R. W. Rumke

SSC-95

THERMAL STRESSES IN SHIPS

by

R. A. Hechtman

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:

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

October 30, 1956

Dear Sir:

In order to determine better the effect of thermal stresses on ships in service, the Ship Structure Committee has sponsored a review of theoretical and experimental work on the subject. This has been part of the research program of the Ship Structure Committee related to the improvement of hull structures of ships. Herewith is the Final Report, SSC-95, of this project, entitled "Thermal Stresses in Ships," by R. A. Hechtman.

The project has been conducted with the advisory guidance of the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council.

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

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

Yours sincerely,

K K Cowart

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

Serial No. SSC-95

Final Report
of
Project SR-129

to the

SHIP STRUCTURE COMMITTEE

on

THERMAL STRESSES IN SHIPS

by

R. A. Hechtman
The George Washington University
Washington, D. C.

transmitted through

Committee on Ship Structural Design
Division of Engineering and Industrial Research
National Academy of Sciences-National Research Council

under

Department of the Navy
Bureau of Ships Contract NObs-72046
BuShips Index No. NS-731-036

Washington, D. C.
National Academy of Sciences-National Research Council
October 30, 1956

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THERMAL STRESSES IN SHIPS

I. SYNOPSIS

This report reviews the information in the literature on thermal strains and stresses in ships as well as theoretical methods of analysis which may be applied thereto. Localized heating by the sun has been observed in a number of ships. Almost no observations of temperature effects have been made on ships under the weather conditions and sea temperatures which prevailed at the time of the serious ship failures. Evidence was found in connection with brittle fractures of Group I severity that thermal stresses may have been a significant factor in the failure of at least thirty tankers and an equal number of dry cargo ships. In some of these cases thermal stresses were the prime factor. In the remainder, heavy weather or other elements were also effective.

Theoretical methods were found which would predict with fair accuracy the nominal thermal stresses and deflections in the hull girder of a ship if the distribution of temperature were known. No theoretical solutions applicable to the ship structure were found which would yield actual rather than nominal stresses.

The small amount of information on the subject of thermal stresses applicable to ships indicates the desirability of more research in this field.

II. INTRODUCTION

1. Earliest Interest in Thermal Stresses. The designers of large bridges were apparently the first to study the effects of temperature change. Molitor[44] reported that he found temperatures of 130 F in the parts of a steel arch bridge exposed to the sun and 104 F in the shaded portions when the air temperature in the shade was 90 F. These temperatures were very close to those reported more recently in ships. Molitor also indicated that stresses could arise from this differential. The first published paper mentioning thermal stresses in ships[45] which the writer found was dated 1913. No very extensive research with respect to ships was accomplished until about ten years ago.

2. Nature of Thermal Stresses. A thermal stress may be considered to be a stress which is developed as the result of a nonuniform temperature distribution within a body. In the respect that thermal stresses arise from temperature differences, they are different from residual stresses which may exist when a structure is at a uniform temperature. If elastic conditions prevail in a structure, thermal stresses disappear upon the return to the initial temperature, while residual stresses remain locked in the structure. It will be pointed out subsequently that potential energy may be stored in a structure as a result of thermal stresses, and therefore some of the same effects may occur as when residual stresses are present.

3. <u>Object and Scope of this Investigation</u>. The initial objective of this investigation was to search the literature for all information on thermal stresses in ships and similar plate structures and for theoretical methods of analysis applicable to ships. This literature survey would indicate the present state of knowledge on the subject and also point out the future course of the investigation in developing further information.

The naval architect is interested principally in five aspects of temperature effects in ships:

1. Temperature gradients in the hull--their shape and magnitude.
2. Deflections of the hull girder caused by thermal expansion.
3. Thermal stresses in the hull structure.
4. Buckling of the hull plating resulting from thermal expansion.
5. Contrubution of thermal stresses to brittle fracture.

Information has been sought on these subjects in particular.

The plating in ships is sufficiently thin so that usually no significant temperature difference can exist across the plate thickness. Therefore, in this report only those theoretical solutions for thermal stresses in plates have been included which assume uniform temperature across the thickness.

