering only the ordinary strength and higher strength hull struc-

TABLE 1

Requirements for Ordinary-strength Hull Structural Steel Grades A, B, D, E, DS, CS

Grades	*A*	*B*	*D*	*E*	*DS*	*CS*
Deoxidation	Any method except rimmed steel for plates over 12.5 mm (0.5 in.)	Any method except rimmed steel	Fully killed fine-grain practice[2] (See 43.3.2d)	Fully killed fine-grain practice (See 43.3.2d)	Fully killed fine-grain practice (See 43.3.2d)	Fully killed fine-grain practice (See 43.3.2d)
Chemical Composition (Ladle Analysis)	For all grades exclusive of Grade A shapes and bars the carbon content +1/6 of the manganese content is not to exceed 0.40%. The upper limit of manganese may be exceeded up to a maximum of 1.65% provided this condition is satisfied.					
Carbon %	0.23 max.[1]	0.21 max.	0.21 max.	0.18 max.	0.16 max.	0.16 max.
Manganese %	2.5x carbon min. for plates over 12.5 mm (0.5 in.)	0.80–1.10 0.60 min. for fully killed or cold flanging	0.70–1.35 0.60 min. for thickness 25 mm (1.0 in.) and under	0.70–1.35	1.00–1.35	1.00–1.35
Phosphorus %	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.
Sulphur %	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.
Silicon %		0.35 max.	0.10–0.35	0.10–0.35	0.10–0.35	0.10–0.35
Tensile Test						
Tensile strength	For all Grades: 41–50 kg/mm² (58,000–71,000 psi); for Grade A shapes 41–56 kg/mm² (58,000–80,000 psi). For cold flanging quality: 39–46 kg/mm² (55,000–65,000 psi)					
Yield Point, min.	For all Grades: 24 kg/mm² (34,000 psi); for Grade A over 25.0 mm (1.0 in.) in thickness 23 kg/mm² (32,000 psi). For cold flanging quality: 21 kg/mm² (30,000 psi)					
Elongation, min.	For all Grades: 21% in 200 mm (8 in.) (See 43.3.4d and 43.3.4e) or 24% in 50 mm (2 in.) (for specimen see Figure 43.2) or 22% in 5.65 $\sqrt{A}$ (A equals cross-sectional area of test specimen). For cold flanging quality: 23% min. in 200 mm (8 in.)					
Impact Test Charpy V-Notch						
Temperature		0C (32F) Over 25 mm (1.0 in.)	−10C (14F)	−40C (−40F)		
Energy avg. min. Longitudinal Specimens or Transverse Specimens		2.8 kg-m (20 ft-lbs) 2.0 kg-m (14 ft-lbs)	2.8 kg-m (20 ft-lbs) 2.0 kg-m (14 ft-lbs)	2.8 kg-m (20 ft-lbs) 2.0 kg-m (14 ft-lbs)		
No. of Specimens		3 from each 50 tons	3 from each 50 tons[3]	3 from each plate		
Heat Treatment			Normalized over 35 mm (1.375 in.) thick[4]	Normalized		Normalized
Marking	$\frac{AB}{A}$	$\frac{AB}{B}$	$\frac{AB^{5}}{D}$	$\frac{AB}{E}$	$\frac{AB}{DS}$	$\frac{AB}{CS}$

Notes

[1] A maximum carbon content of 0.26% is acceptable for Grade A plates equal to or less than 12.5 mm (0.5 in.) and all thicknesses of Grade A shapes.

[2] Grade D may be furnished semi-killed in thickness up to 35 mm (1.375 in.) provided steel above 25.0 mm (1.00 in.) in thickness is normalized. In this case the requirements relative to minimum Si & Al contents and fine grain practice do not apply.

[3] Impact tests are not required for normalized Grade D steel when furnished fully killed fine grain practice.

[4] Control rolling of Grade D steel may be specially considered as a substitute for normalizing in which case impact tests are required for each 25 tons of material in the heat.

[5] Grade D hull steel which is normalized or controlled rolled in accordance with Note 4 is to be marked $\frac{AB}{DN}$.

TABLE 2

Requirements for Higher-strength Hull Structural Steel, Grades AH32, DH32, EH32, AH36, DH36, and EH36

Process of Manufacture: Open Hearth, Basic Oxygen, or Electric Furnace

Grades[1]	*AH32*	*DH32*	*EH32*	*AH36*	*DH36*	*EH36*
Deoxidation	Semi-Killed or Killed[3]	Killed, Fine Grain Practice[4]	Killed, Fine Grain Practice[4]	Semi-killed or killed[3]	Killed, Fine Grain Practice[4]	Killed, Fine Grain Practice[4]

Chemical Composition for All Grades
(Ladle analysis)

Carbon, %	0.18 max.	
Manganese, %[2]	0.90–1.60	
Phosphorus, %	0.04 max.	
Sulfur, %	0.04 max.	
Silicon, %[3]	0.10–0.50	
Nickel, %	0.40 max.	These elements need not be reported on the mill sheet unless intentionally added.
Chromium, %	0.25 max.	
Molybdenum, %	0.08 max.	
Copper, %	0.35 max.	
Columbium, % (Niobium)	0.05 max.	
Vanadium, %	0.10 max.	

Tensile Test

	AH32, DH32, EH32	AH36, DH36, EH36
Tensile Strength	48–60 kg/mm^2; 68,000–85,000 psi	50–63 kg/mm^2; 71,000–90,000 psi
Yield Point or Yield Strength, min.	32 kg/mm^2; 45,500 psi	36 kg/mm^2, 51,000 psi

Elongation, min. For All Grades: 19% in 200 mm (8 in.) or 22% in 50 mm (2 in). (for specimen in Figure 43.2) or 20% in $5.65\sqrt{A}$ (A equals area of test specimen)

Impact Test
Charpy V-Notch

	AH32	*DH32*	*EH32*	*AH36*	*DH36*	*EH36*
Temperature	None Required	−20C (−4F)	−40C (−40F)	None Required	−20C (−4F)	−40C (−40F)
Energy, avg. min.						
Longitudinal Specimens		3.5 kg-m (25 ft-lb)[5]	3.5 kg-m (25 ft-lb)		3.5 kg-m (25 ft-lb)[5]	3.5 kg-m (25 ft-lb)
or						
Transverse Specimens		2.4 kg-m (17 ft-lb)[5]	2.4 kg-m (17 ft-lb)		2.4 kg-m (17 ft-lb)[5]	2.4 kg-m (17 ft-lb)
No. of Specimens		3 from each 50 tons	3 from each plate		3 from each 50 tons	[illegible] each plate
Marking	AB/AH32	AB/DH32[6]	AB/EH32	AB/AH36	AB/DH36[6]	AB/EH36

Notes

1 The numbers following the Grade designation indicate the yield point or yield strength to which the steel is ordered and produced in kg/mm^2 or psi.

2 Grade AH 12.5 mm (0.50 in.) and under in thickness may have a minimum manganese content of 0.70%.

3 Grade AH to 12.5 mm (0.50 in.) inclusive may be semi-killed in which case the 0.10% minimum *Silicon does not apply.* Unless otherwise specially approved, Grade AH over 12.5 mm (0.50 in.) is to be killed with *0.10 to 0.50 percent Silicon.*

4 *Grades* DH and EH are to contain at least one of the grain refining elements in sufficient amount to meet the fine grain practice requirement. (See 43.5.2d).

5 Impact tests are not required for normalized Grade DH.

6 The marking AB/DHN is to be used to denote Grade DH plates which have either been normalized or control rolled in accordance with an approved procedure.

Heat Treatment Requirements for Higher Strength Hull Structural Steels

Grade	*AH*[1]	*DH*[1]	*EH*
Aluminum Treated Steels	Over 35 mm (1⅜ in.) Thick	Over 25.5 mm (1 in.) Thick	All Thicknesses
Columbium[2] or Vanadium	Over 12.5 mm (0.5 in.) Thick	Over 12.5 mm (0.5 in.) Thick	All Thicknesses

Notes

1 Control rolling of Grades AH and DH may be specially considered as a substitute for normalizing in which case impact tests are required on each plate. In these cases Grade AH is to be tested at 0C (32F) to meet an absorbed energy requirement of 3.5 kg-m, (25 ft-lb) longitudinal, or 2.4 kg-m (17 ft-lb) transverse. Grade DH is to be tested in accordance with Table 43.2 for Grades DH 32 and DH 36.

2 When Columbium or Vanadium are used in combination with each other or with Aluminum, the heat treatment *requirements for Columbium* or Vanadium apply.

3 When Columbium or Vanadium are used in *combination* with Aluminum, the heat treatment requirements for Columbium or Vanadium apply.

tural steels, the specification can be seen to be relatively complex and includes many of the metallurgical and mechanical factors that influence strength and toughness in C-Mn steels. From Grade A to Grade CS, the nominal strength is the same: 34 ksi yield strength and 58-71 ksi tensile strength, with a few exceptions. Tensile ductility is also the same, over 21% elongation. The toughness will vary depending on composition, heat treatment, thickness and deoxidation practice, and may generally be expected to increase from Grade A to Grades E, DS and CS. Across this spectrum of grades, the carbon content decreases and the manganese content increases. Grades D, E, DS and CS require fine-grain practice, verified by a minimum aluminum content or a Mc-Quain Ehn grain size of 5 or finer, and Grades E and CS are normalized.

In addition, there are size limitations on each grade depending on their characteristic toughness and whether they are used in high stress regions. For example, Grade A is limited to 0.75 in. except in less critical ship locations, where the limitation is 2.0 in. Grade B is permitted up to 1.0 in. except as a substitute for Grade A where the 2.0 in. limitation applies. Grade DS is acceptable to 1.37 in. and Grades D, E and CS are acceptable to 2.0 in. It should be noted that toughness specifications are set for Grades B, D, and E, and they are increasingly more severe across these grades. The toughness specifications for Grade B, like the heat-treatment specification for Grade D, depend on plate thickness.

It should be noted that the current specifications do not include Grade C. This grade was a significant portion of the Ship Structure Committee program, but has been discontinued by ABS during the course of the investigation. Grade C was ordinary strength hull steel made to fine grain practice, and for which impact testing was not required but could be substituted for verification of deoxidation practice. It was to be normalized over 1.25 in. in thickness.

The higher strength hull structural steels, Table 2, follow a similar pattern to the ordinary strength steels, except that compositions all fall within the same general bands. The yield and tensile strengths are uniform, 45.5 ksi and 68-85 ksi, respectively, for Grades AH32 to EH32 and somewhat higher for Grades AH36 to EH36: 51 ksi for yield strength and 71 to 90 ksi for tensile strength. Deoxidation practice changes across the grades, as does toughness specifications. The greatest toughnesses are found in Grades EH32 and EH36, a 25 ft-lb. longitudinal transition temperature at -40°F.

The use of these steels, both ordinary and higher strength, is also governed by the ABS design rules for various types of vessels. For example, Sections 15.13, 16.7, 22.33 and 23.11 refer to "special materials" and Sections 15.15, 16.9 and 23.1.5 refer to higher strength materials. Special design requirements are recognized in the use of these materials.

B. Special Materials and Crack Arrest

Special material is used in several sections as an approach to the problem of crack arrest, which is discussed in some detail in the report of Rolfe, et al.[3] The special material portions of Section 43, i.e., 43.3.8b and 43.5.3b, called "special applications," further limits the permissible thicknesses of most grades, presumably to control toughness. Crack arrest itself is not mentioned in the current ABS design rules, however, as a substitute for special materials it is possible, under some conditions, to use a crack-arresting riveted seam at that location. Moreover, the special materials are required at those locations where crack-arrest systems would be traditionally applied. That is, they are applied to deck stringer plates, at the sheerstrake and at the lower turn of the bilge. From this, it may be assumed that the intent is to provide a higher toughness material at these locations to either inhibit crack initiation or to provide additional resistance to crack propagation.

Experience with ship construction indicates that most ships are constructed predominately with ABS B steel in the central portions, with the higher quality grades being reserved for the special materials. Thus, the grades such as D, E, DS and CS and their equivalent high-strength grades are the usual special materials.

