SERIAL NO. **SSC-63**

# REVIEW

of

# WELDED SHIP FAILURES

by

HAROLD G. ACKER

Bethlehem Steel Company

Shipbuilding Division



Prepared for

**NATIONAL RESEARCH COUNCIL'S**

**COMMITTEE ON SHIP STRUCTURAL DESIGN**

Advisory to

## SHIP STRUCTURE COMMITTEE

**Division of Engineering and Industrial Research**

National Academy of Sciences - National Research Council

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U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

15 December 1953

Dear Sir:

The enclosed report entitled "Review of Welded Ship Failures" by Harold G. Acker, Bethlehem Steel Company, Shipbuilding Division, is one of a group prepared for the Committee on Ship Structural Design to assist it in assessing the present state of knowledge of the motions of and stresses in ships at sea and the structural aspects of brittle fracture. These reports have materially assisted in determining areas in which research directed toward the elimination of brittle fracture in welded steel merchant vessels may be most successfully undertaken.

Other reports in this series, SSC-62 and SSC-65, have recently been published.

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

Very truly yours,

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

# REVIEW OF WELDED SHIP FAILURES

## INTRODUCTION

The purpose of this report is to review critically the available information on structural failures in welded ships.

Although buckling failures in a few naval vessels and several transversely framed European tankers have been reported, this report will review failures from the brittle fracture point of view.

Welded ship fractures were of the brittle-cleavage type and usually propagated at high velocity. There was no evidence of fatigue although high, local cyclic stresses in some cases undoubtedly contributed to crack initiation. The loud noise accompanying extensive fracture indicated the instantaneous release of a large amount of energy.

As far as the engineer is concerned, the basis of any tensile strength criterion of steel in a structure must be its ability to resist brittle-cleavage type fractures. If there can be no brittle failure, the structure will not fail in tension under service loading. Specifically, the engineer wants to know:

1. the conditions under which a brittle-cleavage crack will start, and
2. the conditions under which a brittle-cleavage crack will propagate.

In order to find realistic answers to the above questions, considerable weight must be given to the actual service performance of structures, and all research must be related to it.

Although the present ship structure research was prompted by welded ship failures, it should be remembered that riveted ships are not immune to fractures. Since 1900, over a dozen riveted merchant ships have broken in two during heavy weather or are listed as missing. It is significant that most of these vessels were of the tanker type, the same type that has given the most trouble as far as welded ships are concerned. Several of the riveted tankers which broke in two were said to have been heavily loaded amidships. This was also the most prevalent loading condition when serious failures occurred in welded tankers. In most cases, failure occurred in riveted ships when the ships were less than 10 years old; in a few cases, however, the ships were over 20 years old.

Sizeable cracks developed in several large passenger liners. Both the LEVIATHAN and MAJESTIC experienced cracks in upper strength decks, the cracks starting at square uptake openings and extending to the side shell. Some of the breaks extended down the shell. In at least one case a loud report was heard when the structure gave way indicating that the fracture was probably of the brittle-cleavage type. The EUROPA had deck cracks starting from square uptake openings and sheer strake cracks starting at airports.

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Minor fractures have occurred in riveted ships, and frequent mention of cracks at hatch corners, bulwarks, etc., has appeared in the technical literature. It is probable that many of these cracks were of the brittle-cleavage type rather than the fatigue type as was generally suspected in earlier years. It is not unlikely that some of the serious riveted ship failures may have been associated with plate buckling.

## ANALYSIS OF WELDED SHIP FAILURES

The three categories of casualties discussed are defined as follows:

Group I casualty - A casualty (a ship) having one or more fractures which have weakened the hull so that the vessel is lost or in a dangerous condition.

Group II casualty - A casualty having one or more fractures which are generally less than 10' long and do not endanger the ship. These fractures, however, do involve the main hull structure and are potentially dangerous.

Group III casualty - A casualty having fractures which do not involve Group I or II fractures. Examples are fractures in internal bulkheads, deckhouses, masts, etc. Some of these fractures have been extensive and costly to repair.

During the past ten years there have been about 250 Group I and 1200 Group II casualties in welded ships over 350' long. Very few failures have occurred in smaller vessels. Nineteen (19) welded ships have broken in two or were abandoned after their backs were broken:

| | |
|---|---|
| 9 | - T2 Tankers |
| 2 | - Other Tankers |
| 7 | - Liberty Ships |
| 1 | - Converted LST |
| 19 | |

<u>Comparison of Welded and Riveted Ships Built Since 1938</u>*

A comparison of welded and riveted ships based on about 6000 vessels classified with the American Bureau of Shipping has recently been reported [(1)].

Since 1938 there have been four times as many welded ships built as ships with riveted shells or decks. The great majority were welded Liberties and welded T2 Tankers built during World War II. Many of these ships experienced failure.

A condensation of data in reference 1 is given in Figure 1 and Table I and shows that:

1. For the same material and essentially the same design and quality of workmanship both frequency and severity of fractures increased as the amount of welding increased.

2. Welded tankers have had much more trouble than welded (dry) cargo ships.

For the Liberties, the majority of fractures started at square hatch corners and square cutouts in the top of the sheer strake. The frequency of serious failures in the Liberties

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*Since welding was beginning to be used rather extensively about 1938, "Riveted Ships" here and throughout the remainder of this report means ships built with riveted seams. The amount of seam riveting is noted in each case. Butts were usually welded.

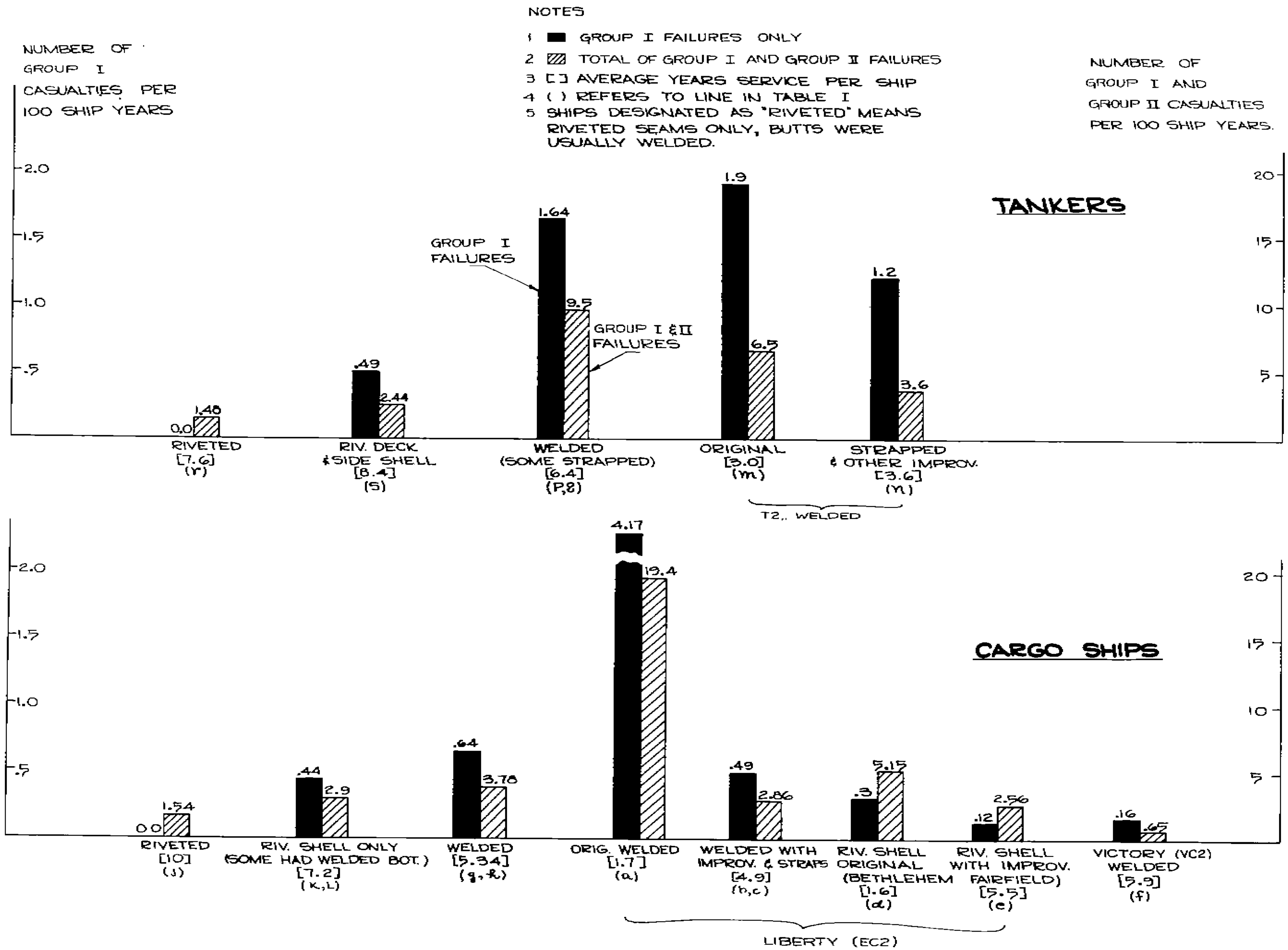



FIG. I - FREQUENCY OF CASUALTIES FOR SHIPS BUILT SINCE 1938

TABLE I

COMPARISON OF STRUCTURAL RECORD OF WELDED AND RIVETED SHIPS

Condensation of Table I in paper by D. P. Brown, September 1952

| SHIPS | | NO. OF CASUALTIES GROUP I | NO. OF CASUALTIES GROUP I & II | NO. OF SHIPS | SHIP YEARS | AVE. YEARS PER SHIP | CASUALTIES PER 100 SHIP YEARS GROUP I | CASUALTIES PER 100 SHIP YEARS GROUP I & II | REF. LINE See note ** |
|---|---|---|---|---|---|---|---|---|---|
| LIBERTIES (EC2) | | | | | | | | | |
| Welded | Original | 88 | 408 | 1220 | 2100 | 1.7 | 4.17 | 19.40 | a |
| Welded | Improved details | 14 } 45 | 94 } 266 | 1890 | 2600 } 9285 | 4.9 | .54 } .49 | 3.61 } 2.86 | b |
| Welded | Improved details and straps* | 31 | 172 | 1554 | 6685 | | .46 | 2.58 | c |
| Riveted shell (Beth.Fairfield) | Original | 1 | 17 | 208 | 330 | 1.6 | .30 | 5.15 | d |
| Riveted shell (Beth.Fairfield) | Improved details | 2 | 44 | 313 | 1713 | 5.5 | .12 | 2.56 | e |
| VICTORIES (VC2) | Riv. gunwale angle | 4 | 16 | 414 | 2450 | 5.9 | .16 | 0.65 | f |
| CARGO (Over 350') | | | | | | | | | |
| Welded | All welded | 13 } 16 | 85 } 94 | 388 } 457 | 2123 } 2487 | 5.4 | .61 } ..64 | 4.00 } 3.78 | g |
| Welded | Riv. gunwale angle | 3 | 9 | 69 | 364 | | .82 | 2.47 | h |
| Riveted | Deck and shell | 0 | 2 | 13 | 130 | 10.0 | 0 | 1.54 | j |
| Riveted | Shell only | 6 } 9 | 51 } 59 | 186 } 295 | 1288 } 2031 | 7.2 | .47 } .44 | 3.96 } 2.9 | k |
| Riveted | Side shell only | 3 | 8 | 109 | 743 | | .40 | 1.07 | l |
| T2 TANKERS (Welded) | | | | | | | | | |
| | No Straps | 28 } 49 | 97 } 161 | 502 } 994 | 1483 } 3255 | 3.0 | 1.90 } 1.50 | 6.55 } 4.96 | m |
| | Straps (some other improvements)* | 21 | 64 | 492 | 1772 | 3.6 | 1.18 | 3.61 | n |
| TANKERS (Over 450') | | | | | | | | | |
| Welded | No Straps | 4 } 5 | 20 } 29 | 38 } 48 | 248 } 305 | 6.4 | 1.61 } 1.64 | 8.06 } 9.5 | p |
| Welded | Straps | 1 | 9 | 10 | 57 | | 1.75 | 15.8 | q |
| Riveted seams | Deck and shell | 0 } 2 | 5 } 15 | 40 } 94 | 336 } 746 | 8.4 | 0 } .27 | 1.48 } 2.0 | r |
| Riveted seams | Side shell and deck | 2 | 10 | 54 | 410 | 7.6 | .49 | 2.44 | s |

* Straps added after ships had seen service as all-welded ships. Straps or gunwale angles installed on some Liberties before delivery.