4. <u>Definition of Terminology</u>. The phrase "temperature distribution" is used hereafter to describe the temperatures at a given time at selected points in a structure. The term "thermal stress" refers to the changes in stress which are computed from an actual or an assumed temperature distribution. The algebraic signs given the thermal stresses indicate the direction of the change and do not describe the nature of the stress, tension or compression, unless the initial temperature condition was accompanied by zero stress. Insolation is the rate of solar radiation striking an exposed surface. The symbols T_A and T_W will be used frequently and refer to the air and water temperatures, respectively.

III. THERMAL STRAINS AND THERMAL STRESSES

Before the magnitudes of the thermal stresses observed in ships are discussed, it might be well to consider how thermal strains are related to thermal stresses. Fig. 1 shows an unstressed bar fitted between two rigid supports. As the temperature of the bar increases, no longitudinal strain occurs because the bar is restrained. The thermal stress developed corresponds to the strain which would have taken place if the bar had been free to expand.

Now suppose as a second example that this same bar for the given temperature rise would elongate an amount Δ if free to expand and that the distance between the rigid supports is

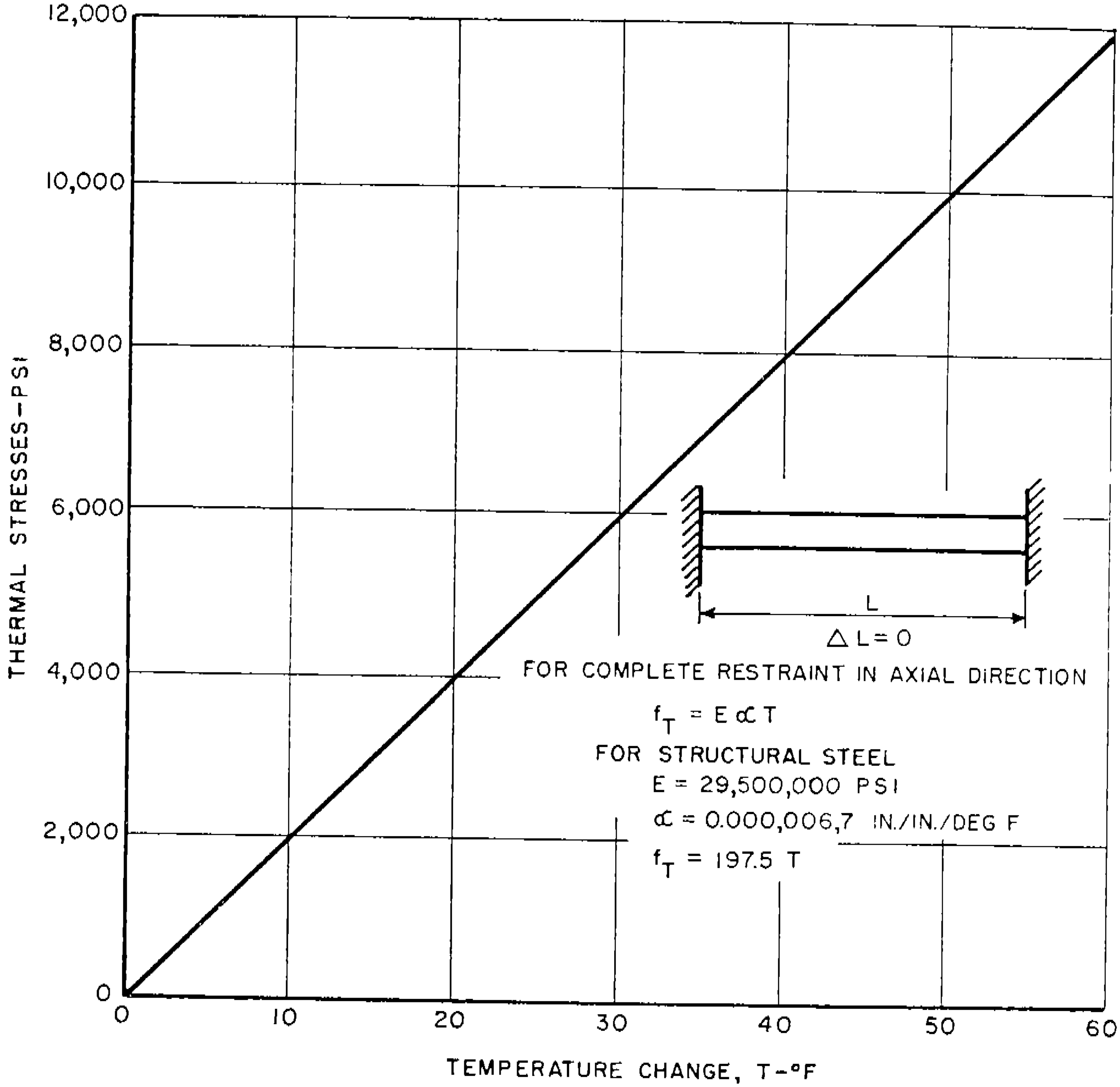


Fig. 1. Thermal Stress Developed in Structural Steel Bar with Complete Restraint in Axial Direction.

longer than the bar by the amount 0.4Δ. As the bar expanded under increasing temperature to close this gap, a thermal elongation of 0.4Δ would be observed; but no thermal stress would be developed in the bar. However, as the bar continued to expand beyond this point to its final temperature, no additional thermal strain would be observed; but a thermal stress proportional to the elongation, $(\Delta - 0.4\Delta)$ or 0.6Δ, which the bar was restrained from developing, would occur. A somewhat similar situation would exist if instead of a gap the bar was attached to adjacent deformable members. The thermal stress in the bar would be proportional to the portion of the free temperature expansion which was prevented by the attached members from occurring.

A distinction should be made between the strains arising from a change in temperature and the strains resulting from external loads. In the latter case, the stresses are proportional to the strains. By contrast, thermal stresses arise when the thermal strains are inhibited. It is important to recognize that the thermal strains observed in ships represent the free expansion part of this process and cause no stress but rather are manifested in elongation and bending of the hull. When considered together with the temperature distribution, the measured thermal strains can be used to determine the amount of thermal strain which has been prevented from occurring by the rigidity of the surrounding structure. This amount determines the actual thermal stress.