C. Welding Control

Qualification of welders, welding design, and testing and inspection of welds is covered in Section 30 of the ABS Rules for Building and Classing Steel Vessels.[10] Welding procedure controls are set in this section as well as qualification tests. Welding procedure qualifications in Section 30.43.4 require only tension and bend testing. Impact testing of weldments is included in Section 30.43.5 "Special tests," which may be required for certain applications. Specific toughness requirements for weldments are not stated.

Composition of the steel welded exerts considerable control over weldability, particularly with respect to delayed cracking. The C + Mn limitations in Tables 1 and 2 provide a control on steel weldability that should limit delayed cracking. Nondestructive examination requirements of Section 30 also recognize the potential for delayed cracking and recommend an inspection schedule that will take this into account.

III. Review of Ship Structure Committee Reports on Guidelines for Ship Hull Steels

A. Proposed Guidelines by Rolfe and Co-workers

The essence of the work done by Rolfe and his co-workers on Ship Research Committee Project 202, (published as SSC Report 244), was to reduce the general requirements for ships hulls to a fracture-control plan that included materials, design and inspection, and was based on fracture-mechanics principles. In their evaluation of the requirements for ship hulls, Rolfe and co-workers stated that three things were necessary to establish an effective fracture-control plan for ship steels. These were: 1. material toughness at the service temperature, loading rate and plate thickness involved; 2. a knowledge of the anticipated flaw size in the structure which would initiate brittle fracture; 3. a knowledge of stress, including residual stress, which might be expected at the point of fracture initiation. Of course, all three factors can be interrelated by use of fracture-mechanics concepts and they can be used to define conditions under which brittle fracture could initiate or could be prevented.

In the report that eventually resulted from the Ship Research project, it was apparent that definition of these factors was difficult. For example, stress levels in ships are not well defined and, thus, it was not possible to calculate the flaw sizes which are critical. The resulting position taken was that a flaw is under a high stress level due to weld residual stress and, thus, fracture control must occur in the presence of the yield point stress. While at first assumption this may appear to be a fairly reasonable one, it places a severe requirement on the plate material in terms of the toughness that it must provide. A second parameter, not well defined in the analysis of ship behavior using fracture mechanics concepts, was typical flaw sizes. It was known that ship hulls can have fairly large flaws from the experience of inspection of ships at dry docking, and the assumption was made that large flaw sizes would be present. This again places a severe requirement upon the toughness of the ship hull material.

Another assumption in this report was that the loading rate appropriate for ship service is fully dynamic. This assumption was presumably based on the general concept that wave slamming and service conditions in high seas will produce fully dynamic loads, and these could be reproduced by Charpy or other impact types of tests. As will be described later, impact test rates are indeed quite high, and the toughness of materials used in ship hulls is very sensitive to loading rate. The selection of impact rates for tests adds an element of great significance to the proposed fracture-control plan.

The sum effect of these three assumptions was that the primary element of fracture control would be the hull material. If ship hull stresses, flaw sizes and loading rates were considered difficult, if not impossible, to define, the only resort is to expect the material to be able to resist fracture under the most unfavorable of conditions.

With material toughness thus playing the key role in the fracture control plan, it is not surprising that the report by Rolfe et al. suggested that a fracture-toughness test, specifically the drop weight test, be performed on all ship plate and that this test be used in place of processing control as the primary fracture-control technique.

The basic elements of the proposed plan are as follows.

1. Fracture Control in Hulls

The level of toughness proposed for primary load-carrying members in the main-stress regions of the hull was an NDT temperature of $0^{o}F$. It was argued that this level of fracture toughness implies that a K_{Id}/σ_{yd} ratio of 0.9 will be achieved at $32^{o}F$ in a normal material if a $0^{o}F$ NDT temperature is used as a checkpoint. It was understood that $0^{o}F$ is below the service temperature of ship plate but it was pointed out that if $0^{o}F$ is used as a test temperature then it may reasonably be assumed that the K_{Id}/σ_{yd} ratio for this material would be approximately 0.6 at $0^{o}F$. All material with normal rising toughness characteristics would bring the K_{Id}/σ_{yd} ratio at $32^{o}F$ into the range of 0.9 or above. This should assure that the fracture toughness in the service temperature range for this material, provided it was at a thickness of 2" or less, would be in the non-plane-strain regime, that is, the fracture toughness would be sufficiently high that through-thickness yielding would occur prior to fracture under impact loading conditions.

An NDT temperature of $0^{o}F$ alone could not guarantee in all cases that steel toughness was rising rapidly in the temperature range immediately above the NDT temperature. This condition was assured by requiring the dynamic tear test at a higher temperature with a minimum energy level to be met depending on the strength level of the steel. The higher temperature was proposed to be $75^{o}F$. If the yield strength of the steel in static tests was 40 ksi then the energy required in a 5/8 inch DT specimen was 250 ft-lb. at $75^{o}F$. For steels of higher strength levels--50, 60, 70 up to 100 ksi, the energy absorption requirement for a 5/8 inch DT specimen rose regularly to a maximum of 500 ft-lbs. An effort was made to develop equivalent Charpy V-notch toughness values for the required DT values. This was a recognition that the Charpy test was much more widely applied to ship plate and other structural materials than the dynamic tear test. However, the correlation between dynamic toughness in the DT tests and the Charpy V-notch test was not entirely certain. The DT test requirements for these steels are listed in Table 3.

In addition to a standard for load-carrying members in the main stress regions, a toughness requirement was also established for primary load-carrying members in the secondary stress regions. For these regions, it was considered that stresses were less than one-half the value in the main stress region and accordingly the required K_{Id}/σ_{yd} ratio was less. It was established that a K_{Id}/σ_{yd} of 0.6 was all that was required. To determine that this requirement was met, the test specified was the drop weight test and the NDT temperature was to be at or below $20^{o}F$. This was less demanding than the requirement that the NDT temperature be $0^{o}F$ and it was an attempt to recognize the lower stress regions do not require the levels of fracture toughness that higher stresses necessitate. The test was performed at $20^{o}F$ rather than at $32^{o}F$ to insure that the K_{Id}/σ_{yd} was greater than 0.6 at $32^{o}F$.

TABLE 3

Ship Structure Committee Report 244

Fracture-Control Guidelines

Main Stress Dynamic Tear-Test Energy Requirements

Yield Point σ_y ksi	Dynamic Yield Point σ_{yd} ksi	Energy at 75°F(ft-lb) (5/8" spec.)
40	60	250
50	70	290
60	80	335
70	90	375
80	100	415
90	110	460
100	120	500

Arrester Dynamic Tear-Test Energy Requirements

Yield Point σ_y ksi	Dynamic Yield Point σ_{yd} ksi	Energy at 32°F(ft-lb) (5/8" spec.)
40	60	600
50	70	635
60	80	670
70	90	700
80	100	735
90	110	770
100	120	800

2. Crack Arresters

The report by Rolfe, et al., dealt with a third aspect of ship structure, namely, the problem of crack arresters. In order to assure proper crack-arrest behavior, the report specified that crack arresters should be fabricated into the ship hull with steels of appropriate toughness for this application. It was pointed out that the crack arresters themselves must satisfy three criteria. There must be a proper spacing of arresters within the hull cross section, they must be of the proper geometry or detail, and they must be of steel with the proper level of toughness. It was suggested that the level of toughness required should be significantly above that for the ordinary ship plate. It was proposed that for an arrester with a 40 ksi yield point that the proper level of toughness was a 5/8 inch DT test energy of at least 600 ft-lbs. at 32°F. For higher strength steels, ranging up to 100 ksi yield strength, the energy absorption requirements for 5/8 inch DT specimens ranged to 800 ft-lbs. A careful reading of the report indicates that these toughness criteria were somewhat arbitrary and did not include any effect of arrester geometry on toughness. These requirements are also listed in Table 3.

3. Welded Joints

A fourth aspect of the ship fracture-control plan was that dealing with welds. No unique weld fracture-toughness-control plan was presented in the report, but rather it was indicated that the toughness requirements must apply equally to ship plate and to weldments. It was suggested that tests that were performed for the plate should also be performed for weld metal, base metal and heat-affected zones in the region of the weld. It was pointed out that there was no one "heat-affected zone" but suggested that the heat-affected-zone center be tested in an NDT or DT test to show that it had properties that were matching to the materials that were being joined. Thus, presumably, the requirement for a maximum NDT temperature of 0°F combined with a minimum dynamic tear energy for 5/8 inch specimen at 75°F was to be used for weldments as well as plates in the primary load-carrying main stress members.

4. Discussion of the Plan

An examination of the details of the fracture-control plan developed by Rolfe and his co-workers indicates that it contains aspects that can be considered very conservative. For example, the fundamental intent of the establishment of the NDT temperature at 0°F was to produce elastic-plastic or plastic behavior in materials at the temperature of service. Moreover, this condition is to be fixed under impact loading conditions, which is a loading rate perhaps not duplicated in service. The establishing of the dynamic tear requirement at the proposed levels will insure, of course, that a relatively high plastic toughness will exist in service.

On the other hand, the fracture-toughness level specified may be interpreted, for full dynamic behavior, to be non-conservative with respect to heavy plates; for example, over 2 inches in thickness. In these cases, the specified K_{ID}/σ_{yd} is marginally close to plane strain behavior and critical flaw sizes become quite small. As Rolfe indicates, for nominal stresses on the order of 14 ksi, the critical crack size at 32°F can be estimated to be 8 to 10 inches long. If stress ranges are increased to the 25 ksi level, critical crack sizes shrink to about 3 inches. For the worst possible case, dynamic loading of yield point magnitude, the dynamic critical crack size shrinks to 1/2 inch. This latter crack size is extremely small and from some viewpoints would be quite non-conservative.

Again, in establishing the impact energy level required in the DT test, the value eventually arrived at is somewhat arbitrary. First, it is recognized in the report that the material at 75°F is in the elastic-plastic range and thus no exact procedure is available for scaling the desired K_{Id}/σ_{yd} ratio of 0.9 at 32°F to an equivalent acceptable DT energy at 75°F. It is noted that a scaling factor much greater than the one finally adopted in the report would have to be used for plane-strain conditions. The extension is into the elastic-plastic region, however, and a nonlinear extrapolation to 250 ft-lbs. at 75°F for primary main stress ship plate was adopted. It was suggested that for crack-arrester materials, dynamic tear toughness considerably greater than required in primary load-carrying members be specified. For 40 ksi yield strength steels, a scaling factor of 4 was applied, that is to say, the crack-arrester material had to exhibit a toughness 4 times greater than that of the primary plate material. There is no engineering justification for such a factor. Moreover, if the DT energy requirements for arrester plates are adjusted for increasing yield strength, the required toughnesses become increasingly large and at the highest strength levels, DT values of as high as 1200 ft-lbs. would be required to meet the same criteria applied to the lower strength steels. The authors of the report recognize that the 1200 ft-lbs. dynamic tear energy level is excessive and, therefore, arbitrarily scale the values to smaller ones for the higher strength steels. The value required of materials of the highest yield point is set at 800 ft-lbs. not 1200 ft-lbs. Required toughness values for steels whose yield strengths lie between 40 and 100 ksi are scaled linearly between a minimum value, 600 ft-lbs. and the maximum value, 800 ft-lbs.

Perhaps one of the most significant decisions in the preparation of the report was to select as the relevant loading rate for ships the loading rate employed in normal impact testing. It is not clear that ship structures, or any large structure for that matter, can experience failures with initiation load rise times between 10^{-4} and 10^{-5} secs., which are the loading rates in impact tests. Since ship hull materials are strain-rate sensitive, the specification of full impact toughness severely penalizes materials of higher inherent toughness at slower strain rates.

The conclusions in the report by Rolfe and his co-workers stated there are current materials available which can meet these toughness requirements.

Thus, it was supposed that most existing ship plate material would meet the requirements, verifying their current good service history.