** Reference lines in Mr. Brown's Paper.

a - 1
b - 2
c - 3,4
d - 5
e - 6

f - 7
g - 10,12,17,20,23,27,33
h - 15,18,24,28,34
j - 14,32

k - 11,13,22,26,31,36
l - 9,16,19,21,29,30,35
m - 40
m - 41

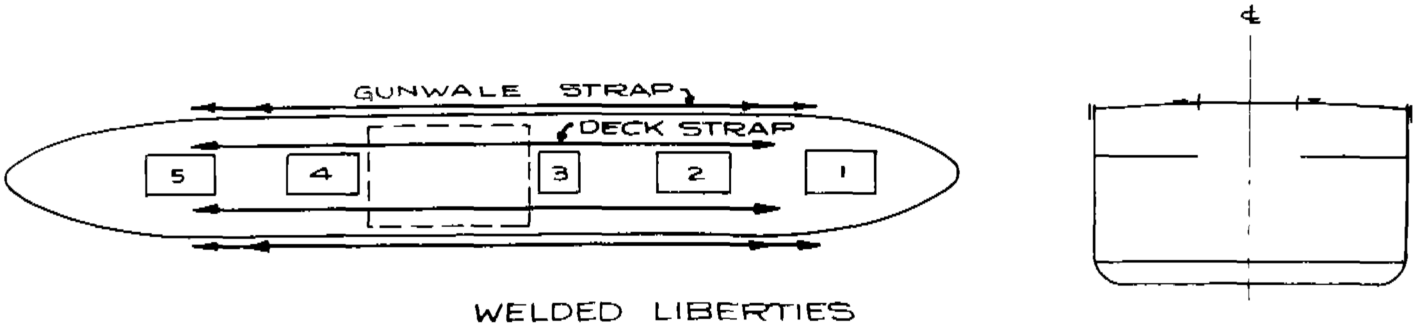
p - 44,48,52,55
q - 53
4 - 46,50,54
s - 45,47,49,51

was substantially reduced after a few structural details, particularly the hatch corner and sheer strake cutout, were improved. This is illustrated in Figure 1. In addition, riveted crack arrestor straps were installed in the deck and at the gunwale of the welded Liberties, Figure 2.

For the T2 tankers, most of the trouble stemmed from defects in bottom shell butt welds, and no simple remedial measures could be applied. Eventually at least 4 crack arrestor straps were installed in the T2 tankers--two on the deck and two on the bottom, see Figure 2. The straps covered the midship length of the ship where serious cracking had been experienced. While crack arrestors have been effective in limiting the extent of cracks, they have not decreased the incidence of cracks or prevented the breaking in two of ships. The frequency of Group I fractures in the T2's did not diminish significantly. Fractures in T2 tankers have therefore remained the major ship failure problem.

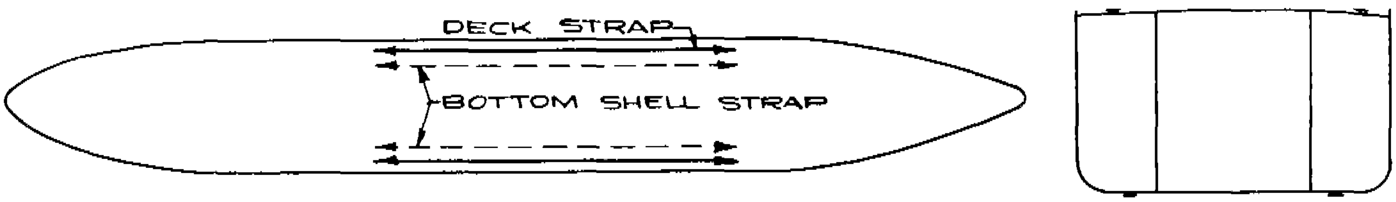
A new directive for structural modifications of T2 tankers was issued by the American Bureau of Shipping in April 1952. This included installing additional crack arrestor straps to bring the minimum number to eight and increasing the section modulus of the hull girder by 15%.

It is interesting to note that the welded Victories, which had the benefit of improved design details, have had the lowest percentage of casualties (Group I plus Group II).



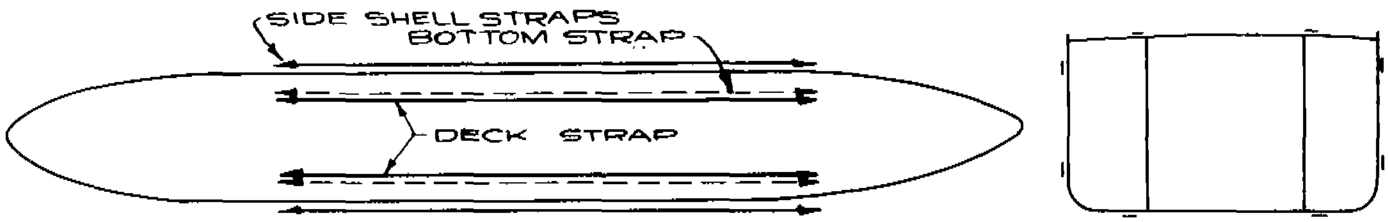

WELDED LIBERTIES

(NO STRAPS WERE REQUIRED ON THE BETHLEHEM FAIRFIELD LIBERTIES, WHICH HAD RIVETED SHELL SEAMS.)




ORIGINAL MINIMUM REQ'D FOR T-2 TANKERS

(NEW REQUIREMENT OF 1952 CALLS FOR A MIN. OF 8 STRAPS.)




ARRANGEMENT INSTALLED ON T-2'S BY SOME PRIVATE OWNERS

**FIG. 2 - LOCATION OF CRACK ARRESTOR STRAPS**

See Figure 1. However, these ships have had four Group I failures. Two of the four started at poorly made repair welds. One of these failures started at a place where a short saddle weld was made after a through padeye in the deck was flushed off. The other fracture (an unusual 66' fore and aft fracture) started in a poorly made seam weld which was part of a bottom shell repair made in a foreign port. This illustrates that repair yards as well as building yards can be involved in contributing to failures in welded ships. It also illustrates one of the practical reasons why the shipbuilding industry is relying on improved material to minimize cracking.

The third Group I Victory ship failure developed in the deck where two cracks, running approximately parallel to each other, extended from a hatch corner to the shell. This ship was in light condition and was being driven hard in very heavy weather. Nothing is known of the fourth casualty since the ship was lost.

Although there is no reference in Figure 1 or Table 1 to the new postwar designed super tankers of about 28,000 tons dwt, it is gratifying to find that over 40 of these vessels have been operating through at least one severe winter without a casualty reported. The postwar tankers are all-welded except for about 12 strategically located riveted seams and have been constructed of steel meeting the new American Bureau of Shipping specifications. In addition many of these ships have been subjected to random radiographic inspection of main hull welds. This inspection does not guarantee that there will be no defective welding, but it has markedly improved the weld quality over that in wartime and prewar built ships.

Figure 1 shows that fractures in the original Bethlehem-Fairfield (B-F) Liberties (which differed from all other Liberties only in that they had riveted shell seams) were less extensive and less frequent than in the original welded Liberties. Incidentally the more serious failures in the B-F Liberties were in the shell, and not in the deck as in the case of the welded Liberties. The less serious fractures in the B-F Liberties, however, generally occurred in the all-welded deck, primarily at hatch corners. After corrective alterations were made to all Liberties, the frequency of failure in both riveted and welded types was about the same although the cracks in the B-F ships were still less extensive.

Several attempts have been made to find reasons for the better record of the B-F Liberties, but no obvious reason was found except perhaps in a few instances where cracks stopped at riveted seams. The weather conditions, at least during the war, were, if anything, more severe for the B-F ships. There is no evidence that workmanship or steel quality was superior in the B-F ships. It was also found that the locked-in welding stress pattern in the welded upper deck was essentially the same for both the B-F and welded Liberties.* There is no evidence of rivet slip at normal working loads, and it is difficult to see how any slip in a seam 6 to 30 feet away from areas in which fractures commonly originated could be instrumental in preventing cracks from starting in these locations or even preventing crack propagation.

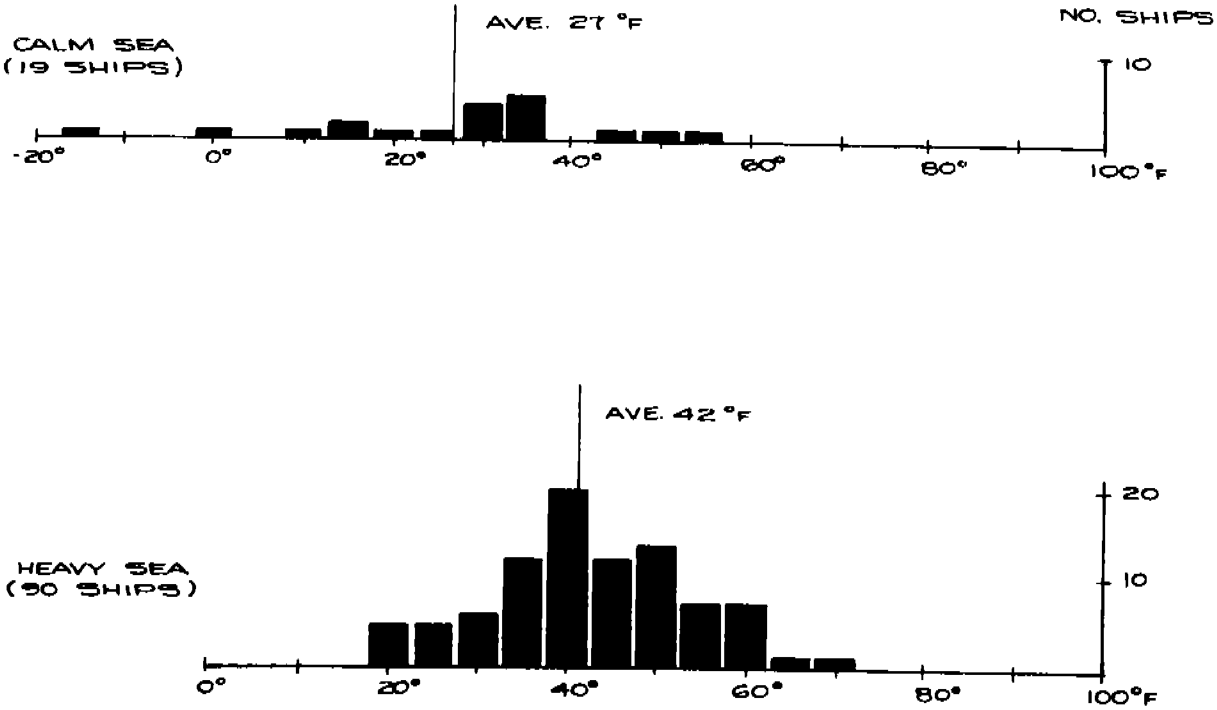
Conditions Surrounding Welded Ship Failures[2,3,4,5]

The majority of failures occurred during heavy weather and near freezing temperatures, Figures 3 and 4.