As a final example, suppose that the bar in Fig. 1 was a flat rectangular plate restrained on all four edges by rigid supports so that expansion in its plane would be impossible. A uniform temperature rise would tend to cause expansion in the longitudinal and transverse directions and therefore biaxial compressive thermal stresses. Moreover, because of the Poisson effect, each longitudinal component of stress would produce an additional compressive stress in the transverse direction, and vice versa. Thus, either of the components of biaxial stress in this last case would be greater than the longitudinal stress developed by the same temperature increase in the bar in Fig. 1. Since a panel of plating in a ship ordinarily has restraints on all four edges, a condition approaching the one just described occurs.

For complete restraint in the axial direction only, the thermal stress σ for uniform temperature change T in a bar where no bending occurs is

$$\sigma = - E\alpha T. \tag{a}$$

The symbols in this equation are defined in the List of Symbols in Section X. For partial restraint in the axial direction, Eq. (a) becomes

$$\sigma = E\varepsilon - E\alpha T, \tag{b}$$

where ε is the observed thermal strain.

For a rectangular flat plate partially restrained on the four edges and subjected to uniform temperature change, the biaxial thermal stresses are

$$\sigma_x = \frac{E}{1-\nu^2}(\varepsilon_x + \nu\varepsilon_y) - \frac{E\alpha T}{1-\nu}$$

$$\sigma_y = \frac{E}{1-\nu^2}(\varepsilon_y + \nu\varepsilon_x) - \frac{E\alpha T}{1-\nu}. \qquad \text{(c)}$$

In the case of a uniform temperature change, the thermal stress in a fully restrained steel bar is 197.5 psi per degree F, and in a fully restrained rectangular steel plate, 274 psi per degree F.

A review of the theoretical solutions for stresses in ships or flat plates is given in Appendices A and B.

IV. THERMAL STRESS PATTERNS IN TYPICAL CARGO SHIPS

Before a review of the observations of thermal strains and stresses in ship tests, it would be well to discuss the thermal stress patterns which may arise in the hull of a ship under typical weather and sea conditions. Methods of computing thermal stresses are presented in Appendices A and C, and computation sheets are shown in Appendix C for some of the thermal stress patterns appearing in Figs. 2--7.