B. Material Characterization Studies

1. Ship Structure Committee Report 248

The publication of the report by Rolfe et al. in 1974 immediately created interest concerning the toughness of existing ship plate steels, specifically grades ABS A, B and C, with respect to the criteria that had been proposed. The data that were available on these steels were generally in the form of Charpy V-notch impact test results. Since the correlation between NDT temperature, DT energy and Charpy impact test data was not very precise, it was not possible to determine if these materials could actually meet the criteria of the SSC 244. For this reason, the Ship Structure Committee saw the need for further investigation that would clearly establish whether or not existing ship plate material could meet these toughness criteria. This investigation took the form of a survey of a number of ship plate materials by researchers at the Naval Research Laboratory which was published as Ship Structure Committee Report 248, "Fracture-Toughness Characterization of Ship Building Steels," authored by J. R. Hawthorne and F. J. Loss.[5] This timely investigation involved the testing of a series of plates, including ABS grades A, B, C, C normalized, D normalized, E, EH, and CS. A minimum of 3 plates of each of these steels was tested with a sample size for grades B and C of 5 or 6 plates. The plates were obtained both from normal ship plate suppliers and from shipyards. They were selected to represent a reasonable cross-section of plate thickness, chemistry and nominal properties. Plate thickness ranged from a minimum of 3/4 inch to a maximum of 2 inches with a majority of the plates in the 1 inch thickness range. The test plates were given conventional mechanical property tests including impact tests, and drop weight and dynamic tear tests. The latter, of course, established the temperature-energy characteristics for the material and provided results that could be compared to the criteria established by Rolfe and his co-workers.

The conclusions of this report were that typical NDT temperatures for non-heat-treated grades A, B, and C were not at or below the 0°F level but actually between 20 and 30°F. The heat-treated grades, C-normalized and D-normalized, had lower transition temperatures, which indicated that a normalizing heat treatment could produce transition temperatures that were at or below 0°F. The DT energy level tests run in this program, although performed on 1-inch-thick specimens rather than the 5/8 inch specimens suggested in the previous investigation, provided data suggesting that the non-heat-treated steels generally would not pass the proposed DT energy requirement at 75°F, that is to say, 250 ft-lbs. of absorbed energy. It also appeared that, as with the NDT requirement, the normalized grades of steels might be able to meet this specification. It should be noted that this conclusion was based on a conversion of the 1 inch-thick DT test specimen data to equivalent 5/8-inch-thick specimen values, a procedure which can lead to some error.

The arrester plate toughness requirement, that is 600 ft-lbs. at 32°F for ordinary strength steels, was not met in the estimation of these investigators. It was suggested that grades E and CS should be able to meet the requirements, but only in the higher quality plates from the production viewpoint. Another conclusion was that all the steels would reach an adequate upper shelf energy in the longitudinal orientation for the requirement but this shelf was not reached until the material was between 120-180°F. Transverse specimens performed uniformly poorer. In the parallel Charpy tests on these plate steels, it was observed that there was a substantial variation of impact energy at the NDT temperature and that no accurate NDT energy "fix" was possible.

2. Program Outcome

From these test results, it appeared that the A, B, and C ship plate materials could not meet the toughness guidelines proposed by Rolfe and his co-workers. Moreover, it further suggested that materials now used in arrester applications would not be adequate to meet the proposed requirement and that material of substantially higher quality would be required for this application. The study by Hawthorne and Loss did not contain any welded plates, thus, it was not possible to determine how weldments might fare with respect to the proposed criteria; however, it did raise some doubts as to the ability of weldments to meet these criteria and, thus, it appeared that additional tests, specifically tests on weldments, would be necessary.

These questions eventually led to two research programs at Southwest Research Institute aimed at determining first, the fracture behavior of weldments and second, the quantitative effect of strain rate on the behavior of strain-rate sensitive material such as ship plate. These two studies, referred to previously, were both performed at the Southwest Research Institute by P. H. Francis, T. S. Cook and A. Nagy. They eventually resulted in Ship Structure Committee Reports 276, "Fracture-Behavior Characterization of Ship Steels and Weldments"[6] and 275, "The Effect of Strain Rate on the Toughness of Ship Steels."[7]

3. Ship Structure Committee Report 276

The first of these reports, dealing with the characterization of weldments, essentially extended to work done at the Naval Research Laboratory on ordinary ship plate in two dimensions. First it provided additional information on existing heats of ship plate material in the ABS B, AH, EH and CS categories. It also included other materials used in ship construction, specifically ASTM A517 Grade D, ASTM A678 Grade C, and ASTM A537 Grade B. The second dimension was to examine weldments of these materials, and to that end tests were performed on weld metal, base plate, and heat-affected zones in ship plate welded by the shielded metal arc and submerged arc processes. Tests performed on the weldments included those recommended by Rolfe and his co-workers, i.e., drop weight NDT and dynamic tear tests, as well as the normal tensile characterizations. In addition, a number of tests involving explosive loading, specifically explosion crack-starter tests and explosion tear tests, were applied to some of the weldments.

The conclusion of the plate material study essentially mirrored the results obtained at the Naval Research Laboratory, that is to say, ABS B material was not able to meet the proposed NDT temperature requirements for either primary or secondary stress regions. The dynamic tear requirements were met by the ABS B material for main stress regions. This material failed the crack-arrester test. The CS material was acceptable for application primary structures and marginally acceptable for crack-arrester structures.

The primary stress member requirement was met by the CS steel with shielded metal arc welding but the submerged arc weld failed to meet the NDT requirement for the primary stress regions or the crack-arrester toughness. The AH32 material did not pass the primary stress region NDT guideline requirement and was only marginal with respect to the secondary stress region requirement. It failed to meet the primary stress toughness requirement at 75°F and also failed the crack-arrester toughness requirement.

The high-strength steels, ASTM A517 Grade D, A678 Grade C and A537 Grade B all met the toughness requirements for the primary stress material i.e., they successfully passed the NDT temperature requirement at 0°F and also passed the required toughness level at 75°F. However, the A517 Grade D did not pass the crack-arrest-toughness requirement and A678 Grade C and A537 Grade B passed this only in some heats. The same was true of their weldments.

A subsidiary result of the investigation related to whether or not the toughness requirement at 75°F should be determined by the Charpy impact test rather than the DT test suggested by Rolfe. It was found that the correlation between the two tests was not sufficiently precise to justify the lower cost of the Charpy test compared to the DT test.

4. Explosion Tests

The explosion tests applied to weldments in this program reinforced the results of the dynamic tear tests in that a large portion of the weldments tested failed to meet the requirements of the two explosion tests applied. These tests are, of course, very severe; requiring the material to deform plastically over a rather extensive range. While the application of the first of these, the explosion crack starter test, to ships is not clear, it should be noted that the ABS CS shielded metal arc weldment passed the test at 75°F only and failed the test welded with the submerged arc process at all temperatures. The ASTM A517 Grade D material passed the test when shielded metal arc welded at 0°F but also failed the test at all temperatures when submerged arc welded. ASTM A678 Grade C material passed the test at 0°F when submerged arc welded and at 75°F when welded with the shielded metal arc process. The explosion tear tests, which are similar to those just described, produced similar results. This test, by its construction, is more a test of the arrest capacity of the base material rather than the weldment behavior. Evaluation of the test specimen was in terms of its ability to arrest a running crack developed in explosive loading. ABS CS material in 1 inch thickness failed to pass this test. A517 Grade D passed in 1 inch thickness but failed in a thickness of 1¼ inch. A678 Grade C had one specimen pass and one fail at the same thickness, 1¼ inch. All of these tests were performed at 32°F. They therefore confirm that no material could consistently produce crack arrest under these conditions.

This author considers these tests to be not particularly pertinent to normal ship application and therefore, refers to them only as confirming information with respect to the crack-arrest criteria established by Rolfe and his co-workers rather than an indication of a failure of these weldments to perform successfully in normal ship service.

5. Program Outcome

The overall impact of this report was to confirm the results of the previous investigation, that is, many of the materials proposed or in use for main-stress regions of ships would not be able to meet the guidelines proposed by Rolfe and his co-workers either as plate materials or in the form of weldments. Moreover, even some of the more sophisticated high-strength materials which might be considered suitable for crack-arrester applications would not be able to meet the arrester guideline in all heats or all thicknesses, nor would their weldments be able to meet these guidelines in all conditions of welding. One material in this investigation, ABS CS, did show itself to be able to meet the requirements for primary and secondary stress applications when welded with the shielded metal arc process. One other material, EH32, clearly passed all the tests for primary and secondary structure applications and could be used for crack arrest according to the criteria established by Rolfe and his co-workers.

6. Ship Structure Committee Report 275

The last of the three major investigations undertaken by the Ship Structure Committee with respect to the fracture toughness and fracture behavior of ship plate materials was concerned with loading rate effects on ship steels. This report was published in 1978 and includes data on the effect of strain rate and temperature upon the fracture toughness of seven ship steels. These ranged from lower strength as-rolled steels up to higher strength quenched-and-tempered steels. One or two heats each of ABS B, DS, AH, EH, and ASTM A517 Grade D, A678 Grade C and A537 Grade B were studied. Both yield strength and fracture-toughness surveys (as measured by dynamic tear tests) were done on the steels. The dynamic tear specimens were 5/8 inches in thickness and were prepared with a pressed-in notch and a fatigue-cracked notch. The difference in behavior between these two notches was part of the investigation.

The tension tests, which were designed primarily to measure the influence of testing rate on dynamic yield point, supplemented data from Ship Structure Committee Report 276 undertaken by the same investigators. The new tension test data were obtained at two rapid loading rates, one using a cross-head speed of one tenth of an inch per second and one with a cross-head test speed of six inches per second. Tear tests were also undertaken at three different loading rates, an impact rate using a 2,000 ft-lb. capacity standard dynamic tear machine and two other rates achieved by use of a Universal testing machine. The strain rates used in the tension test were 1.3 x 10^{-4} in./in./sec. for the static tests, 0.08 in./in./sec. for the intermediate rate tests and 5 in./in./sec. for the impact tests. In the DT test strain rates are much more difficult to establish because the significant rates are those at the tip of a relatively sharp crack. However, these crack tip rates are estimated as to be something on the order of 4 x 10^{-3} in./in./sec. for the static tests, 1 in./in./sec. for the intermediate tests, and a much higher impact rate for the dynamic tear tests, something on the order of 10-100 in./in./sec.

The results of this investigation show that the tensile yield point decreases linearly with temperature and increases logarithmically with strain rate. The most significant influence, therefore, was temperature unless the loading rate changed substantially, i.e., over several orders of magnitude.

Considering the part of the program that dealt specifically with toughness, the results of the tests at three loading rates were limited to only certain heats of material. These showed that the transition temperature region shifts to higher temperatures with increased loading rates, that is, the mean transition temperature increases. The shift was relatively small between the static and intermediate tests up to 1 in./sec. in loading rate, but this shift jumped dramatically when moving from intermediate to impact loading rates.

The transition temperature measured by the conventional DT test was, therefore, relatively high compared to transition temperatures measured for the same materials when loaded at more moderate rates. There was a tendency for the width of the transition temperature region to narrow as the loading rate was increased. When comparing the press-notched to the notched and fatigue-cracked specimen, it appeared that the press notched specimen produced higher energy values in the upper shelf region, undoubtedly because more energy was absorbed in crack initiation in this regime with this type of notch configuration, although the transition region occurred over the same temperature range regardless of notch condition.

7. Program Outcome

Perhaps one of the easiest ways to interpret the results of these tests was in terms of the K_{Ic}/σ_y or K_{Id}/σ_{yd} ratio. For CS material, for which sub stantial data were obtained, it was shown that for impact loading rates at 75°F (in the standard 5/8 inch DT test) the K_{Id}/σ_{yd} ratio was 1.66. The intermediate rate K_{Id}/σ_{yd} ratio was 7.2 and for quasi-static testing, it was 6.96. Clearly then, for this steel there was a substantial difference in K_{Id}/σ_{yd} ratio when going from the intermediate to the impact test rate. The ASTM A517-D showed a similar variation at 75°F although not as great. At impact test rates, the K_{Id}/σ_{yd} was found to be 1.32. For the intermediate rate, this ratio rose to 2.12 and was 1.73 for the quasi-static rate. Thus, the relative toughness showed a large strain-rate effect, a larger effect for CS than for A517-D. Comparable data for other materials in the program were not available because of the limited testing undertaken but shifts in apparent toughness were observed for these materials as a result of strain rate as well. These test data were interpreted by the investigators to mean that impact test rate data are conservative when applied to ship service because intermediate rates, which are already quite high, produce substantially higher K_{Id}/σ_{yd} ratios at the same temperature and are relevant to ship hull loadings.