Figure 3b shows that the probability of failure increases rapidly as the temperature is lowered. Although the failure temperatures include some sea water temperatures, there were very few cases where the water temperature was markedly different from the air temperature, and therefore the sense of the probability curve is valid. These curves, of course, are for ships built of wartime steel, and they indicate that the chance of failure increased about four times when the temperature was lowered from 50°F to 30°F.

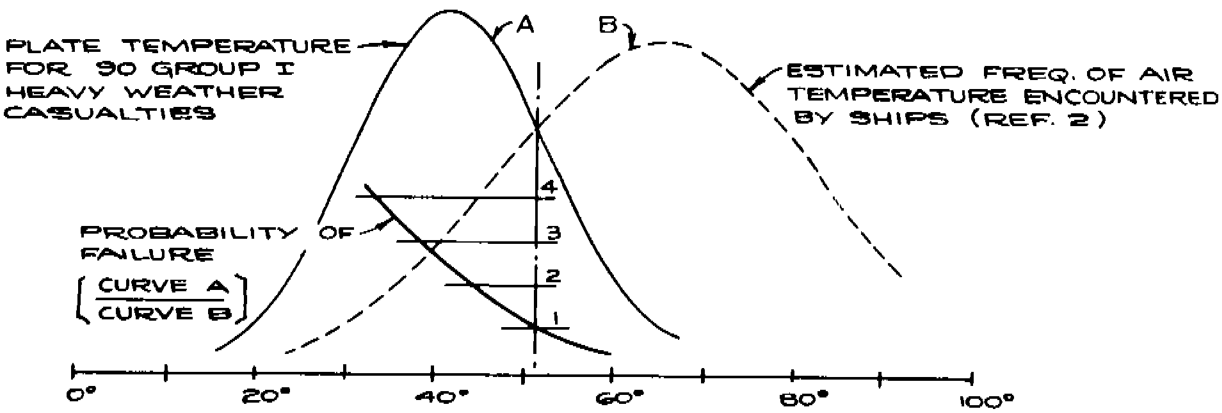
Figure 4 shows that failures occurred more frequently

*See Appendix I for a brief review of residual welding stress studies conducted on ships.




NOTES
1. TOPSIDE FAILURE - AIR TEMP.
2 BOTTOM FAILURE - WATER TEMP.
3. AVERAGE OF 15 MODERATE SEA CASUALTIES WAS ABOUT SAME AS FOR HEAVY SEA CASUALTIES

(a) PLATE TEMPERATURE AT TIME OF FAILURE




(b) SHOWING INCREASE IN PROBABILITY OF FAILURE AS TEMPERATURE IS LOWERED

FIG. 3 TEMPERATURE AT FAILURE
GROUP I CASUALTIES

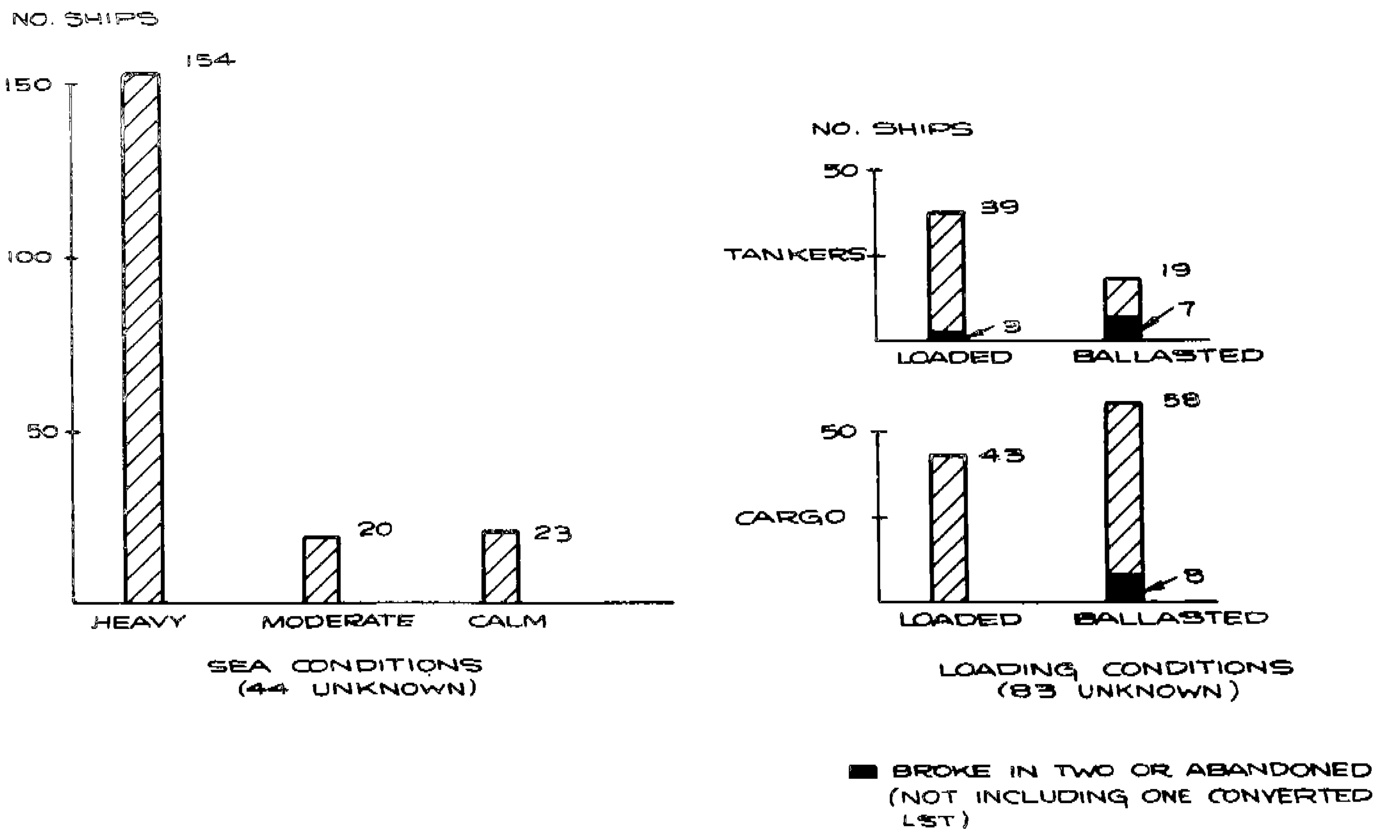



FIG. 4 - SEA AND LOADING CONDITIONS AT TIME OF FAILURE
GROUP I CASUALTIES

in cargo ships when they were in ballast and in tankers when they were loaded. It seems significant that the great majority of ships that broke in two were in ballast.

Still water (nominal) bending moment stresses of approximately 5 tons per square inch have not been uncommon in tankers including those which failed. Seaway stresses are, of course, to be added. Recommendations for loading and ballasting tankers to avoid excessive bending stresses have been issued recently. This is particularly important because in tankers, or any ship with a long cargo space amidships and machinery aft, small changes in load distribution can result in large changes in bending moment stresses.

Except for the early Liberty failures in 1943-45, the frequency of failures in both cargo ships and tankers has not shown any particular trend either to increase or to decrease with length of service, Figure 5. For the Victories, however, all four Group I failures and 80% of the Group II failures occurred during the last two years, i.e., failures began to develop after the ships had given about 4 years of nearly trouble-free service.

## Origins and Locations of Fractures

Known origins of Group I failures are listed in Tables II and III. In no case did a fracture start in a sound weld, and seam welds have given practically no trouble. A welded joint of some kind was associated with every fracture origin.

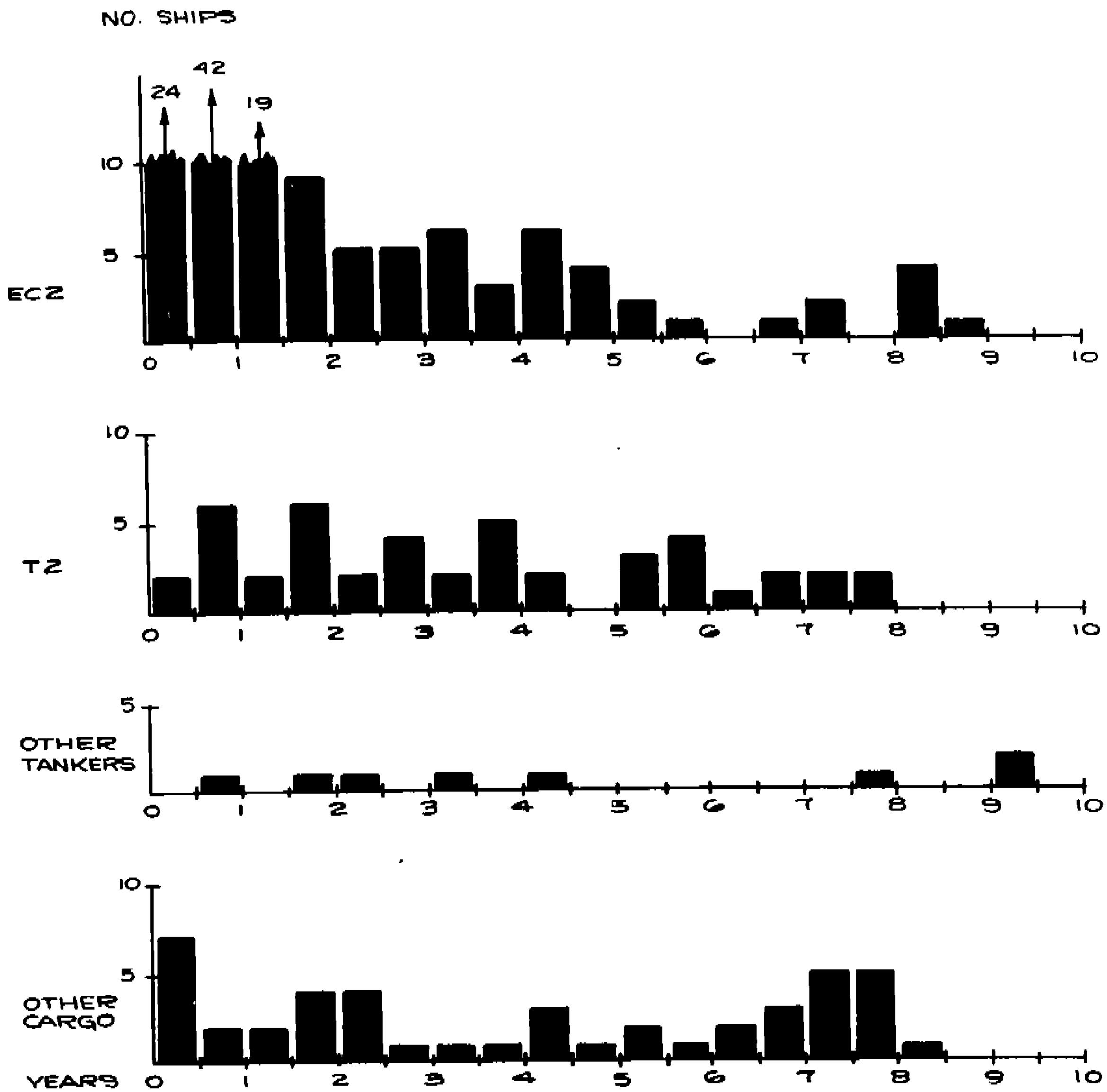



FIG. 5 - YEARS IN SERVICE AT TIME OF FAILURE
GROUP I CASUALTIES

## TABLE II

### Known Origins of Group I Failures

**TANKERS**

| | T2's No. | T2's % | | Others No. |
|---|---|---|---|---|
| Defective Butt Welds | | | | |
| (a) deck and sheer strake | 2 | 6) | | 1 |
| (b) shell, mostly at bilge | 11 | 32) | 47% | 4 |
| (c) bilge keel | 3 | 9) | | |
| End of longitudinal | 7 | 21 | | 2 |
| Bilge keel (scallops, end of keel) | 8 | 23 | | 1 |
| Elsewhere | 3 | 9 | | 1 (Bessemer Steel H.R) |
| Total | 34 | | | 9 |