Brittle fractures have most frequently occurred in ships when the air temperature T_A was lower than the water temperature T_W and heavy clouds greatly reduced the amount of insolation. Under these conditions, the portion of the hull below

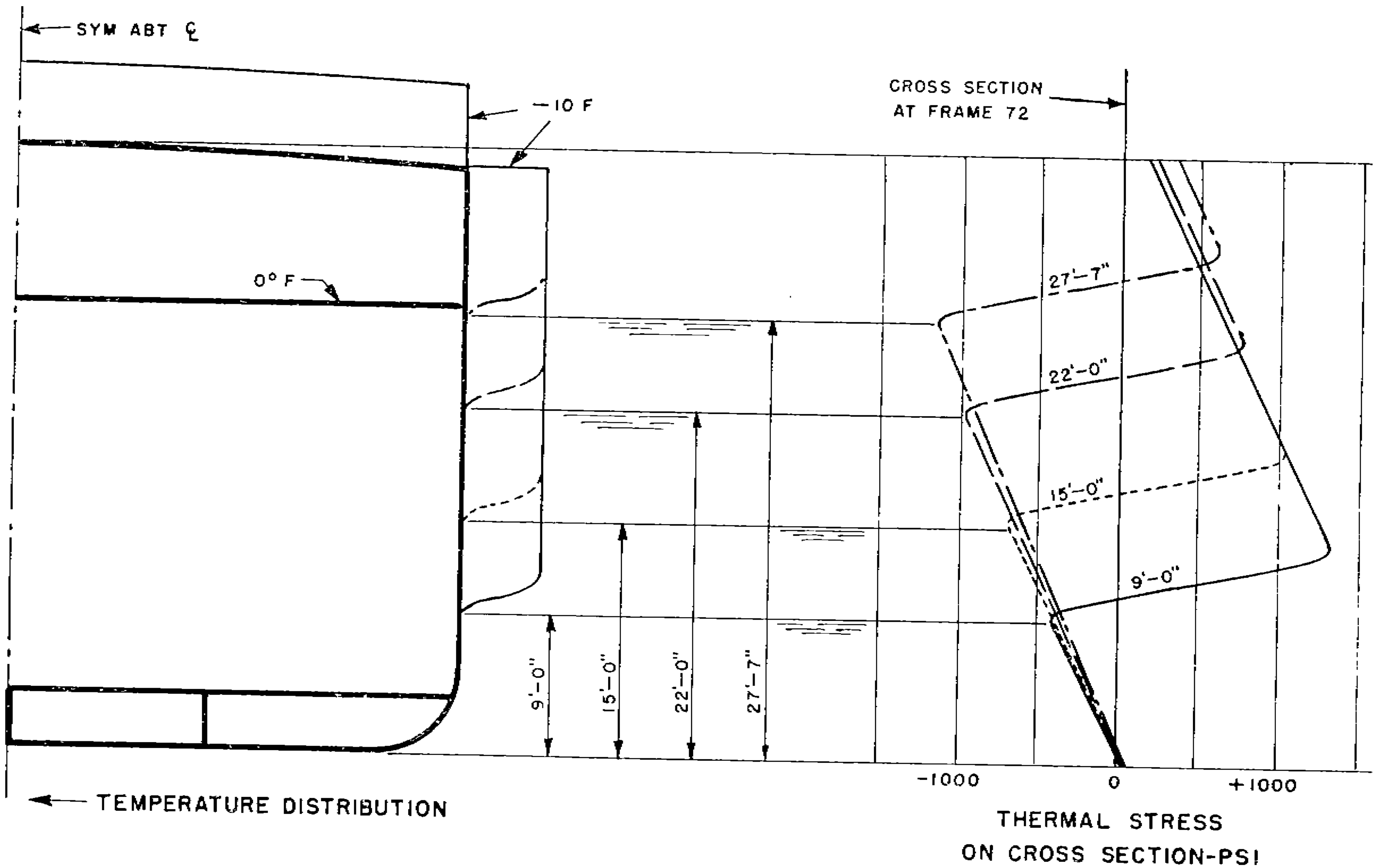


Fig. 2. Computed Thermal Stress in Shell and Upper Deck Plating of Liberty Ship for Different Drafts. Frame 72. $T_W - T_A = 10°$ F. Second Deck at 0° F.