Although the overall trends observed in these tests are clear, the toughness of the CS material at slower strain rates was very high. This makes the interpretation of the energy to fracture measurements more complex. Static test results are elastic-plastic or fully plastic and the significance of a very high quasi-static K_{Ic}/σ_y ratio is probably qualitative rather than quantitative. In spite of this limitation, this author accepts these data as showing a real increase in effective fracture toughness for the intermediate and static strain rates as compared to the impact rate. Moreover, the slight decrease in effective toughness in the static rate tests is reasonable based on yield point effects, i.e., moderately higher strain rate raises the ductile fracture energy.

The levels of K_{Id}/σ_{yd} ratio determined at 75°F are of some importance because in the original report of Rolfe and his co-workers it was established that the desirable ratio at 75°F would be a K_{Id}/σ_{yd} of 1.5. The CS material passed the required K_{Id}/σ_{yd} ratio even using standard DT (impact test) loading. On the other hand, the A517 Grade D did not. If a more moderate rate, intermediate loading was used, the K_{Id}/σ_{yd} is quite high for CS and the A517 Grade D material has the required K_{Id}/σ_{yd} ratio.

Energies to failure in the DT tests run at intermediate and impact test loading rates also reveal some very interesting trends. For example, the ABS DS material that failed the DT energy requirement at 75°F for main stress members in ship structures would pass these same requirements if loaded at the intermediate rate. The EH32 material was able to pass these requirements at either intermediate or impact loading rates and the energies involved were not substantially different. This suggests that the toughness had already risen to substantial levels at 75°F regardless of loading rate i.e., the transition temperature for these materials by either test was well below the 0°F temperature range. For ASTM A517-D, the required impact energy is substantially higher because of its relatively high yield point; thus, it was not possible to achieve the required level according to the criteria of Rolfe and his co-workers for this material for primary main stress members. For such materials as ASTM A678 Grade C, A537 Grade B and even ABS B, results of these tests showed that these materials could, without exception, pass primary main stress member criteria if loaded at the intermediate rather than the impact loading rate. For crack arrester toughness applications, even the intermediate loading rate was not able to produce toughness levels high enough to meet the proposed crack-arrester requirements at 32°F.

One major value of this report was in the establishing of K_{Id}/σ_{yd} ratio levels for two of the important materials studied in the previous programs. In a sense, it confirmed the analysis of Rolfe and his co-workers that the K_{Id}/σ_{yd} was substantially influenced by loading rate and that there is a significant transition from ductile to brittle behavior, as is evident by examination of the fracture toughness vs. temperature curves presented in the report. However, one of the weaknesses of this report is that the methods used to evaluate fracture toughness were not ones on which there could be universal agreement.

IV. Evaluation of Existing Ship Structure Reports and Other Data

A compilation of NDT temperature and dynamic-tear-energy data relevant to the fracture-control criteria proposed by Rolfe and his co-workers is presented in Table 4. These data represent all of the tests performed as part of the Ship Structure Committee programs and also the information provided by ship plate producers. The data covers all of the ordinary strength plates, ABS Grades A, B, C, C normalized, D, E, CS, AH32 and EH32, as well as a number of special plates consisting of ABS V051,* V057* and ASTM A678 Grade C, A537 Grade B, A514 Grade H, A517 Grade D and HY-80. Multiple heats of most of these grades are represented. In each case, the plate properties are compared on a Pass-Fail basis to the criteria proposed by Rolfe and his co-workers for main-stress primary member plates, for main-stress secondary member plates and for crack-arrester plates. In some cases, the data were incomplete and estimates were employed. For example, NDT temperatures were not available for all of the heats of ABS CS listed. NDT temperatures for these were estimated from DT energy curves that were available. The NDT was presumed to occur when the DT curve had risen from its minimum to 10% of its maximum value, i.e., at the toe of the curve.

Examination of the data in this table reveals clearly that ordinary strength ship steels such as ABS Grades A, B, and C will not meet the fracture criteria proposed for main-stress primary members, nor will all pass the main-stress secondary member requirement. That is to say, the NDT temperature will generally be above 0°F and the toughness of the primary members in terms of the dynamic tear energy will be less than that required. The grades that are fine grained, i.e., grade D and are fine grained and normalized, grades E and

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*ABS Rules for Building and Classing Steel Vessels, Table 43.6 "Materials for Low Temperature Service." For service to -50°F.

TABLE 4

Ship Steel Toughness Survey

ABS Steel Type Orientation & No.			Main Stress Primary Requirement				Arrester Requirement DT Energy		Main Stress Secondary Requirement NDT Temperature	
			NDT Temp		DT Energy					
			P	F	P	F	P	F	P	F
<u>Ordinary Strength Plates</u>										
A	L*	7	0	7	0	7	-	-	5	2
	T*	2	-	-	0	2	-	-	-	-
B	L	9	0	9	3	6	-	-	7	2
	T	3	-	-	0	3	-	-	-	-
C	L	7	2	5	2	5	0	5	6	1
	T	2	-	-	1	1	0	2	-	-
(CN)	L	3	3	0	3	0	0	3	3	0
D	L	4	3	1	2	2	2	2	4	0
E	L	5	4	1	5	0	2	3	5	0
	T	2	-	-	2	0	1	1	-	-
CS	L	13	13	0	13	0	10	0	13	0
	T	10	8	2	10	0	1	9	10	0
AH32	L	1	0	1	0	1	0	1	0	1
	T	1	-	-	0	1	0	1	-	-
EH32	L	1	1	0	1	0	1	0	1	0
	T	1	-	-	1	0	1	0	-	-
<u>Special Plates</u> (ASTM Spec. when noted)										
ASTM A517-D	L	2	2	0	1	1	0	2	2	0
	T	2	-	-	0	2	0	2	-	-
ASTM A678-C	L	2	2	0	2	0	1	1	2	0
	T	2	-	-	2	0	0	2	-	-
ASTM A537-B	L	3	3	0	3	0	2	1	3	0
	T	3	-	-	3	0	0	3	-	-
HY-80	L	1	1	0	1	0	1	0	1	0
	T	1	-	-	1	0	0	1	-	-
ASTM A514-H	L	1	1	0	1	0	0	1	1	0
	T	1	-	-	0	1	0	1	-	-
V051	L	1	1	0	1	0	1	0	1	0
	T	1	-	-	1	0	0	1	-	-
V057	L	2	2	0	2	0	2	0	2	0
<u>Welds and Heat Affected Zones</u>										
CS	W	2	2	0	1	1	1	1	2	0
	HAZ	2	-	-	2	0	0	2	-	-
A517-D	W	2	2	0	1	1	0	2	2	0
	HAZ	2	-	-	2	0	0	2	-	-
A678-C	W	2	2	0	2	0	0	2	2	0
	HAZ	2	-	-	2	0	1	1	-	-
ABS B	W	1	1	0	1	0	0	1	1	0
	HAZ	1	-	-	1	0	0	1	-	-
A537-B	W	1	1	0	1	0	0	1	1	0
	HAZ	1	-	-	1	0	0	1	-	-

*L = Longitudinal specimen

T = Transverse specimen

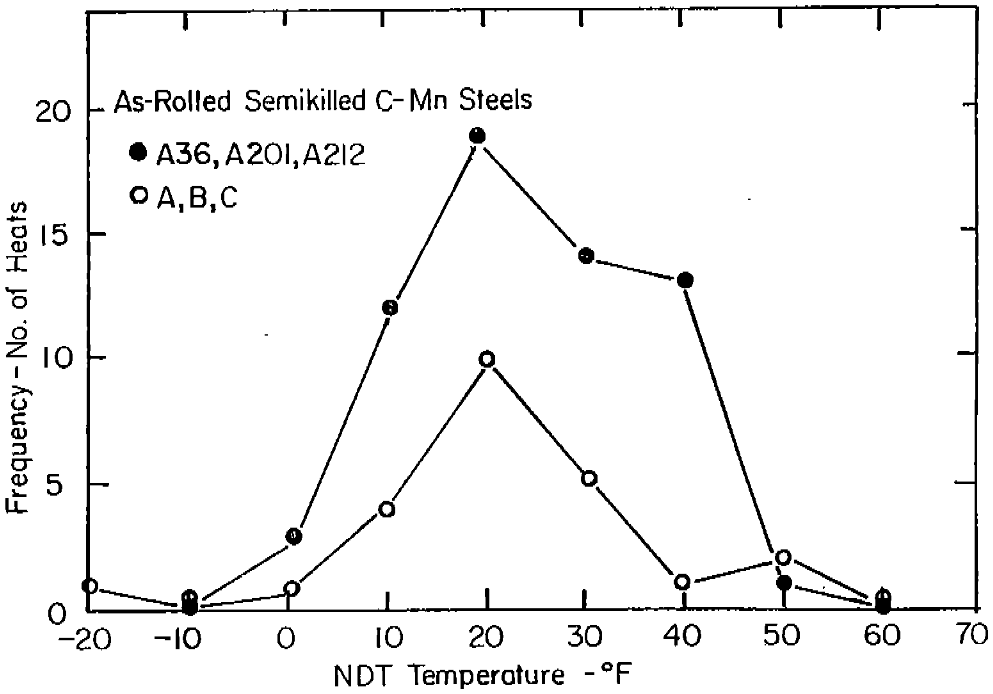


Figure I. NDT Temperature Distribution for As-Rolled Semikilled C-Mn Steels

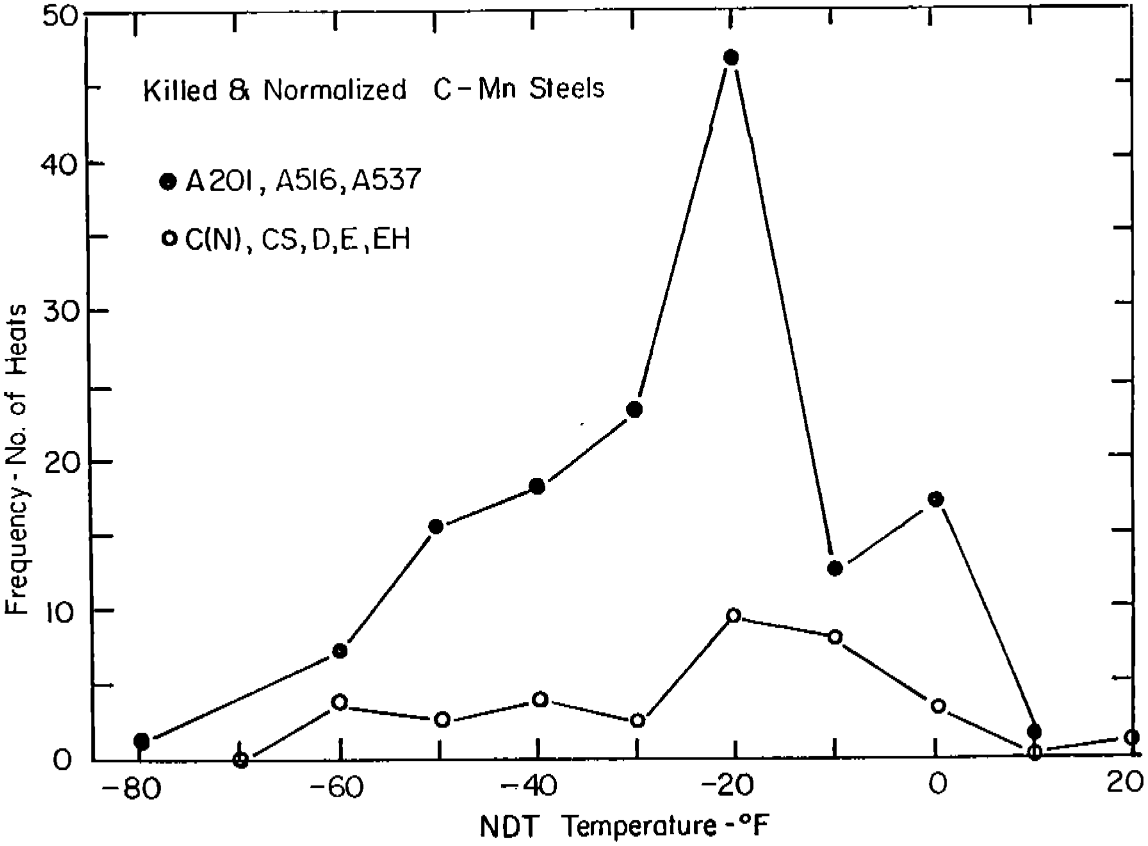


Figure 2. NDT Temperature Distribution for Killed & Normalized C-Mn Steels

CS, have fared considerably better and many, but not all, of the heats tested will meet the primary stress requirement. The higher strength materials, ASTM A514-H, A517-D, A678-C and A537-B, among others, will meet the NDT requirement for main stress members. When these materials are considered in the light of arrester requirements, many of them will not meet the arrester dynamic tear energy at 32°F. Indeed, the energy requirement is set sufficiently high that there are heats of these materials that would not meet the arrester energy requirement at any temperature.