**CARGO SHIPS**

| | Liberties No. | Liberties % | | Others No. |
|---|---|---|---|---|
| Hatch corner | 39 | 54 | | 11 |
| Cutout for Acc. ladder | 14 | 19 | | 4 |
| Defective butt welds | | | | |
| (a) shell | 7 | 10) | | 3 |
| (b) bulwark | 4 | 6) | 23% | 1 |
| (c) deck | 3 | 4) | | 1 |
| (d) half-rounds (probably Bessemer Steel) | 2 | 3) | | - |
| Elsewhere | 3 | 4 | | 2 |
| Total | 72 | | | 22 |

## TABLE III

### General Location of Group I Fracture Where Origin Not Known

**TANKERS**

| | T2's No. | T2's % | Others No. |
|---|---|---|---|
| Bottom shell and bilge | 10 | 59 | 1 |
| Deck and gunwale | 2 | 12 | |
| Elsewhere | 5 | 29 | |
| Total | 17 | | |

**CARGO SHIPS**

| | Liberties No. | Liberties % | Others No. |
|---|---|---|---|
| Upper deck and gunwale | 57 | 90 | 18 |
| Bottom shell and bilge | 4 | | 3 |
| Elsewhere | 2 | | 1 |
| Total | 63 | | 22 |

Hatch Corners. The hatch corners of the older welded ships were square and many had small inserts and doublers. In addition, several welded joints terminated exactly at the corner where it was practically impossible to make a good fit or a sound weld. In the Liberties, the hatch corners have been rounded, and this has greatly reduced the frequency of hatch corner failures.

Cutouts in Top of Sheer Strake for Accommodation Ladder. These cutouts have been eliminated on later ships and rounded off or eliminated on earlier ships.

Ends of Tanker Longitudinals. Approximately 15% of the Group I and II failures in T2 tankers originated in the bottom shell plating at the end of longitudinals interrupted at transverse bulkheads. The number of ships involved was 24 (5%) out of approximately 500. About 100 tankers other than T2's have a similar longitudinal detail and only one failure of this type has been reported. On many recently built tankers the ends of the longitudinals have been cut to a large radius to ease the stress condition. On the new Navy Oilers the continuity of the longitudinal is carried through the bulkhead by a deep bracket.

Bilge keels. Welded bilge keels have been particularly troublesome on T2 tankers. At first most of the trouble started at faulty bilge keel butt welds and at the abrupt ends of the keel which terminated in the middle of a plate panel.

Scallops were cut in the web of the bilge keel at the butt welds to prevent any cracks in the butt from extending into the shell plate. Other scallops were cut in way of shell butts. On a few occasions where the scallops were crudely flamecut, cracks started in way of the scallops. (It is common practice now to drill the rounded corners of bilge keel scallops.) The ends of the bilge keels were tapered and a doubler plate added. However, in order to facilitate welding and fitting, a small scallop was cut in the bilge keel in way of the doubler. Several recent Group I casualties originated in way of these scallops.

Included in the new directives for the structural modification of T2 tankers is the requirement that bilge keels be riveted to the hull plating and that bilge keel scallops are to be eliminated.

The great majority of tankers other than T2's built since 1938 have welded bilge keels. The depth of the keels ranges from 10" to almost 30". Very few keels have scallops in way of butt welds and only the more recent tankers have the keel ends tapered. Although some bilge keels have been damaged or even torn from the shell, there have been very few cases reported other than in T2's where shell cracks have started from a welded bilge keel attachment. If there have been such failures, they were probably not of a serious nature.

On small naval vessels, such as destroyers, DE's and escorts, the flat plate bilge keels developed fractures in the web next to the shell connection and in several cases the keel just peeled off. British naval vessels had similar experiences. One remedy was to weld a flat bar on the bilge keel web near the shell connection to increase the stiffness at that point. The measure helped but did not eliminate the trouble.

Bulwarks. Several serious fractures have started in defective bulwark welding. To prevent such cracks from spreading into the main hull plating, the bulwarks have been separated from the hull and are supported by brackets.

Light welds on heavy plating. The breaking in two of a T2 at dockside initiated much discussion of the effect of arc strikes and light welds on heavy plate. This failure started in the deck between a small clip and a chock foundation. The space between the two was less than one inch. There was no weld defect, and the Charpy V-notch transition temperature of the deck plate was the lowest of any of the source plates tested. It was thought that the light clip weld, through a rapid quench, might have further embrittled the deck plate material which had already undergone thermal treatment as a result of welding the chock foundation, i.e., a light weld on a heat-affected zone.

In several instances cracks have started at small single fillet welds (involving low heat input) of pads welded to the deck. In one case the weld was about an inch from a deck butt; the crack spread both inboard and outboard through the stringer plate. Even though light welds and arc strikes may not present a major problem, efforts are being made to minimize the number of light welds on heavy plate. The Navy now requires a fairly heavy minimum size fillet weld on heavy plate. The American Bureau of Shipping has taken similar steps.

Mast Failures. Mast failures have occurred on 10 Victory ships. Five unstayed foremasts, sometimes referred to as forward kingposts, broke off during heavy weather. The masts were made of 1 1/4" to 1 1/2" plate rolled to about 40" diameter and had a machine welded seam running the full length of the tube section. The mast joint at the end of each section was butt welded or lapped 8" and fillet welded. In all but one case the fracture developed within an inch of a circumferential weld at the mast house top or just below the lower fillet weld at the first mast joint above the mast house. The temperatures at time of failure were not particularly low; for the five reported temperatures, the average was 40°F. Except for one case there was no obvious defect reported at the origin.

The mast design details of Victory ships are not unlike those of the Liberties and other cargo ships in which no serious mast failures have occurred. The self-supporting feature of the Victory ship foremast was probably a major contributing factor in causing failure.

Buckling of plating. The Victory ships which are transversely framed have a 36" frame spacing amidships and 3/4" shell plate. These ships have exhibited buckling tendencies in the bottom shell which may be attributed to the somewhat greater than usual frame spacing. Some owners have installed reinforcing members to reduce panel sizes.

Several cruisers experienced buckling of the upper deck and side shell in way of the forward turret where the heavy armor ended and the light welded forward section began. Additional framing was added as reinforcement in this transition area. Light plating in deck and shell of Destroyers and DE's also buckled occasionally. Six Norwegian transversely framed tankers which broke in two are said to have failed principally due to buckling of deck plating.(6) All of these tankers were loaded amidships (sagging).

Miscellaneous fractures. There have been innumerable nuisance cracks in internal tanker bulkheads, deckhouses and even in main strength members. Many cracks are of long standing and might never be repaired. There are others that go undetected.

In several vessels, large pieces of bottom shell plating forward have been literally punched out. Slamming may have been responsible. Slams are violent shock loads thought to be caused by local, instantaneous hydrostatic pressure differentials on the bottom shell. Transient stresses in the order of 5000 psi double amplitude have been recorded during slamming.

A common source of trouble on tankers is at places where a rigid member either lands on or penetrates the middle of a flexible panel (of a bulkhead for example). Another detail that presents a problem is the connection of fluted transverse and longitudinal bulkheads.

<u>Ships that Failed in Calm Sea</u>

Twenty-three (23) or about 10% of the Group I failures occurred in calm or essentially calm water.

10 Liberties

9 T2 Tankers (3 broke in two; these were hogged in ballast condition)

4 Miscellaneous

Figure 3 shows that the average plate temperature for 19 of the 23 "calm water" casualties was about 15°F lower than for the heavy weather casualties. This trend would be expected. It is interesting to note that these 23 ships were built at 12 different yards.

The calculated nominal bending moment stresses for the three tankers that broke in two ranged from 4.5 to 5.5 tons per square inch, which is not abnormally high; and the air temperature (which was the plate temperature) was between 25°F and 40°F.

There were a number of minor failures that occurred in various types of ships, and several cracks occurred while the ships were being repaired. In one instance, a ship was at dock after a rough voyage in Alaskan waters. The temperature was zero degrees, and three cracks developed. The source of each crack was at a place where an alteration had been made to the original ship.

One of the Group I fractures is the previously mentioned longitudinal 66' crack in the bottom of a Victory ship. What may have been an important factor here is that oil was being heated in way of the fracture origin.

Thermal Stresses

The heating of a large portion of the internal structure, such as in fuel oil tanks, could drumhead the shell plating in way of the tanks. Since several shell failures occurred in way of tanks where oil was being heated, this drumhead effect may be important. These fractures occurred in both tankers and cargo ships and were all in the bottom shell where the shell was in contact with the water. When oil is being heated, thermal stresses are produced in the hull structure. However, the temperature of the steel is also raised generally and the structure is therefore better able to accommodate the resulting higher stresses by virtue of the increased notch toughness.

A small coaster suffered a fractured inner bottom and vertical keel immediately after launching. The air temperature was zero degrees. The water temperature was 32°F which was considerably warmer than the hull as the ship entered the water. It is likely that the expansion of the bottom shell which was warmed by the water caused the keel to stretch and in so doing contributed to the failure.

Thermal stresses in refrigerated ships have caused trouble where exposed decks in refrigerated areas (15°F) were all-welded. Thermal stresses in the 'tween decks may amount to 10,000 psi tension*. Most fractures occurred in welded 'tween decks of C2 Reefers which had riveted side shell seams. Some cracks extended from the hatch to the shell. The fractures were well distributed over the welded 'tween deck refrigerated areas while those of the C2 cargo ships of similar design were confined to the highly stressed upper deck area amidships. In addition to improving some hatch corner details, one or two riveted joints have been incorporated in the 'tween decks of refrigerated vessels. These changes have apparently been effective since no further failures have been reported.

## STEEL FROM FRACTURED SHIPS

The survey of steel from fractured ships is one of the

*See Appendix II for a review of thermal stress studies on refrigerated and other ships.

most important conducted in that it provides basic data for assessing the notch properties of mild steel plates. Definitions of plate classifications are as follows:

Source plate - plate where fracture started at a structural discontinuity. Although welding or the heat effect of welding was present at the origin, the cracks propagated immediately into the plating.