When examining the materials in the light of meeting the requirements for either the main stress members or the arrester members, it will be observed that there is a sensitivity to orientation of the plate. Not unexpectedly, the failure rate of the transverse orientation specimens is higher than that for the longitudinal orientation specimens for all the materials examined.

Particular note should be made of the data for ABS Grade C on Table 4. This material is listed in two conditions--with and without normalizing heat treatment. For the normalized material, in which finer grain size might be expected, it will be observed that all of the heats tested passed the primary main stress drop weight NDT temperature and dynamic tear energy requirement. This was considerably better performance than experienced by those plates that did not receive normalizing treatment. This result is quite in keeping with information found in the literature concerning the expected NDT temperatures of materials similar to those listed in this report. Figures 1 and 2 show a distribution of NDT temperatures for a series of heats of as-rolled carbon-manganese steels as found in a recent NRC report.[11] Superimposed on this distribution is the NDT temperature distribution obtained for ABS Grades A, B and C in connection with this report. Figure 1 shows the materials in the as-rolled condition, while Figure 2 shows the same distribution for materials which have been either normalized or made to fine grain practice. The median NDT temperature for the as-rolled materials is 20°F, with the distribution ranging between -20°F and +50°F. For the normalized or fine grain practice materials, the median temperature is closer to -20°F with data ranging from -80°F to + 10°F. Results of the ship steel survey are therefore in keeping with the data obtained from similar materials.

Analysis of the distribution of dynamic tear energies at 75°F is not as direct because some of the data were obtained on dynamic tear specimens of different thickness. Examination of data for the CS material reveals, however, that if the NDT temperature is below the specified 0°F, the DT energy requirement will be met for this steel. The data also indicate that lower strength materials with NDT temperatures in the range specified can often meet the arrester dynamic tear requirement in longitudinal specimens. The higher strength steels, ASTM A517 Grade D, A514 Grade H, A537 Grade B and A678 Grade C, will not necessarily meet the arrester requirements even though their NDT temperatures are significantly below any of the plates discussed thus far. Because of their relatively high yield point and lower ductility, the shelf toughness of these materials is not as great as that of the lower strength

ABS materials. Under these conditions, the lower strength CS material is a more ideal crack-arrester steel than those higher strength A517F with a somewhat lower shelf toughness.

Table 4 also shows data for a series of welds. Relatively speaking, the welds in the survey had properties superior to the plates that they joined. In the weldment survey, all of the welds tested (weld metal only) met the NDT temperature requirement for main stress primary members and, thus, met all the requirements for secondary stress members as well. As far as dynamic tear toughness at 75°F is concerned, mixed behavior was observed, but on the whole the welds were able to meet the primary member requirement. Heat-affected-zone data are less extensive than that for the weld metals in that the drop weight NDT temperatures were not determined for the heat-affected-zone samples. On the basis of the main stress region dynamic tear energies at 75°F, the weld heat-affected zone will probably meet the requirements that have been proposed. It is also true that these regions do <u>not</u> pass the requirements for crack-arrester material even though they might be in material of relatively high toughness. For example, the CS material heat-affected zones are adequate in terms of dynamic tear energy for primary stress plates but fail the requirements for crack-arrester toughness. Although these data are quite limited and there are exceptions, the trend of the results that have been obtained indicate that as far as the weld composite is concerned, the most critical region does not lie in the weld or the heat-affected zone but rather it is the plate material.

A. Loads and Loading Rates in Ships

It had already been pointed out by investigators who performed the ship material studies at Southwest Research Institute that the strain rates employed in dynamic tear testing are usually high compared to those measured in ships.[7] Since the time that report was published, a number of investigations of actual loading rates of ships have been made available for study.[12-17] These rates have been substantiated by instrumented tests on ships and by estimated rates of loading from the study of ship models and from laboratory investigations. The summary of these studies shows that, by and large, loading rates in ships are not comparable to those typical of high speed or impact laboratory testing. For example, sustantial long-term data have been obtained from instrumented tests on Sealand SL7 and from other similar ships, such as the <u>Wolverine State</u>. These show that measured rates of loading usually have rise times between 25 and 250 milliseconds with minimum pulses of stress occurring over no less than 10 milliseconds. In many of these cases, it was not certain that the instrumentation used might not have failed to observe stress pulses at more rapid frequencies, however, investigators indicated that they believed that the load rise times recorded as minimum in their investigations were, in fact, minimum values. Translation of these load rise times into strains, especially strains in notched or cracked samples, is extremely difficult.

Francis and co-workers[7] estimate that load rise times of 25 to 150 milliseconds translate into strain rates and stress-intensity-factor rise rates of 5 to 10 x 10^{-3}/sec. and 200-400 ksi$\sqrt{\text{in.}}$/sec., respectively. These are quite low compared to those experienced in laboratory impact testing in which the strain rates are as high as 100/sec. Calculation of impact strains at notches is, of course, extremely difficult and these rates may run as high as 1000/sec. in laboratory tests. In an overall summary on the response of metals and metallic structures to dynamic loading published by the National Research Council,[18] the behavior of ships in terms of loading rates experienced in service, were listed as load rise times of 5 milliseconds to 100 milliseconds with the most common rates being in the range of 10-20 milliseconds. These are consistent with the rates determined in the Ship Structure Committee investigations.

The shortest rise times or most rapid loading rates recorded in the Ship Structure Committee studies are those associated with slamming. The response of the ship as a whole to slamming phenomenon does not allow for uniform strain in main stress parts of the hull at the maximum rates but rather at rates in the 25-100 millisecond rise time range. In summary, it is possible to estimate that the minimum rise times are on the order of 5 to 10 milliseconds in main stress members.

The same ship reports[12-17] provide information on maximum service stresses observed in ships under these conditions. Maximum stresses seen in instrumented ship studies have varied from as low as 10 ksi to exceeding 35 ksi, although the actual stresses vary from ship to ship and condition to condition. A summary of stress pulse data from ship service is seen in Figures 3 and 4. Some peak stresses are seen only rarely in the life of the ship, perhaps once or twice. Nonetheless, stresses in the range of the yield point are occasionally experienced during ship service so maximum stresses of 35 and occasionally 40 ksi have been reported. Therefore, it is realistic to use the yield point as the reference stress for ship studies. Not only is this stress appropriate for plates, but also it is appropriate for welds in which residual stresses at this level are almost always present. Since weld residual stresses are local, they will not contribute to the general stress field in the plate. However, they can contribute to "pop-in" behavior i.e., short crack advance, which will be discussed later.

With the data available from the instrumented ship studies, the assumption of yield point stresses in the development of proposed ship plate toughness requirements appears to be necessary. However, these same studies show that intermediate rather than impact loading rates are appropriate to ship service.

B. Loading Rate Effects on Toughness

On the basis of the documented high peak stresses but only moderate

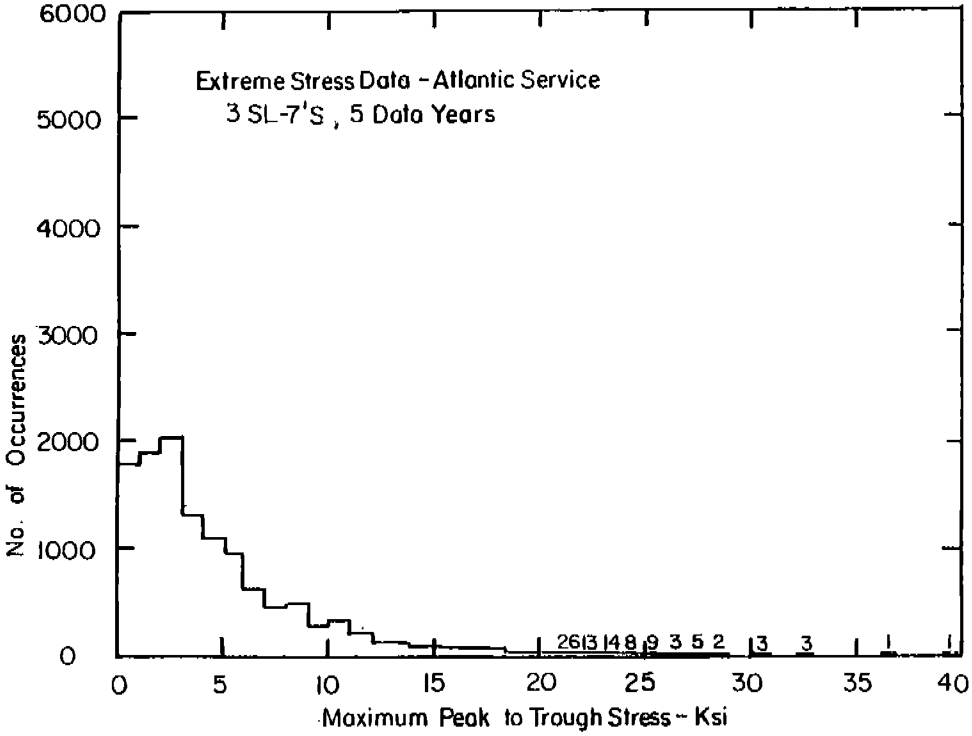


Figure 3. Extreme-Stress Data for SL-7 Atlantic Service

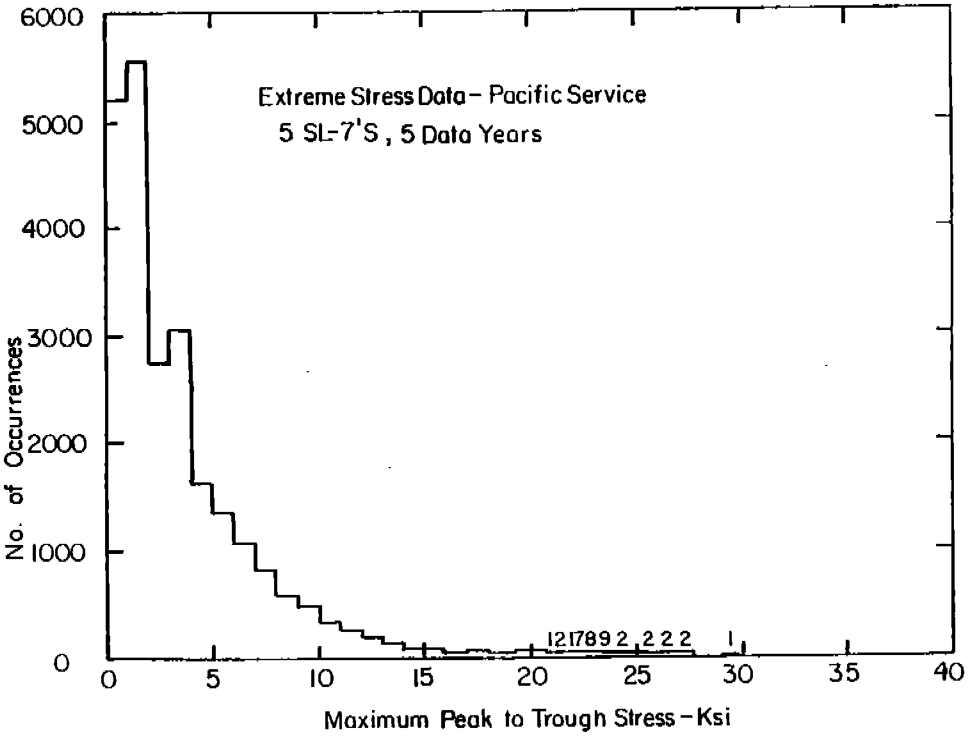


Figure 4. Extreme-Stress Data for SL-7 Pacific Service

load rise times experienced by ships, it is possible to center the attention of this review on toughness data obtained with tests using loading rates of intermediate magnitude. Fortunately, such intermediate rate data are available from the information obtained in Ship Structure Committee Reports and elsewhere. These data are shown on Table 5. The type of loading produced rise times in the order of 100-300 milliseconds, slower by perhaps as much as an order of magnitude than those experienced in ships. On the other hand, they contrast sharply with the load rise times experienced in the dynamic tear tests which are less than 10^{-4} seconds and are unrealistic for ship service.

Translation of these intermediate rate load rise time data into fracture-behavior predictions is clearly difficult. Especially so because one of the issues involved in the control of brittle fracture is not only the loading rates at crack initiation, although this is an important consideration, but also the rate of crack propagation and the conditions for crack arrest in structures in which localized embrittled regions have produced segments of brittle crack propagation. The relative fracture toughness of ship steels varies considerably during initiation, propagation and arrest phenomena.

Evidence of this comes from Ship Structure Committee Report 256, "Dynamic Crack Propagation and Arrest in Structural Steels," by Hahn, Hoagland and Rosenfeld.[19] In this investigation, one of the more interesting results was the fact that K dynamic, i.e., the energy consumed in crack propagation, could be quite different from the energy consumed in crack arrest. In this report, three types of crack-toughness characterizations are considered. These are: (1) the crack toughness associated with the onset of crack extension in a dynamically loaded specimen, (2) the crack toughness in the presence of a propagating crack, and (3) the arrest toughness. These three types of toughnesses were not equivalent and, as a result, the conditions for crack arrest were determined to be different than those for crack propagation. The materials tested in connection with this study were ASTM A553 and A517 Grade F, and ABS steels C, D and EH. The A517 Grade F steel was tested at or below its NDT temperature while the ship steels were tested in the range below and above the NDT temperature.

It was observed that the dynamic fracture toughness associated with a propagating crack is a function of crack velocity. For small crack velocities, the fracture toughness is quite high and decreases regularly with propagation rate up to crack speeds in the order of 1000 meter per second. Above this level, however, there is some indication that the crack speed has little further influence on toughness and, indeed, there is evidence that at higher speeds the dynamic fracture toughness again increases. This is a reflection of the complexity of the measurement of dynamic toughness at high crack speed because as crack speed increases, the influence of other factors such as the kinetic energy lost to the pieces that are being separated will begin to overshadow the material toughness. If the crack toughnesses measured at the higher speeds are indeed representative of the ship steels, it may be observed that these toughnesses are also higher than the toughnesses measured in the DT test or in other high-speed impact tests by a substantial margin.

TABLE 5

Dynamic Tear Energies at Two Loading Rates(ft-lb)

Steel Type	Temperature of Test			
	32°F		75°F	
	Impact (DT) Rate	Intermediate Rate	Impact (DT) Rate	Intermediate Rate
B	75	490	350	465
CS	540	540	630	600
DS	80	430	265	545
AH-32	30	150	100	310
EH-32	565	470	555	405
A517D	195	205	350	400
	525	470	615	425
A678C	-	630	-	655
	-	660	-	640
A537B	-	555	-	510
	545	400	550	360

This finding has a direct and important bearing upon the toughness level required of ship plate steels because at the NDT temperature, the K_{Id}/σ_{yd} is assumed by Rolfe and his co-workers to have a value of about .63. In fact, in this Ship Structure Committee investigation,[19] the K_{Id}/σ_{yd} at the NDT temperature was found to be 1 to 1.3. This would be expected because the value of K_{Id}/σ_{yd} that is normally measured at the NDT temperature is estimated from impact fracture toughness tests. If, indeed, the energy and associated K values for a propagating crack in a ship are greater than those for impact initiation in a specimen, then the value of K_{Id}/σ_{yd} will be higher than that measured by conventional impact testing. This again suggests the analysis by Rolfe and his co-workers is a conservative one with respect to testing philosophy for ship plate materials. It would also appear that the intermediate rate values of K reported by the Southwest Research Institute investigators in Ship Structure Committee Report 275 more closely approximate the actual behavior of a propagating crack than do impact tests on dynamic tear specimens. As previously discussed, their K_{Id}/σ_{yd} intermediate rate values were between 2 and 7 above the NDT temperature. These were, as described above, based on maximum load elastic-plastic analysis.

The results of the two independent Ship Structure Committee investigations are consistent with each other and with the anticipated loading rates for ships. The data reported in Ship Structure Committee Report 256[19] had some built in conservatisms which were not included in other tests. The primary specimen of this investigation was the double cantilever beam specimen, and in order to insure crack curvature did not occur during the test, deep side grooves were used for the tests. The side grooving is significant in that it restrains the development of shear lips which would normally be characteristic of structural steels tested above the NDT temperature. Thus, the data for K_{Id} measured in this investigation are conservative estimates of true values of K_{Id} for structural steels. A compilation of K_{Id} and K_{Id}/σ_{yd} data from several investigations, including those mentioned above, is found in Table 6. Both intermediate and impact rate data are represented.

C. Transition Temperature Strain Rate Shifts

Another aspect of the effect of strain rate on toughness is the shift in the transition temperature range that occurs between the normal impact rate and intermediate rate data. Data for a typical steel from the Ship Structure Report 275 are compared in this way in Figure 5. It is important to recognize that if a temperature of test is sufficiently high above the NDT temperature, either no difference in energy absorption will be observed between the two loading rates or else the impact loading rate data may lie slightly above those for intermediate rate testing. That is to say, the major differences in energy absorption between these two rates would only occur in the transition region for the material. For the material shown, ABS DS steel, a transition from relatively brittle to relatively tough behavior with temperature is seen for the three loading rates of the investigation. If static loading

TABLE 6

Intermediate Rate Fracture-Toughness Data

Steel	At NDT Temp.		At 32°F		At 75°F	
	K_{Id}(ksi√in)	K_{Id}/σ_{yd}(√in)	K_{Id}(ksi√in)	K_{Id}/σ_{yd}(√in)	K_{Id}(ksi√in)	K_{Id}/σ_{yd}(√in)
From Ship Structure Committee Report 275						
ABS B	389	6.08	389	6.08	407	8.48
ABS CS	357	4.30	-	-	425	7.20
ABS DS	88	1.47	466	9.13	-	-
ABS AH32	118	1.59	301	4.42	-	-
ABS EH32	358	4.21	-	-	352	5.42
ASTM A517-D	146 118	1.08 0.84	- 147	- 1.13	284 267	2.40 1.26
ASTM A678-C	- -	- -	- -	- -	407 404	5.02 4.81
ASTM A537-B	380 211	4.00 2.11			340 285	4.72 3.56
From Ship Structure Committee Report 256						
ABS C	120	1.64	175	2.40	165	2.80
ABS E	81.8	1.09	105	1.40	164	2.52
ABS EH	104	1.22	123	1.64	150	2.31
ASTM A517-F	205	1.58	-	-	-	-
ASTM A533-B	-	1.06	-	-	-	-
From Electric Power Research Institute Report 1225						
AISI 1018	-	-	-	-	85	1.54
ASTM A533-B	-	-	-	-	110	1.29

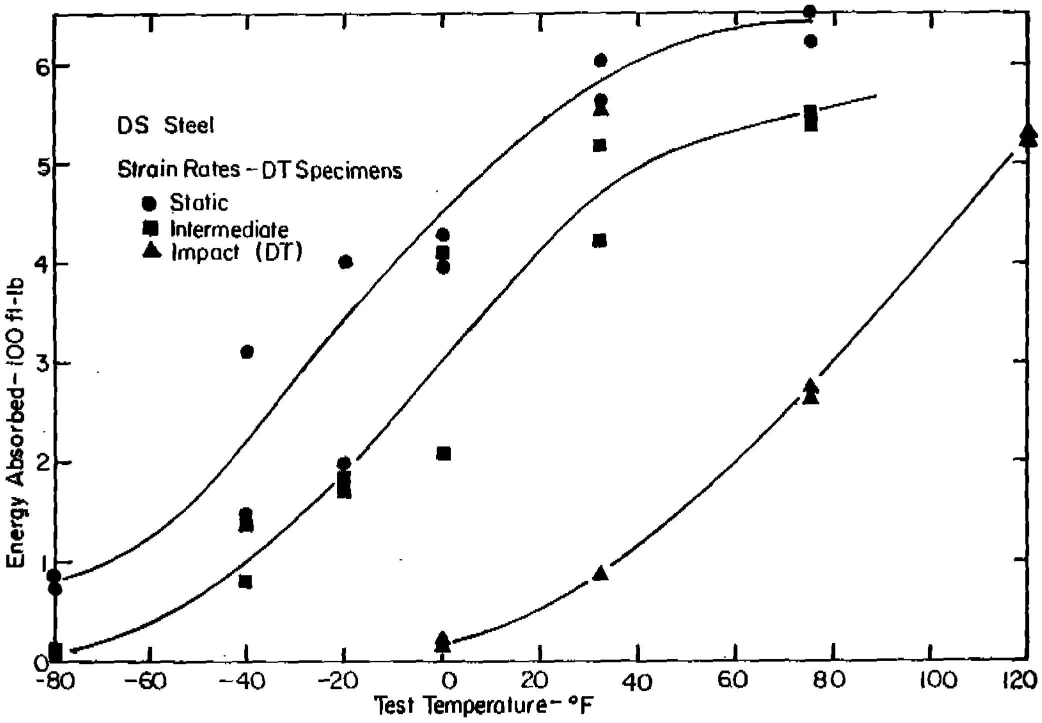


Figure 5. Fracture-Toughness Data for DS Steel

rates are used, the transition occurs somewhere between -80 and about 0°F with the energy absorbed by the specimen rising from something less than 100 ft-lb. to on the order of 650 ft-lb.

At the intermediate rate, the same transition occurs but is shifted by about 40°F. Impact testing produces another shift. The temperature shift between the impact and intermediate rate is about 80°F. A substantial difference in absorbed energy as a function of loading rate would be expected to occur at a temperature where the one load rate curve was on its upper shelf while the other was on the lower end of its transition. For the ABS DS of Figure 5, the maximum effect would probably be seen at a temperature of 40°F. It will be observed, however, that a substantial effect still occurs in the range of 75°F, the test temperature proposed by Rolfe and his co-workers for this material. Although NDT temperature data were not available for this heat, from the impact normal DT curve it may be anticipated that the drop weight NDT would be at the toe of the curve, between 20 and 25°F. In this case, which is the type case for the proposed criteria, the impact DT test produces values of toughness which are below that required for material with a 50 ksi yield point while intermediate rate testing produces values that would pass the proposed requirement.

Strain rate shift data are shown for a number of materials in Table 7. In constructing this table, it was necessary to bring together data from different sources. The procedure used was to identify midheighth points on the energy-temperature or energy-ductility curves as footnoted on Table 7. The difference in temperature between the two positions was assumed to be the temperature shift. In some cases, complete curves were not available and midheighth positions were estimated. Because of the way in which these data were developed, it is not appropriate to attach too much significance to the absolute values, but rather general trends. The data from Table 7 for ABS B, CS, DS and AH32, show significant shifts i.e., a significant sensitivity to loading rate in the very temperature range which is considered critical in the analysis of Rolfe and his co-workers. Materials such as CS and EH32 are also sensitive but not in the critical temperature range. Materials such as A517 Grade D have a different behavior. They are less strain-rate sensitive but also do not meet the requirements. This is because of their lower shelf toughness rather than because the toughness is measured in a region of transition.

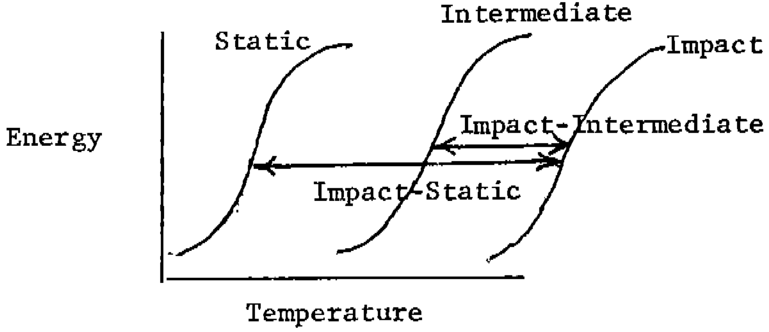
It should be pointed out that, when using the K_{Id}/σ_{yd} as the parameter of control for ship plate material behavior, intermediate rates have a dual effect; i.e., they not only increase the fracture toughness, the K_{Id}, but they also decrease the yield point, σ_{yd}, with respect to impact loading. The tension test results reported in SSC Report 275 for intermediate testing rates produce yield points very close to those produced in static tests. Thus, the yield point in intermediate rate tests is considerably lower than that in impact testing and the intermediate rates of loading result in larger values of K_{Id} and thus K_{Id}/σ_{yd} in the transition region tests.