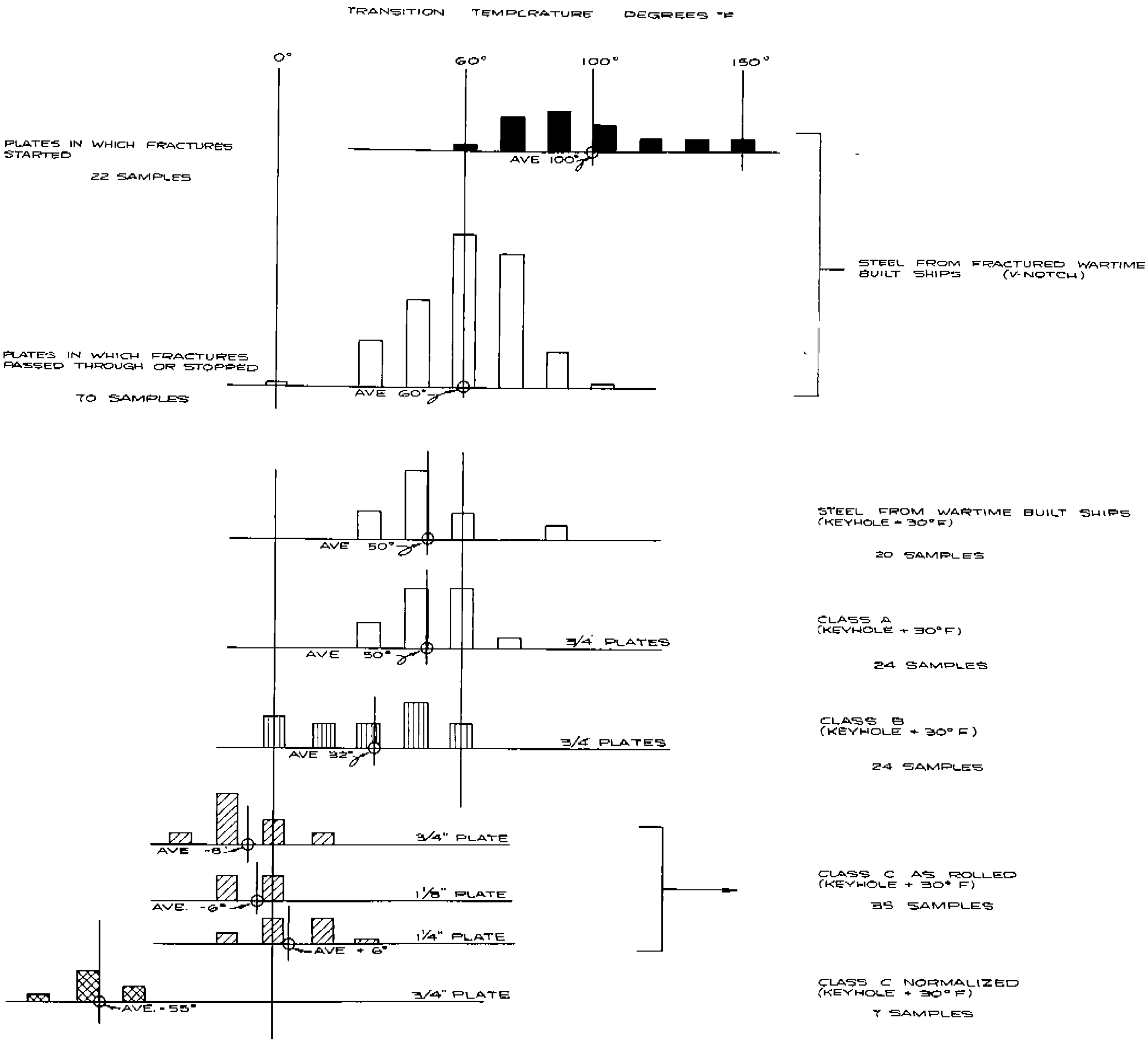
Thru plate - plate where fracture passed through. Also a plate into which a crack propagated after progressing along a weld for say a foot or more (practically all failures originating in butt welds for example).

End plate - plate in which crack stopped.

Transition Temperature

Figure 6 compares the transition temperature of the old and new ABS steels assuming that the steel taken from the fractured ships is representative of the old steel[8]. The Charpy V-notch values were obtained by the National Bureau of Standards[9]. The keyhole values were obtained by the American Bureau of Shipping and several steel companies[10,11,12].

Statistically, the source plates are specially selected plates in that they have significantly higher Charpy V-notch transition temperatures than the other plates. Another important finding is that the source plates have a considerably higher carbon content. There is essentially no difference in transition temperature between the thru and end plates; this means that whether or not the crack stopped cannot be




NOTES:

1. V-NOTCH BASED ON 15 FT-LBS
2. KEYHOLE BASED ON 20 FT-LBS.
3. V-NOTCH VALUE APPROXIMATELY EQUIVALENT TO KEYHOLE VALUE + 30°F

FIG. 6 - COMPARISON OF CHARPY TRANSITION TEMPERATURES OF WARTIME AND PRESENT ABS STEELS

explained solely by the notch toughness quality of the plates.

Some of the plating used during the war was rimmed steel. Although this steel is rather susceptible to strain aging, the transition temperatures of the few plates tested were of average value. Rimmed steel is now in effect excluded for hull plating over 1/2" thick.

Three Group I failures started at welds fastening half rounds to the main hull. At least one of these half rounds was Bessemer steel, and it is probable that the other two were also. Bessemer steel, which has been used for chafing bars and mouldings, is very susceptible to strain aging. The present ABS rules do not permit the use of Bessemer steel for half rounds.

The notch toughness of steel from fractured Victory ship masts (1 1/4" to 1 1/2" thick) was low. It is, of course, expected that the Charpy impact transition temperature for these thick plates would be say 20°F higher than for the average shell plate (3/4") due to the thickness effect (metallurgical effect only). The mast tubes were undoubtedly cold formed and this would tend to further decrease their notch toughness.

<u>Effect of Cold Forming Steel Plates</u>

Straining and aging raises transition temperature. The increase in the 20 ft-lb keyhole Charpy transition temperature for nine project steels and two new ABS steels is shown in Figure 7. Some steels are more susceptible to straining and strain aging than others. In general the rimmed steels are most susceptible and the fully killed steels are the least, especially at small strains.

The effect of cold forming bilge plates (outside fibre strain up to 1%) should be of little consequence, but the effect of cold forming masts tube plates (outside fibre strain 3 to 4%) might be significant.

In the case of two deformed plate specimens from fractured ships, the transition temperature of the bent area of the plate was about 20°F higher than that of the flat area of the same plate. However, on comparing the transition temperature of the curved portions of eight bilge plates and twenty-one other shell and deck plates[9], it was found that the distribution and average transition temperatures were essentially the same for both groups. Thus, the bilge plates did not seem to be adversely affected as a result of the required forming.

Reduction in Thickness at Fractured Surface[9]

The average thickness reduction for the origin plates ranged up to about 2%, while that for the thru and end plates ranged up to 4%. The greater thickness reduction for the end plates might have been due in part to a reduction in crack velocity. The per cent reduction was less for thick plates than for thin plates as would be expected.

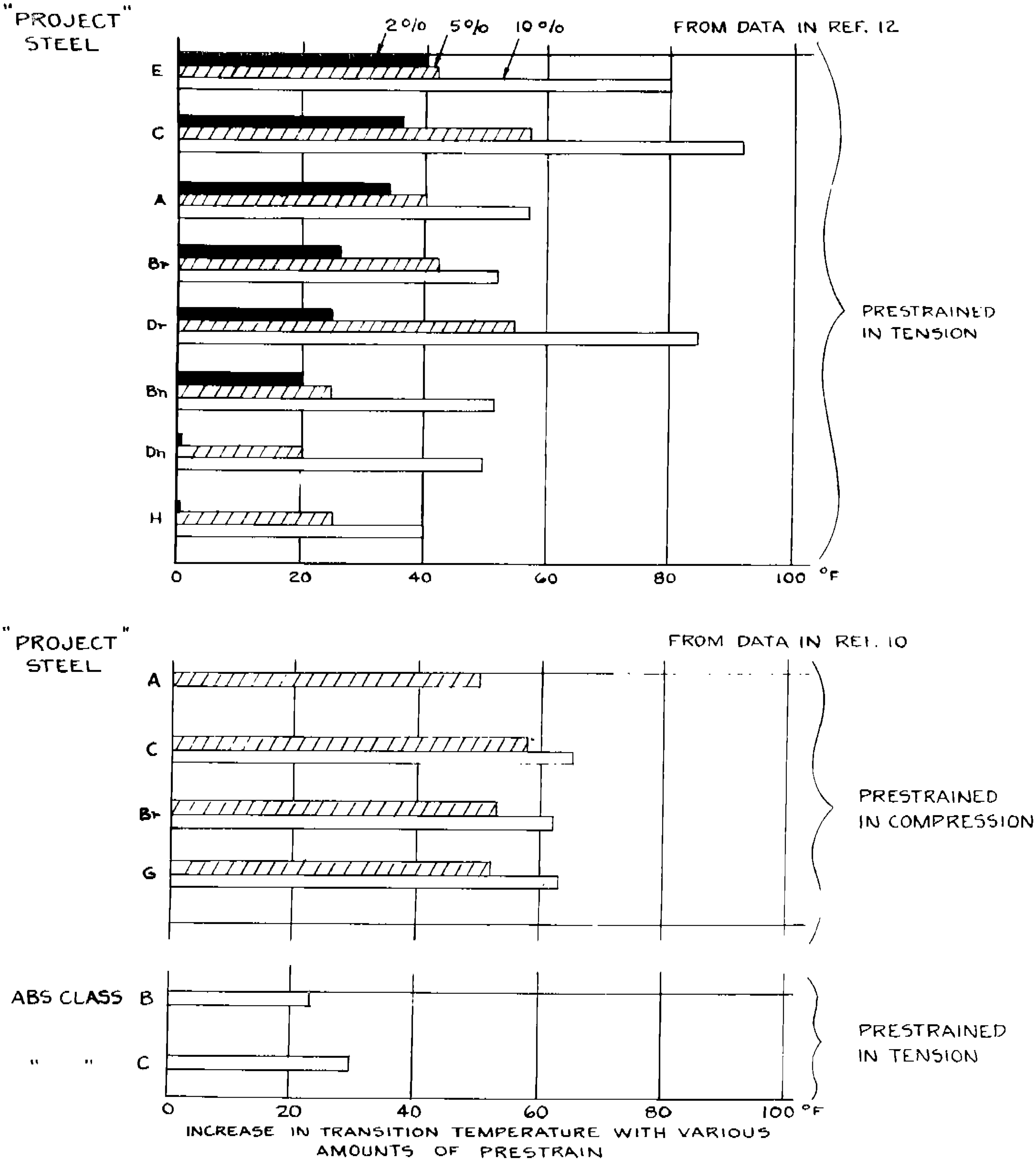



FIG. 7 - EFFECT OF PRESTRAINING

CHARPY 20 FT LBS. KEYHOLE

- 2% PRESTRAIN
- 5%
- 10%

Energy Values at Failure Temperature(9)

Energy values at the failure temperature and 15 ft. V-notch Charpy transition temperatures for a number of source, thru and end plates are given in Table IV. From the table, the average energy values at the fracture temperature are:

| Source | Thru | End |
|---|---|---|
| 7.1 ft-lb | 9.5 | 12.3 |

Although the numerical values are all low, there is a marked difference percentagewise.

The interesting feature of the data is that most of the source plates at failure temperature absorbed less than 10 ft-lb, while most of the end plates absorbed more than 10 ft-lb. Also, the corresponding 15 ft-lb transition temperatures for the source plates averaged about 100°F and were all above 60°F, while those for the end plates averaged about 60°F with the highest at 82°F.