TABLE 7

Strain Rate Temperature Shifts*

Steel Type	Transition Temperature Shifts (°F)	
	Impact-Static	Impact-Intermediate
ABS B	-	50
ABS CS	-	95
	151	-
ABS DS	104	78
	162	-
	81	-
ABS E	67	-
ABS AH 32	-	60
ABS EH 32	-	85
	140	-
ABS AH 36	97	-
ASTM A517-D	-	18
	-	5
ASTM A678-C	108	-

*based on corresponding mid-range energy positions on energy vs. temperature curves. Where ductility curves rather than energy curves were available, mid-position points on the ductility-temperature curves were used.



Consideration of loading rate effects in establishing toughness requirements for structural materials is by no means unique to this report. Very extensive consideration of loading rate effects have been documented and are being utilized in toughness requirements for bridge steels established by the American Association of State Highway and Transportation Officials.[8] The application of these concepts to bridge steel fracture-toughness requirements has, from the very beginning, been somewhat controversial. It has been established that external loads on bridges will not have rise times of much less than 1 sec. As a result, it is considered that impact tests produce toughnesses significantly less than are characteristic of bridge materials under normal loading conditions. This has led to specifications for bridge steel impact testing at temperatures higher than the service temperature. The higher temperature at the impact rate is intended to compensate for the lower temperature service at slower strain rates. For the lower strength steels, these shifts are known to be substantial, the extent of the shift decreasing with increasing yield point. For the higher strength steels, the shifts are smaller, generally following the relationship:

$$T_s = 215 - 1.5\,\sigma_y \qquad 1$$

Where T_s is the transition temperature shift in ^oF and σ_y is the yield point in ksi. The impact to static rate shifts are described by this equation, that is, a strain rate change over 5 or 6 orders of magnitude. Impact to intermediate rate shifts are smaller but still substantial, and are estimated to be about 75% of those predicted by Equation 1.[8]

Unfortunately, the strain-rate-shift data on ship steels are limited and it is difficult to apply a quantitative treatment to the use of such a shift in a fracture control specification. The effect is significant, however, and should not be ignored in the consideration of the ship plate properties that are available for fracture control of ship hull structures. The data of Table 7 are generally consistent with Equation 1. It should be noted, however, that this equation was developed primarily with the Charpy test, and since Table 7 contains data from several sources, it may not strictly describe these data.

D. Crack Arrest Systems

As has already been discussed, crack arrest in ship designs is now approached through the use of special materials, although "crack arrest" is not used in the current ABS Rules for Building and Classing Steel Vessels. Alternately, it can be approached without use of special material by employing riveted seams at strategic locations in the ship.

Crack arrest itself is a characteristic that some investigators attribute to the material where others believe it is a function of both the material and the boundary conditions of loading that accompany the propagation of cracks in large structures. An interesting recent report on crack-arrest published by the Electric Power Research Institute entitled "Crack Arrest Studies" and authored by Crosley and Ripling[20] described a series of experiments that include a carbon-manganese steel, 1018, whose crack propagation behavior is considered to be similar to many ship steels. In this investigation, the authors have proposed that crack-arrest toughness, K_{Ia}, is a meaningful parameter that can be measured reliably using laboratory specimens. Their evaluation shows the crack-arrest toughness of a typical material such as 1018 falls in the range of about 85 ksi$\sqrt{\text{in.}}$ at room temperature. Based on general knowledge of 1018 steel, it may be assumed that this is above the NDT temperature. It is shown that the K_{Ia} is a constant and does not depend on the K_Q, the initiating value of K, nor on crack propagation rates over the range included in the study. This range was not great, 1200-3000 ft/sec. because of the specimen size. Within this limitation, it does provide for a measure of crack toughness at arrest which could be used in crack-arrest methodology. It should be noted that some of the conclusions of this report are at variance with the assumptions and conclusions of Ship Structure Committee Report 256.[19] If crack-arrest toughness can be measured reliably in laboratory specimens and does not require the use of a dynamic analysis, then crack-arrest toughness can be reasonably factored into a fracture-control plan for ship steels. Values of K_{Ia} for steels taken from several sources are listed in Table 8.

However, there is also support for the concept that arrest toughness may not be considered a simple material property, but is a complex composite of the many factors. If, as the authors of Ship Structure Committee Report 256 contend, arrest toughness requires a dynamic analysis, then calculation of required levels of arrest toughness is probably not within the capability of current technology.

Clearly, the least justified toughness values in the fracture-control guidelines proposed by Rolfe and his co-workers are the levels selected for crack arrest. The arbitrary use of a multiplying factor of 2 to 4 applied to the toughness proposed for primary main stress members requires levels of toughness for crack arrest that are so high that many of the steels which were considered crack arresters, and even the newer steels considered for crack-arrest functions will not be able to meet the guidelines that are proposed.

Moreover, even these levels could not guarantee that arrest would occur under all conditions. For example, in service where stresses have been measured in the range of 15-30 ksi and for which the distance between crack arresters may exceed 30 ft., as suggested in Ship Structure Committee Report 244, the values of K for a crack initiating between arresters when it strikes the arresting plate may exceed 700 ksi$\sqrt{\text{in.}}$ Requiring toughness in this range may be an unrealistic expectation. For example, for the ABS CS material dynamic fracture toughnesses on this order may be equivalent to DT energies well in excess of those suggested by Rolfe and his co-workers. Ship Structure Committee Report 275 shows DT energies to maximum load and values of K_c calculated from the same tests. For the ductile regime, a 5/8 in. DT energy of 400-600 ft-lb. is equivalent to a K_c of 200-300 ksi$\sqrt{\text{in.}}$ Values of DT energy

TABLE 8

Crack-Arrest Toughness Data

Steel	At NDT Temperature K_{Ia} (ksi$\sqrt{in}$)	 K_{Ia}/σ_{yd} ($\sqrt{in}$)	At 75°F K_{Ia} (ksi$\sqrt{in}$)	 K_{Ia}/σ_{yd} ($\sqrt{in}$)
From Ship Structure Committee Report 256				
ABS-C	53 - 82	0.66 - 1.02	89 - 130	1.48 - 2.17
ABS-E	63 - 149	0.79 - 1.86	-	-
ABS EH	-	-	116 - 205	1.78 - 3.15
ASTM A517-F	207 - 217	1.47 - 1.55	-	-
From Electric Power Research Institute Report 1225				
ASTM A533-B	56 - 64	0.70 - 0.80	90 - 134	1.13 - 1.68

required in a 5/8 inch thick specimen for crack arrest under the conditions indicated above could easily exceed 1200 ft-lbs. Upper shelf impact energies for ABS DS were about as high as any achieved in the research investigation of Ship Structure Committee Report 275, about 850 ft-lbs. For ABS CS maximum values were in the range of 650 ft-lbs., for EH32, 550 ft-lbs. and A517 Grade D, 450 ft-lbs. Other reports may list somewhat higher shelf values for these steels, however, not in the 1200 ft-lb. range.

It may be concluded that looking to material toughness to provide capacity for crack arrest is not a reasonable way to provide assurance of crack arrest in these structures. If only one or two of the materials examined in the Ship Structure Committee investigations were able to meet the minimum dynamic toughness requirement for main stress members, then it is certainly unrealistic to expect that many steels could be used for crack arrest in ship structures. More frequent arresters or arresters designed with special provisions for crack bifurcation and finally arrest would not require levels as high as those listed in this report. Unfortunately, there is no simple way to calculate what those levels would be. It is clear at this point, however, that the materials that were tested thus far will generally not meet the proposed requirement and thus design must enter the picture if crack arrest is to be assured.

E. Crack Arrest in Main Stress Plates

Although it is certain that the arrest of very long propagating cracks covering significant portions of the ship's deck or hull cannot be treated simply, some aspects of propagating crack arrest can be dealt with more directly. For example, it is most desirable to build into the material the ability to arrest small cracks that start in regions of a plate that are subject to local degradation of toughness, for example, weld seams, before they can extend into cracks of major size. These regions are generally confined and small. If they lie transverse to the weld seam they are probably not more than several inches in length, and if longitudinal to the weld seam, although they could conceivably be longer, are quite often limited to the same size range. Making the assumption that the entire weld seam must be treated as a crack, as is sometimes done, not only ignores the role of inspection in fabrication but also can only lead to the conclusion, previously reached, that crack arrest cannot be achieved by material alone.

For practical crack arrest then, attention centers on short extension of cracks coming from small brittle zones and extending into plates short distances. These are essentially equivalent to the ones detailed in the previously mentioned EPRI report[20] and several interesting aspects of crack arrest were shown in that investigation. If crack initiation results in fast moving cracks but crack speed is substantially less than that which occurs in impact loading, the dynamic toughnesses for ship steels approach the ratios of K_{Id}/σ_{yd} for intermediate loading rates, that is to say, they may well exceed 2 or more. Moreover, if crack arrest (K_{Ia}) rather than running crack (K_{Id}) data are applicable to this problem, the crack-arrest studies of EPRI indicate that the events shortly or immediately after crack arrest are essentially identical to those just before, i.e., crack propagation decelerates until the point of crack arrest. At the point of crack arrest, yield point elevation as a result of dynamic loading may no longer apply and the ratio of K_{Ia}/σ_{yd}, is as indicated before, may be greater than 1.5. For stress levels at or near the yield point, 40 ksi, through cracks at least 2.0 inches in length can be arrested for materials with a K_{Ia} of 80 ksi$\sqrt{\text{in.}}$ When the crack moves away from regions of high stress to normal stress levels, 14 to 20 ksi, crack sizes of 10 inches can be accommodated. These estimates are confirmed by the data presented in Ship Structure Committee Reports 272 and 294,[21,22] both dealing with in-service performance of structural details in ships, where cracks on this order of magnitude emanating from stress concentrations were either tolerated or arrested.

V. Charpy Impact Test in Relation to Guidelines

The use of the Charpy impact test to establish that desired toughness levels have been achieved in plate materials has both the weight of engineering experience and a successful history in ships in its favor. The Charpy impact energy equivalents proposed by Rolfe and his co-workers were based on this fact and correlations between Charpy energies and impact toughness measured in the DT test. The principal criticism of the use of Charpy test equivalents comes from the empirical fact that substantial deviations between the shape and position of the CVN curve and the dynamic tear energy vs. temperature curve do exist for the materials tested under the programs reported in Ship Structure Committee Reports 248 and 276. Also, CVN toughness variations at NDT temperatures were substantial. For example, CVN values at the NDT temperature varied from 11 to over 200 ft-lb. with an almost uniform distribution of values between 15 and 45 ft-lb. For some materials, for example ABS CS, the longitudinal and traverse orientation specimens had significantly different levels of Charpy energy at NDT temperature. For higher strength steels, as might be expected, CVN values at NDT temperatures were higher. The spread in the data is so great that no meaningful correlation can be obtained by this author.

The viewpoint that must be adopted is that, although CVN values may be used as a quality control test for steels in production, they cannot be used as a substitute for the Drop Weight Test in establishing the NDT temperature or for the DT test. For this reason, the specification of the drop weight test as the control test for establishing material toughness in Ship Structure Committee Report 244 is not amenable to substitution of other tests to obtain the same data. The use of the drop weight test is perhaps more expensive than the Charpy test, but not substantially so. Many laboratories perform this test on a routine basis and the analysis of the test results, as well as the test procedures, are well standardized.

On the other hand, the dynamic tear test does hold certain advantages in terms of establishing shelf toughness energy levels required for crack arrest and is the test of preference for this function. As is described above, no specific recommendations as to energy levels for crack arrest can be made at this time, however, it is probable that, as these are developed, this will be the test of preference. In this regard, it will then become a test with dual advantage. One of the requirements for the arrester materials could be that the material be in the upper shelf regime over the service temperature range. The dynamic tear test will establish this directly as well as determining the toughness of the upper shelf. It could, therefore, be used in place of the drop weight test for main stress material. In this case, a number of specimens would have to be run over a range of temperatures, a procedure that may not be economical in contrast to testing a smaller number of specimens in the two tests at two specific temperatures.

VI. Recommendations on Proposed Fracture Toughness Guidelines

The information reviewed in the previous sections of this report demonstrate that any fracture-control system based on available information will probably undergo modifications as new data are produced and service experience is reconsidered. In the case of recommendations proposed by Rolfe and his co-workers, new information has been developed over the last five years both for ships and other structures that provides insight into the problem of fracture control in ship hulls.

The bulk of the data at this time support the fact that the proposed toughness guidelines are too conservative, especially for main stress primary and secondary members. The fact that three common successfully used ship hull steels, ABS Grades A, B and C, will not pass the proposed toughness standards is in itself an indication that the requirements are not commensurate with service conditions, especially so with respect to ABS Grade C.

This discrepancy appears to be not so much in the fracture-mechanics analysis of the general problem as the elastic-plastic behavior of the steels in service and the testing methods chosen to verify their toughness performance. There is no particular disagreement with the requirement that the ship hull material should be in a non-plane-strain state ($K_{Id}/\sigma_{yd} \geq .9$) during service so that extensive brittle fractures will not occur. However, when an impact test is selected to verify this performance, this places a severe requirement on the material, especially a strain-rate-sensitive material. As has been demonstrated, impact test loading rates are too high to be representative of ship hull service even under adverse conditions. Therefore, a ship plate that does not have the required toughness in testing where it is loaded in impact may well perform in a satisfactory manner in service when its toughness is much greater. This conclusion is supported by the Ship Structure Committee work, the current work on similar materials in other types of service and ship service experience.

To specify how much toughness is actually required for ship service in the absence of an effective recognized intermediate rate test is difficult to do and must be based on engineering judgment. The author has included some proposed modifications to the criteria of Rolfe, et al. that attempt to take this into account (Appendix 1). Beyond these proposals, which are admittedly based on limited information, it can be stated that an operational fracture control plan for ship hull steels does not yet appear to be developed.

The proposed guidelines of Ship Structure Committee Report 244, and the research that they stimulated, have served to advance the state of the art in this important field by centering attention on a new set of fundamental questions. These questions are discussed in more detail in the Recommended Research of this report, however, they can be enumerated here. First, what are realistic macroscopic stresses and loading rates in ships? Ship stress studies have given a partial answer to the first question--they can be fairly high, close to the yield point of the steel. Loading rates are not well documented at this time, and need to be much better understood. Another fundamental question is how intermediate rate toughness in ship steels can be measured quantitatively. Testing of this type is complex because, for many ship materials, intermediate rate tests produce high levels of toughness and change linear-elastic fracture toughness tests to elastic-plastic ones. Procedures for evaluating elastic-plastic toughness are in the developmental stage and this means test development is required. Finally, the whole question of crack arrest is brought into focus as a problem that cannot be dealt with effectively by material properties alone. This is itself an important finding and should be the basis for a new approach to fracture control in ship structures as well as a subject for continuing research.

In the introduction to this report, three questions are listed as the specific charge to the investigator. These questions were, briefly, can we now assess the proposed criteria, are the test methods proposed adequate, and are modifications needed? The answers to these questions are a qualified yes, no, and yes, respectively. As indicated above, enough laboratory data and service experience have been developed to give a preliminary evaluation of the criteria and the conclusion is that they are too conservative. In the process of coming to this conclusion, it has become apparent that the test methods proposed do not necessarily measure service toughness. For this reason the proposed criteria need to be modified both with respect to test methods and the toughness required to form a both effective and economic fracture control plan for ship hull steels.

VII. Recommendations for Future Research

From the standpoint of steel properties it does not appear that additional test data to characterize ship steel plate properties will add anything to the data already obtained except to increase the size of the base. Weldments, however, are a much smaller proportion of the data and relatively few NDT temperatures or other toughness data for weldments are available. It would appear that a much larger data base for weldments made by various processes would be in order. It is possible that much of these data already exist. It would be highly desirable to gather this information and give it some close examination in the light of this review.

Although the drop weight and dynamic tear tests have been proposed as fracture-control tests, they measure impact toughness only. It has become clear that the definition of and measurement of "intermediate rate" fracture toughness is a key issue with respect to ship steel fracture control. Measurement of crack toughness as a function of loading rate is a significant experimental problem; and yet these are exactly the data needed to develop or evaluate fracture-control plans. The weight of the data reviewed in this report suggests that ship loading rates are moderate and crack toughnesses at and above the NDT temperature are high, but it is obvious that toughness data of this type are limited. A substantially improved data base in this area would certainly be in order.

It is a recommendation of this report that crack arrest in ships cannot be treated as a material characteristic alone, but must involve a systems approach using the steels, geometries, locations and details in concert to effect arrest. Minimum arrest levels that can be expected of steels need further study. Provision for crack arrest is especially critical for the use of high-strength steels in ships where allowable stresses may be high and shelf toughness may be relatively low. Arrest of running cracks under these conditions will require sophisticated approaches.

With respect to developing the overall fracture toughness data for the ship steel problem, it is clear that there is still a need, in spite of many efforts, for a simple method for measurement of K_{Id}, K_{Ia} and σ_{yd} directly. These parameters are a necessary component of any fracture-mechanics approach to fracture control. Fortunately, some test methods have been developed over the last five years and are now under intensive study by ASTM subcommittees and task groups. Continued development of these tests will be needed if ship steel fracture-control methods are to be based on fracture-mechanics concepts. One particular difficulty with respect to using such a test for ship steels is that the measurements must extend into the elastic-plastic and even to the fully plastic range. These measurements are difficult enough in static testing, in dynamic testing, they are even more challenging and difficult to interpret. Yet, this is where the techniques are needed and research should be directed.

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APPENDIX 1

Proposed Modifications to Guidelines

On completion of this report, the author believes that modification of the proposed guidelines is necessary and that sufficient data to provide a start on this adjustment are available in the material that has been reviewed.

The problem then becomes how the recommendations of Ship Structure Committee Report 244 can be rationally and quantitatively modified to reflect this fact. Because of the limitations on data, the quantitative modifications are particularly difficult. However, data on measured and estimated ratios of K_{Id}/σ_{yd} at the NDT temperature for various loading rates appear to provide an approach. For low-strength C-Mn steels, data obtained from a number of sources show that, at the NDT temperature, the K_{Id}/σ_{yd} ranges from 1 to 1.3, while at $75^{o}F$, it ranges between 2 and 7 when loading rates that more closely approximate ship service are used. The weight of the data produced in Ship Structure Committee research also supports these values of K_{Id}/σ_{yd} when testing is at the intermediate rather than impact rates. At impact rates, this ratio approaches the value of 0.5 to 0.63, as might be expected.

A. <u>Primary Load-Carrying Main Stress Plates</u>

Using these data, it is possible to propose that the NDT temperature requirement be raised from something well below the minimum service temperature to the minimum service temperature itself; $32^{o}F$. To insure that variations in NDT temperature determinations will not permit marginal material in service, a reduction in the NDT temperature requirement to $20^{o}F$ is an arbitrary but reasonable precaution, $12^{o}F$ below normal minimum hull service. Since this requirement falls close to the minimum service temperature, no additional test is necessary to insure a rising curve of toughness since the required toughness level will be established by the single test. The result of this test should be a service $K_{Id}/\sigma_{yd} > 0.9$.

It must be recognized that such a procedure does not imply all materials tested will have the same relative toughness at $20^{o}F$ since the K_{Id}/σ_{yd} ratio at the NDT temperature is lower for the high-strength steels than that of the lower strength steels. It should, however, establish a <u>minimum</u> level of toughness at a <u>minimum</u> service temperature that will prevent initiation of brittle fractures. This requirement is identical to that proposed by Rolfe and his co-workers for primary load carrying <u>secondary stress</u> members, however the interpretation as to the effective toughness level implied by the test is different.

Table 4, in which the performance of ship steels against the Rolfe et al. secondary stress guideline requirement is listed, shows that this proposal not only agrees well with the experimental data but is consistent with general ship experience. That is, the performance in this test is marginal for Grade A, somewhat better for Grade B and good for Grades C, D, E, CS and EH32. The single plate of AH32 tested did not pass this test. All of the special plates tested also passed this test, as did all of the weldments tested.

B. Primary Load-Carrying Secondary Stress Plates

If the primary load-carrying member requirement for main stress materials is an NDT temperature of 20°F, it might be assumed that a lower level is acceptable for secondary stress members. Secondary stress members do have a lower general stress level, however the residual stress level in weldments in these locations will be identical to those in primary members. From the crack initiation viewpoint, a reduction in required toughness is unjustified. Once crack initiation has occurred, the general stress level in these members will be reduced, however, nominal stress levels in ships are fairly low and the differentiation between primary and secondary stresses on this basis does not appear significant. It is, therefore, reasonable that the same basic requirement be applied to these members as the others, i.e., an NDT temperature of 20°F.

C. Crack Arrest Requirements

The requirements for crack-arrest plate materials are the most difficult of all to specify because of the uncertainties in the measurement technique for crack arrest properties. If, as discussed before, crack arrest can be treated as a static or quasi-static problem, crack-arrest requirements can be calculated or estimated in conjunction with the design of the ship cross section and the spacing and configuration of crack arresters. As was shown before, spacing of arrester systems at distances of more than 30 feet creates values of K that can, under nominal stresses of 15 ksi, exceed values of 350 ksi$\sqrt{\text{in.}}$ For the yield point stresses implied in Ship Structure Committee Report 244, requirements can be twice this value, levels which many otherwise tough materials would fail to provide. Even at shorter spacings, fracture-toughness measurements show that only low-strength steels with very high shelf toughnesses can provide arrest capacity in the steel alone.

Certain aspects of the requirements for arrest toughness can be defined. It is undoubtedly necessary to consider that upper shelf toughness under dynamic loading is the proper regime and, thus, the NDT temperature should be selected to provide this. The data of the various reports shown in Tables 4 and 5 indicate that the few materials that could consistently provide high shelf toughness in DT tests, for example, ABS CS, had NDT temperatures at or below 0°F. This requirement is not sufficient in itself, however, because steels having low NDT temperatures may have low shelf toughness. To establish the shelf toughness energy requirement in the absence of knowledge of arrester configurations is not possible at this time. This is one case where design and materials interact so closely that no simple material specification can be written and it is obviously the area where research is most urgently needed. In general, it can be stated that DT test values of greater than 1000 ft-lb. may be required in the operating regime unless sophisticated arrester designs are used.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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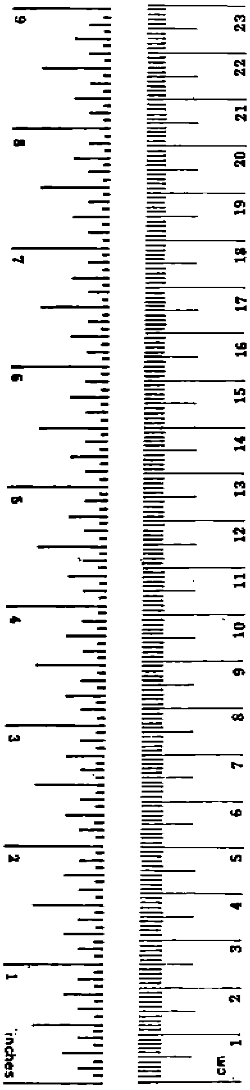
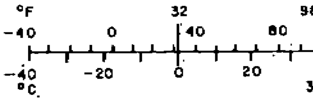
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions fr

Symbol	When You Know	Multiply
		LENGT
mm	millimeters	0.04
cm	centimeters	0.4
m	meters	3.3
m	meters	1.1
km	kilometers	0.6
		AREA
cm^2	square centimeters	0.16
m^2	square meters	1.2
km^2	square kilometers	0.4
ha	hectares (10,000 m^2)	2.5
		MASS (w
g	grams	0.035
kg	kilograms	2.2
t	tonnes (1000 kg)	1.1
		VOLUM
ml	milliliters	0.03
l	liters	2.1
l	liters	1.06
l	liters	0.26
m^3	cubic meters	35
m^3	cubic meters	1.3
		TEMPERATUR
°C	Celsius temperature	9/5 (th add 32)



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