Of the 17 source plates listed here, 10 were from origins of main fractures of Group I casualties. Of interest is that the highest energy value (11.4 ft-lb) at fracture temperature was for a Liberty tanker sheer strake of "dirty" rimmed steel; the crack started at an arc crater near a structural notch--the steel was very hard near the weld. The three lowest energy values (3.2 ft-lb to 4.2 ft-lb) were for steels which had transition temperatures above 140°F. Another interesting observation from Table IV is that the energy values at failure temperature for both the source and end plates of the Group I tanker failures

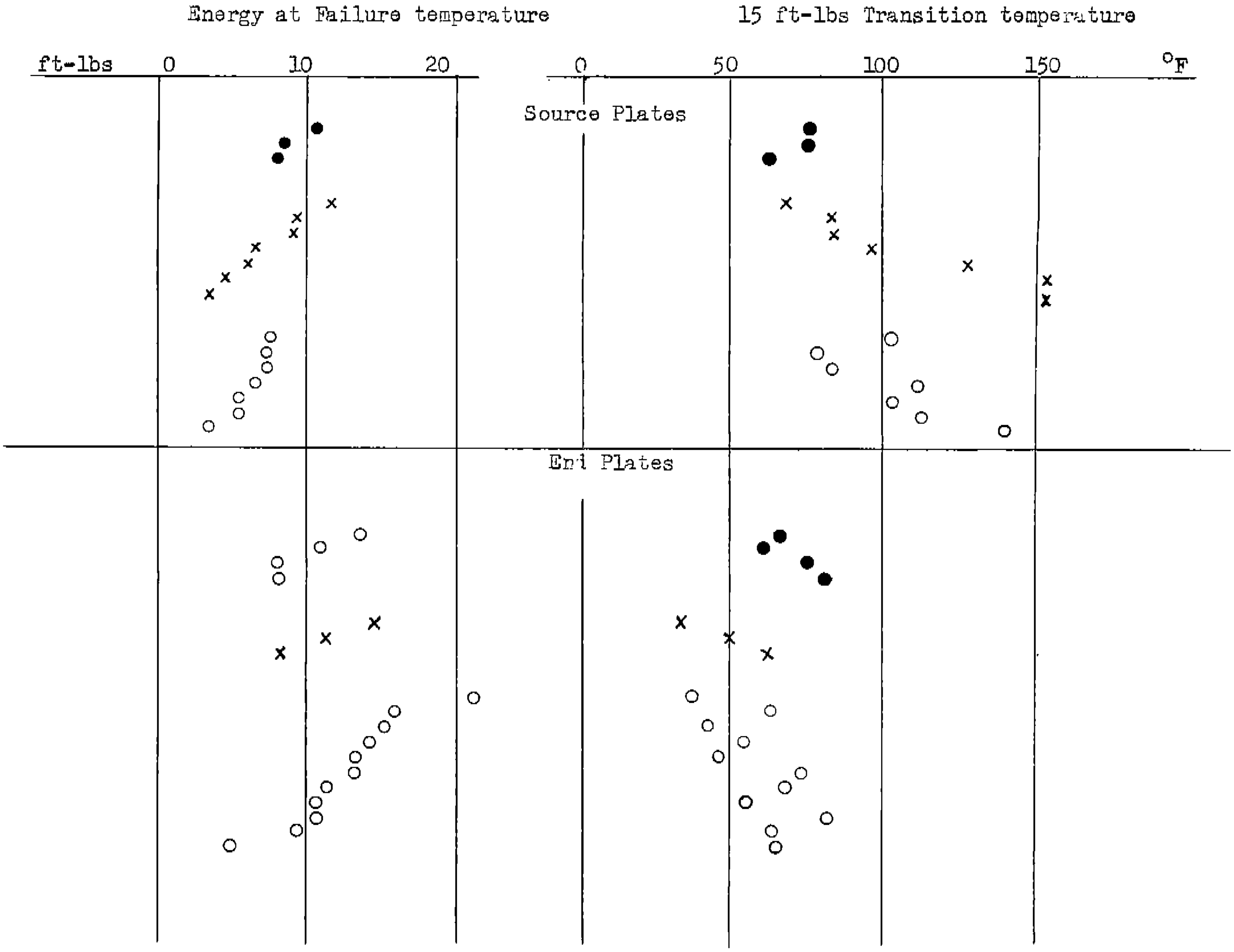
TABLE IV

Comparison of Source, Thru and End Plates, Charpy V Notch

| | Source | Thru | End* |
|---|---|---|---|
| Average energy at fracture temperature, ft-lbs | 7.1 (3.2 to 11.4) | 9.5 (3.8 to 18.7) | 12.3 (5.0 to 21.4) |
| Average 15 ft-lbs transition temperature, °F | 101° (62 to 153) | 65° (38 to 102) | 59° (36 to 82) |

Values for Source and End Plates are plotted below:

Key: ● Tankers - Group I Failures
x Cargo - Group I Failures
o All others (Some Secondary Cracks)




* Three thin end plates which had exceptionally high energy valves and which involved only secondary fractures are not included.

were essentially the same; none of the plates was particularly poor.

The above has shown that there are several ways in which Charpy V-notch impact test results appear to correlate with ship fracture experience.

<u>Cyclic Loading</u>

From a review of the ship casualty record and statistical strain gage studies on actual ships at sea, it is concluded that cyclic seaway stresses by themselves are not particularly important contributors to the ship fracture problem. Such stresses may, however, help initiate cracks, particularly when the still water bending moment stresses are consistently high as would be caused by continued poor distribution of cargo or ballast.

However, the foregoing does not necessarily mean that all cyclic or alternating loadings in ships, even at relatively small number of cycles, are unimportant. For example, the working or deflecting of plate or corrugated panels in way of "hard spots" undoubtedly have contributed to some of the nuisance cracks in the internal structure of tankers. As strains increase beyond the elastic limit, the fatigue life is markedly shortened.

SUMMARY OF FINDINGS

1. On comparing merchant ships built prior to and during World War II, it was found that, for essentially the same materials, designs and quality of workmanship, both the frequency and severity of brittle cleavage fractures increased as the amount of welding increased. This comparison excludes Victory ships and postwar vessels.

2. For the Victory ships, the incidence of fracture has been very low. These ships have, however, sustained four Group I failures (one ship twice). Two of these failures started at faulty welds made in repair yards.

3. Several fractures in various types of ships started at places (a) where repair welds or alterations were made to the original structure, (b) where light welds were made on heavy plates, or (c) where plates had been cold formed. The same is true of non-ship failures[(13)].

4. The postwar designed tankers have been in service for only a year or two, but no casualties have been reported.

5. Very few failures have occurred in the smaller ships with thin plating.

6. Failures occurred more frequently in cargo ships when they were in ballast and in tankers when they were loaded. However, for both cargo ships and tankers, almost all of the ships that broke in two were light or in ballast.

7. About 10% of the approximately 250 Group I casualties occurred in calm water. Another 10% occurred in moderate seas, where the seaway stresses are assumed to have been low.

8. The frequency of failure showed no trend either to increase or to decrease with length of service. However, it is of interest that Group I and II failures in the Victory ships began to develop after this class of ship had given nearly four years of trouble-free service.

9. Nevertheless, the occurrence of failure seems to depend primarily on the severity of weather and sea conditions rather than on length of service.

10. Cracks have occurred in the cold 'tween decks of a few refrigerated ships. Improvement of some structural details and the installation of one or two riveted joints apparently have been effective in preventing further failures.

11. At least seven Group I failures occurred in the bottom shell in way of tanks where oil was being heated.

12. Crack arrestor straps have been effective in limiting the extent of many cracks. In only about 10% of the cases did another crack start on the opposite side of the strap.

13. A weld of some kind was associated with every fracture origin. In no case did a fracture start in a sound weld. Welded seams have given practically no trouble. Known origins of Group I failures are listed in Tables II and III.

14. Cracks which started in defective welded joints (welded

butts for example) always propagated into the plating and followed the welded joint only as long as the weld quality was exceptionally poor. Similar observations were made in several cases of damage by explosion.

15. For ships built of prewar and wartime steels, the chance of failure increased rapidly as the temperature decreased below about 60°F. The chance of failure increased about four times when the temperature was lowered from 50°F to 30°F. Very few failures occurred above 60°F.

16. There is fairly good correlation between Charpy notch bar impact test values and ship fracture experience.

Most of the source plates absorbed less than 10 ft-lb at the failure temperature in the Charpy V-notch test while most of the end plates absorbed more than 10 ft-lb.

The average 15 ft-lb transition temperature for the source plates was significantly higher than that of the average wartime steel plates, as indicated in Fig. 6.

17. There was essentially no difference in the average transition temperature between the thru plates and end plates.

18. As far as notch toughness is concerned, the new ABS Class B steel (1/2" to 1") is somewhat better than the wartime steels. The new ABS fully killed Class C steel is markedly better. Class C quality steel normalized is a further improvement.

19. Residual welding stresses do not seem to be particularly important but are probably a factor in crack initiation especially

in areas under high restraint.

## DISCUSSION AND CONCLUSIONS

### General

During the past five years, since 1947, the number of Group I casualties has been markedly reduced from the number for the five previous years. This improvement was mainly due to the cleaning up of several design details, particularly on Liberty ships. The fabrication items, mainly concerning the older ships, still remain to cause trouble, and probably will for some time. New ships have an excellent record to date but have not been in service long enough to permit drawing any firm conclusions.

The great majority of recent failures have occurred at places where no glaring structural discontinuity existed. In the case of cargo ships, most of the Group I failures since 1947 originated in butt welds and in the vicinity of deckhouse corners. Defective butt welds have been the main source of serious trouble in tankers from the very beginning.

The welding quality in new ships which have had radiographic inspection of main hull welds is considered superior to that in wartime and prewar built ships. This type of inspection is necessarily a ramdom one and therefore will not guarantee that there will be no defective welding, and further, there are many places that cannot be radiographed. There is some question concerning the necessity of obtaining near-perfect welds since the casualty record shows that where fractures have started in defective butt welds the welding quality was especially poor. In order to shed more light on this, the Ship Structure Committee has recently initiated a study to determine the detrimental effects on structural performance of various types of flaws.

However, there have been places where cracks have started where light welds or arc strikes had been made on thick plates. In order to assist in reducing possible trouble from light welds, there are now restrictions on minimum size fillet welds on heavy plate. There are other places of fracture origin where cold forming of plates had been done, and fractures starting from knuckles of flanged plates are not uncommon. Cold forming with its attendant reduction in notch toughness and possible subsequent aging is more serious in the thicker plates for the same grade of steel. However, the fully killed steels now used for plating over 1" thick are generally less susceptible to strain aging than the wartime steels.

The present trend is toward larger and faster ships and the plate thickness, especially for tankers, is increasing. For example, there are now under construction several tankers of about 45,000 tons (dwt.) and 700 feet long. These are 200 feet longer than the T2s, and the plate thickness is approaching 1 1/2" compared to 1" in the T2s. The thickness or size effect (both geometrical and metallurgical) as it affects the ability of the plate to resist brittle failure is of particular concern to the shipbuilder.

Although new ships have the benefit of improved design, welding quality and material, the increase in plate thickness could offset some of the improvements already made. Because of uncertainties regarding resistance to brittle cracking of very thick plate, improved material beyond the existing rule requirements is considered necessary and the American Bureau of Shipping now requires special consideration for main hull plates over 1 3/8" thick. The U. S. Navy, incidentally, requires a somewhat more notch tough steel than is required for merchant work in the thickness range above 7/8".

One of the prime difficulties in determining the reasons for failure has been that fabrication factors (welding, cold forming, flame cutting, fitting, etc.) are involved to such a high degree that it is virtually impossible to separate design and fabrication considerations. When this thought is carried one step further to include considerations of material quality, then the result is a new way of thinking (a new concept) as regards strength of structures in tension. This new concept, which features design for energy absorption as well as for strength, involves the four fundamental variables (state of stress, temperature, strain rate and material quality). It is perhaps the most important contribution of the welded ship research.

Notch Toughness

A question often asked is "What degree of notch toughness is necessary to eliminate brittle fractures under service condition?" A review of the results of the Charpy V-notch impact tests of steel from fractured ships and the plate temperatures at time of failure may help to answer this question. From Fig. 6 it is seen that the transition temperatures of the source plates were higher than the average transition temperature of World War II shipbuilding steels. Lowering the average transition temperature say 50°F while retaining the same distribution about the average could eliminate most of the steels with high transition temperatures comparable to those of the source plates. From Fig. 3b, it is reasonable to assume that the rapid increase in probability of failure reflects directly the decrease in notch toughness of steel at the lower temperatures. Therefore, lowering the average transition temperature should substantially reduce the likelihood of serious fractures particularly at the higher failure temperatures of about 50° to 60°F. It is seen from curves A and B of Fig. 3b that by reducing the average transition temperature the probability of failure would be further reduced because the frequency with which ships encounter successively lower temperatures below about 50°F is markedly reduced. It is, therefore, concluded that a moderate increase in notch toughness over that of the wartime steels would substantially reduce the probability of failure.

Influence of Welding on Notch Toughness

The influence of welding on notch toughness is not clear. The notch toughness of the weld metal itself, as judged by impact tests, is generally better than that of the base metal. Some tests indicate that welding causes a loss in ductility of the base plate material next to the weld(14). Other tests have shown that the notch toughness of welded specimens is much less than that of comparable unwelded specimens(15).

However, it is important to note that in actual ship failures, cracks which started in defective welded joints (welded butts for example) propagated into the plating following the welded joint only as long as the weld quality was poor. It might be mentioned that the plates into which the fracture entered after having originated in a defective weld are in the thru plate category. Cracks did not even follow the plating next to the weld except in a few cases, and then only for a short distance. Similar observations were made in several cases where damage resulted from explosion. This suggests that the influence of welding may be different for crack initiation than for crack propagation. It also suggests that the mechanism of fracture in a welded joint may have directional properties.

Crack Propagation

The casualty record shows that once a brittle crack has stopped it may not start again. If the crack stops, the strain rate is reduced to zero and the transition temperature of the same plate is in effect lowered. This lowering of the transition temperature can be substantial and will serve to resist further propagation of the crack. Immediately after a high velocity crack stops, however, some plastic readjustment undoubtedly takes place at the end of the crack. High seaway stresses in combination with this plastic straining (work hardening causing an increase in the transition temperature) could, under the right conditions, cause the crack to continue. Of course, if a large portion of the hull girder is severed and if the ship cannot be ballasted or maneuvered so as to reduce stresses in the cracked portion of the hull, the fracture would continue in any case, and even an occasional riveted joint might not be able to prevent the continuation of a break.

High speed crack propagation involves the release of elastic energy. The energy released by a crack must be absorbed by the plating and surrounding structure or the crack will continue to propagate. It has been shown experimentally that, in the vicinity of the transition temperature range, a moderate reduction in stress level can lower the minimum temperature at which a high velocity brittle crack is arrested[16]. This can be appreciated when it is realized that the amount of stored elastic energy (that would be released by a crack) is a function of stress level to the second power.

So far practically all work on notch toughness has been conducted with a view to assessing a steel's ability to resist crack initiation, such as that indicated by the Charpy impact tests. It would seem highly desirable to determine the degree of correlation between a steel's ability to resist crack initiation and its ability to arrest a high speed crack, especially in thicker plates.

One important experimental finding worthy of mention is that as the length of a crack increases, the energy released per unit area also increases(17). This means that a crack should be stopped as soon as possible. If a special steel is to be used for crack barriers, it should be located at places where cracks are most likely to start. The beneficial effect would be two-fold, for the special steel would reduce the chance of a crack starting as well as acting as a crack barrier.

## Conclusions

1. Brittle cleavage failures in ships were the result of a combination of circumstances, rather than just one or two factors. From a practical viewpoint, however, the two main causes of failure were (a) design and fabrication notches and (b) a steel which tended to be notch sensitive at the lower operating temperatures.

2. A moderate increase in notch toughness of steel plate over that of wartime steel plates would very substantially reduce the probability of failure. The classification

societies and the U. S. Navy have taken firm steps in this direction.

3. The present situation is that main hull failures due to fabrication faults far outweigh those due specifically to design faults. Failures from both types of faults have occurred in prewar and wartime built ships constructed with prewar quality steel. It remains to be seen if the improved postwar steels and present fabricating practices are sufficient to eliminate serious failures.

4. A reasonably rigid control and supervision of fabrication must be embraced by repair yards as well as building yards.

5. It is now time that broader and more fundamental aspects of design and construction be entertained. The characteristics of brittle failures in ships have been clearly established, and it appears that those of the non-ship failures are similar, i.e., the prevention of brittle failures is common to many land as well as ship structures. (However, the characteristics and history of some of the so-called nuisance cracks, in tankers for instance, are not so well known.) We should have profited from our ship experience and ship research so that issues such as hatch corners and square cut-outs may now be closed. The improvement in details of other structural members such as bilge keels, connection of tanker longitudinals at bulkheads, bulwarks, etc. have been generally not

been wholly successful, and further study of these items appears desirable.

6. One of the immediate problems deals with the ability of various steels and weldments to resist rapid crack propagation, especially in thick plates. The notch toughness of the hull plate must be relied upon as the main line of defense against brittle fractures.

7. Stresses resulting from heating fuel oil or cargo oil have heretofore not been considered particularly significant to failure. However, since several serious fractures have occurred in way of hot oil, these thermal stresses may be more important than at first thought.

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# APPENDIX I

# APPENDIX I

## RESIDUAL WELDING STRESSES

The committee investigating the failure of the T2 tanker SCHENECTADY in 1943 expressed the opinion that residual or locked-in welding stresses might have been a major factor in causing failure. Soon after, investigations were conducted on Bethlehem-Fairfield (B-F) Liberties which have riveted shell seams and on welded Liberties, as well as on Victories, to determine the magnitude and pattern of welding stresses in the deck area[18,19,20]. One purpose of these tests was to see if there existed a difference in stress pattern between the B-F Liberties and the welded Liberties that might help account for the better performance of the former.

The method of measuring the locked-in stress was to trepan small plugs of about 2 1/2" diameter from the plate or weld and measure the amount of relaxation with the aid of electric strain gages, assuming the plugs thus trepanned were stress free.

Residual stress patterns in flat plates as received from the steel mills were also obtained by trepanning plugs from a few as-rolled plates. Tensile stresses up to 2500 psi were found at the center of the plate and compressive stresses up to 6000 psi near the edges[18]. This is important for these rolling stresses were probably present to some degree in the locked-in stresses found in the hull plating in the ship tests.

The results of the ship investigations indicated that the basic welding stress patterns were practically the same regardless of ship type or where the ships were built. Thus the welding stress pattern in the B-F Liberties seemed to be no different from that in the welded Liberties. Welding stresses of yield point value were found in butts and seams parallel to the weld. Stresses across the weld were low. Stresses in the deck plating away from the immediate vicinity of the weld were low and mostly compressive and generally ranged between zero and 10,000 psi compression. It was also found that the magnitude of locked-in stresses was not significantly reduced by the working of the ship at sea.

Although the above basic patterns are typical for the deck area of this type of ship, they are not necessarily characteristic for other locations or for other types of vessels. For instance, locked-in compressive stresses up to 25,000 psi were found in keel plates of some large naval vessels(18). Reaction welded stresses such as these, when located in the right places, might be helpful.

A series of tests was conducted on B-F Liberty and Victory ships to investigate stresses due to erection welding(18). In brief, strain gages were installed on upper deck assemblies to record changes in strain when the assemblies were welded into the ship. The magnitude of erection welding stresses in both Liberties and Victories was small. Large strain differences were recorded in some cases, but it is suspected that factors other than welding stresses were responsible. Furthermore, trepanned values at the same locations failed to reveal any high stresses.

These tests also revealed that moderate reaction welding stresses may be built up where the structure is somewhat restrained. On welding main deck butts where two or three assemblies were tied together both forward and aft, average fore and aft tensile stresses of 3000 to 4000 psi were recorded. The stresses were fairly evenly distributed across the deck and extended fore and aft throughout the plating. Tensile stresses of 8000 psi over sizeable deck areas were recorded in a few cases, but as usual, these high tension stresses were not revealed when plugs were subsequently trepanned from the same areas.

Some of the difference between cumulative and trepanned values may be accounted for by the welding of the sub-assembly seams prior to installation of the assembly into the ship. Compressive stresses of 3000 or 4000 psi were set up between the seams on making the sub-assembly welds.

Similar tests were conducted on Victory ships[20]. In general, the recorded cumulative sub-assembly and erection stresses in the main deck plating were low. Places where high cumulative stresses were indicated actually had low trepanned stress values, thus agreeing with all other trepanned values at similar locations.

The low temperature "stress-relief" process has been applied to many tankers at the request of individual owners to reduce the high welding stresses in the butts and seams of the deck and bottom shell. Although this process reduces the high stresses in the welds, its true effectiveness is not known. Places where it might be desirable to remove welding stresses, such as at hatch corners or other complicated details having three-dimensional restraint, cannot be treated by this process.

APPENDIX II

# APPENDIX II

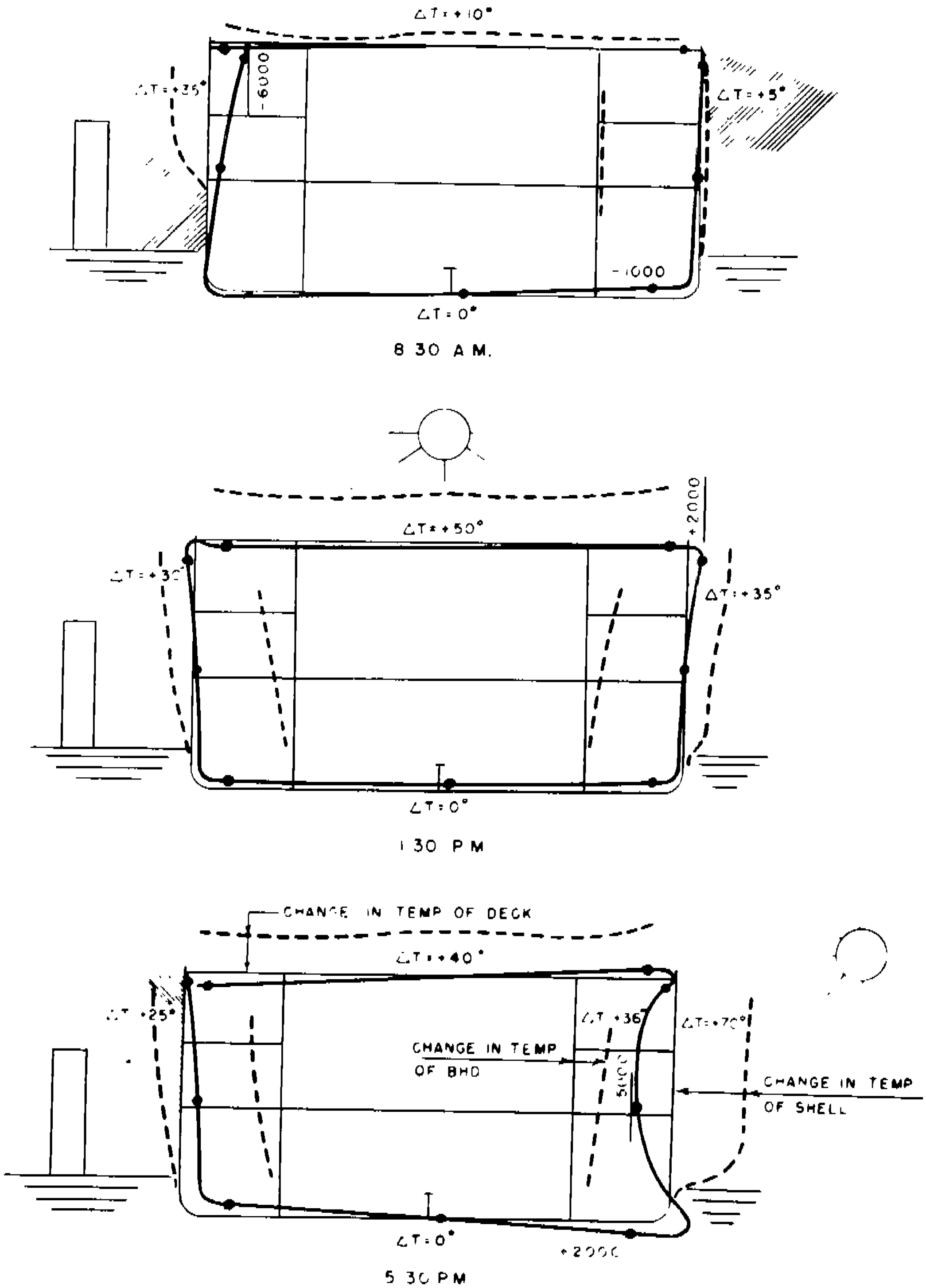
# THERMAL STRESSES

## Diurnal Thermal Stresses

In a test conducted on an LST, the highest tensile stress recorded under ideal weather conditions conducive to high stresses was 2000 psi, based on a reference "zero" temperature condition at night[18]. A maximum compressive stress of 6000 psi occurred in the side shell which was exposed directly to the sun while the deck and opposite side shell were partially or wholly in shadow; Figure 8.

Results of similar investigations on four cargo ships revealed higher stress values for smaller temperature differentials than found in the LST test[21]. Some stress values reported were greater than could be accounted for by thermal expansion and contraction even if the surrounding structure were completely restrained. Nevertheless, the general thermal stress distribution was as would be expected, with moderate tension in the 'tween decks and shaded shell areas and moderate compression in the deck or shell portions exposed to the sun.

The two variables determining thermal stresses are the flexibility of the hull structure and the temperature distribution. Differences in temperature between top and bottom of the ship mean very little; if the temperature distribution is linear, no stress will result. To illustrate this, a comparison




**NOTES:**

1. **All stress changes (psi) in fore and aft direction.**
2. **Tension (+) plotted outbd.**
   **Compression (-) plotted inbd.**
3. **ΔT - Temperature change from "zero" condition taken at night.**

FIG. 8 - **Measured Diurnal Thermal Stresses in LST**

was made of the thermal stresses for one phase of the LST test with those stresses which would have occurred if the ship had been completely restrained. The temperature difference between top and bottom was 50°F, which corresponds to 10,000 psi in a completely restrained structure. In the actual test the maximum stress was only in the order of 2000 psi. The agreement between measured and calculated values was reasonably good. The peak diurnal thermal stresses are usually compressive and should cause no serious trouble; the tensile stresses are of smaller magnitude.

It was thought that the welding stress pattern might be appreciably different if ship welding were done at night rather than under bright sunlight. Butt joints cut at night frequently close 1/8" to 3/16" when the plating is exposed to the sun. Tests on Victory ships indicated that it made little difference to stress whether large deck assemblies were welded in the cool of the night or under bright sunlight even though the assemblies were partially restrained and a non-uniformly varying temperature gradient existed vertically through the ship[18]. Some stress variations were found, but they could not be correlated with temperature.

A test along these lines was conducted on the Liberty ship GASPAR DE PORTOLA[22]. A large section of the upper deck 55' by 14' opposite #3 hatch was twice cut out and re-welded. The welding sequence used was to provide maximum restraint. The first time the section was welded, the section and ship were at the same temperature. The second time, the section when welded was 75°F warmer than the ship. The average fore and aft tensile stresses reported were about 5000 psi and 10,000 psi, respectively. Athwartship stresses were comparatively small. The average increase in stress of 5000 psi due to the 75°F temperature differential indicates that the effective restraint offered by the hull in this area was only about 30%, since 75°F change corresponds to about 15,000 psi under complete restraint.

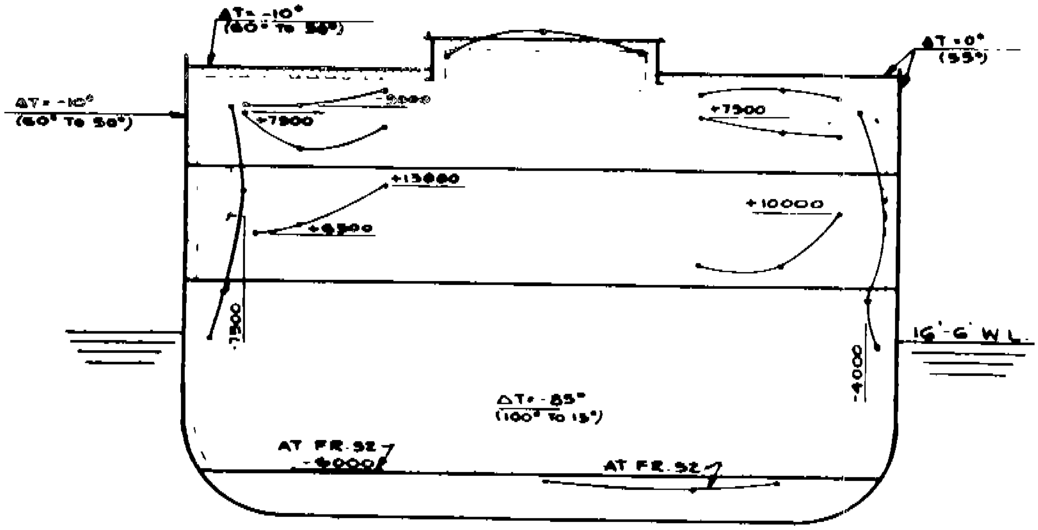
In the NEVERITA experiment, the centerline underdeck girder was stressed in tension to about 2000 psi when the upper deck was warmed[23]. Thus the expansion of the outer skin, by vitue of a small temperature difference between the skin and girder, stretched the girder.

<u>Thermal Stresses in Refrigerated Ships</u>

These are significant and may cause trouble when exposed decks in refrigerated areas (15°F) are all-welded. "Cooling down" to say 15° creates moderately high tensile stresses in the cold 'tween decks, causing the outside hull to be compressed. Calculations show that fore and aft thermal stresses up to 10,000 psi may be developed in the 'tween decks of refrigerated ships if these decks are exposed to about 15°F temperature and the outside hull is warm. This was confirmed by an investigation conducted on a C2 refrigerated vessel[21].

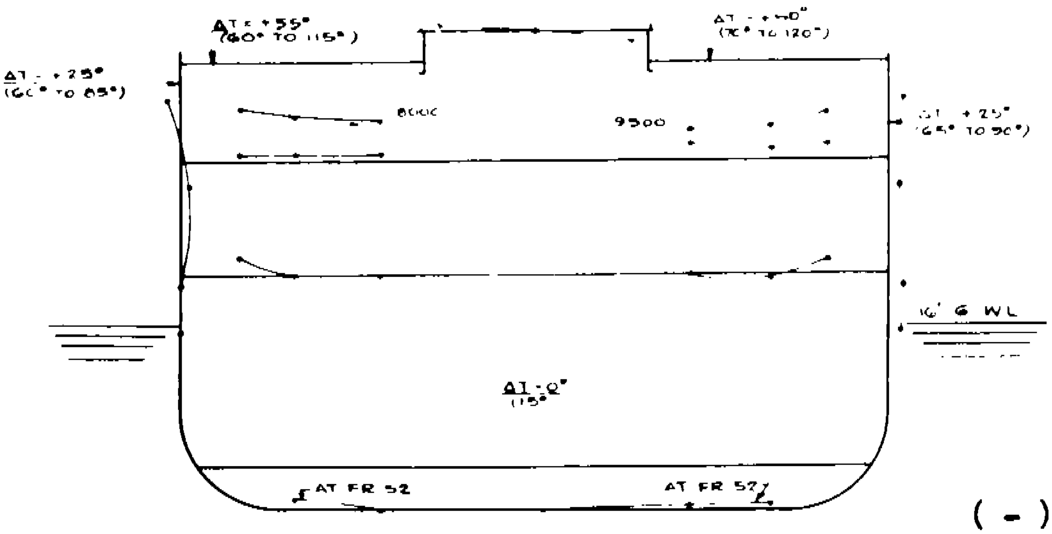
Cooling the hold 85°F in the actual test created tensile stresses in the 'tween decks of from 5000 to 10,000 psi. The outside shell and weather deck were put into compression, by about 3000 psi. See Figure 9.

The low temperature creates biaxial tensile stresses and at the same time lowers the notch sensitivity of the steel. Figure 10 shows diurnal thermal stresses on the same ship when the upper deck was exposed to the sun.




CHANGE BET. JULY 9, 1945, 4 A.M & JULY 12, 4 A.M

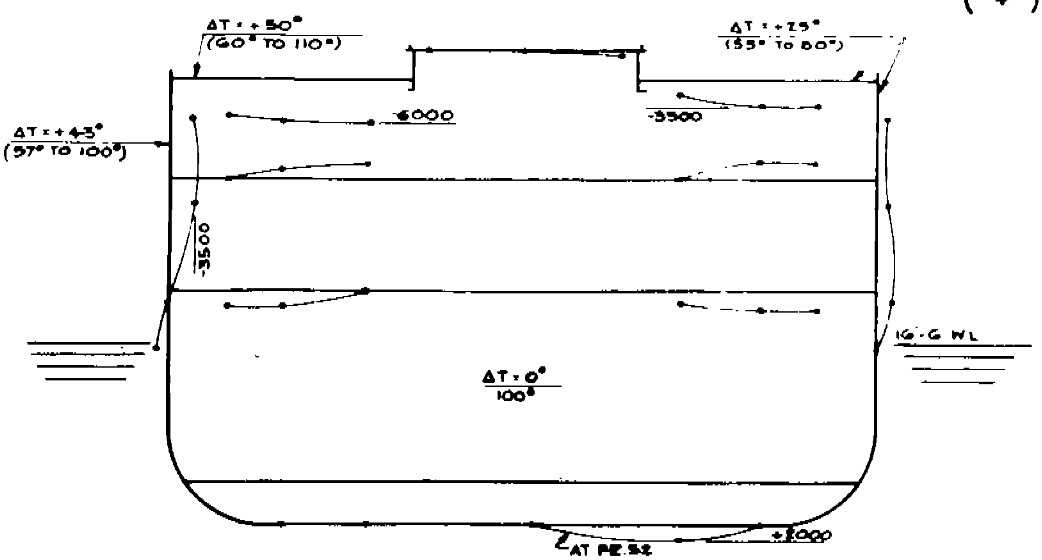
FIG. 9 - **Measured Thermal Stresses in C2 Reefer Due to Cooling Down 85°F.**




CHANGE BET. JULY 12, 1945 8 A.M & 5 P.M, WITH HULL COLD

( - ) Compression

( + ) Tension




CHANGE BET. JULY 5, 1945, 4 A.M & JULY 8, 4 P.M., WITH HOLD WARM

FIG. 10 - **Measured Diurnal Thermal Stresses in C2 Reefer**