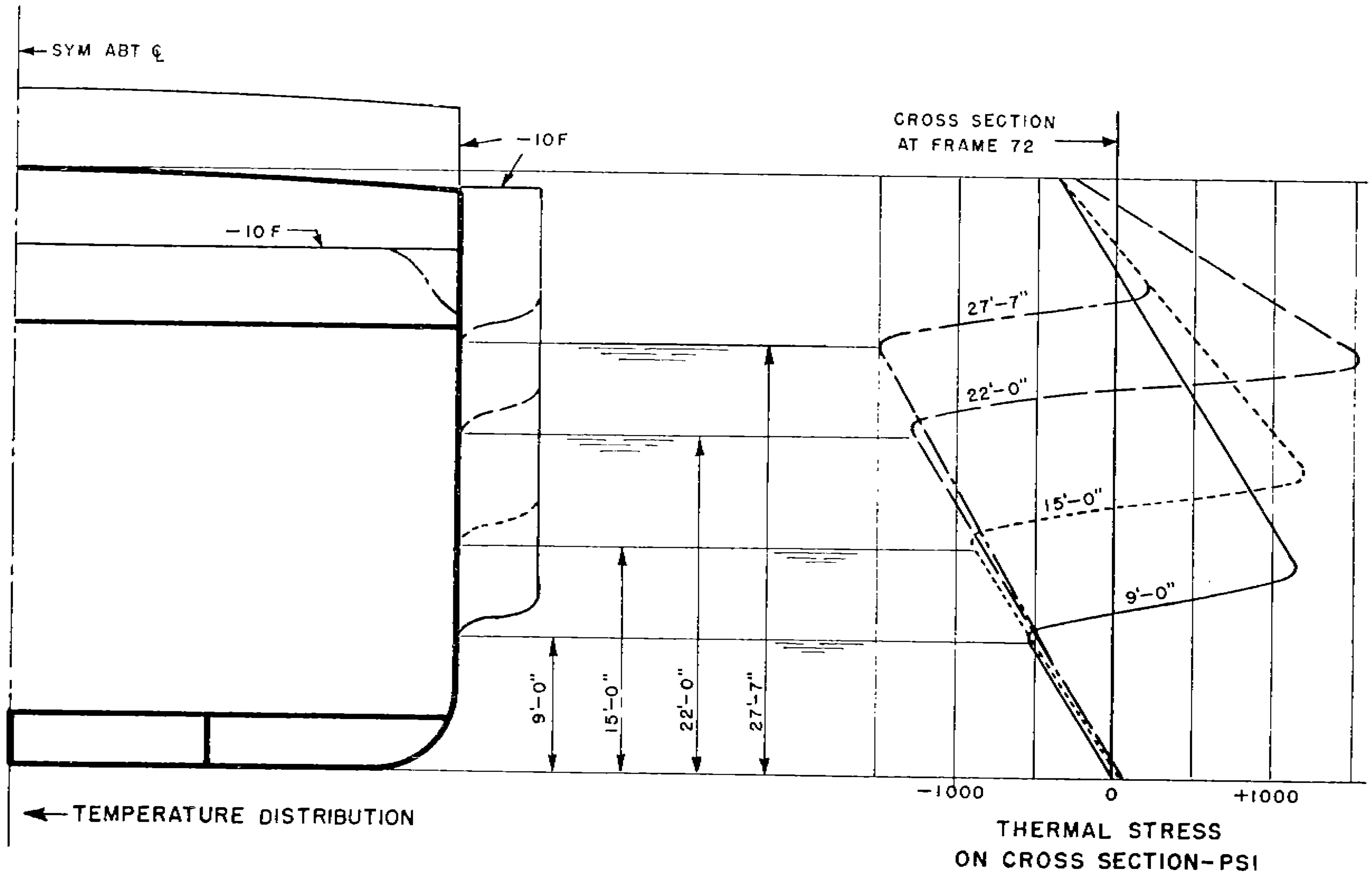


Fig. 3. Computed Thermal Stresses in Shell and Upper Deck Plating of Liberty Ship for Different Drafts. Frame 72. $T_W - T_A = 10° F$. Second Deck at -10° F.

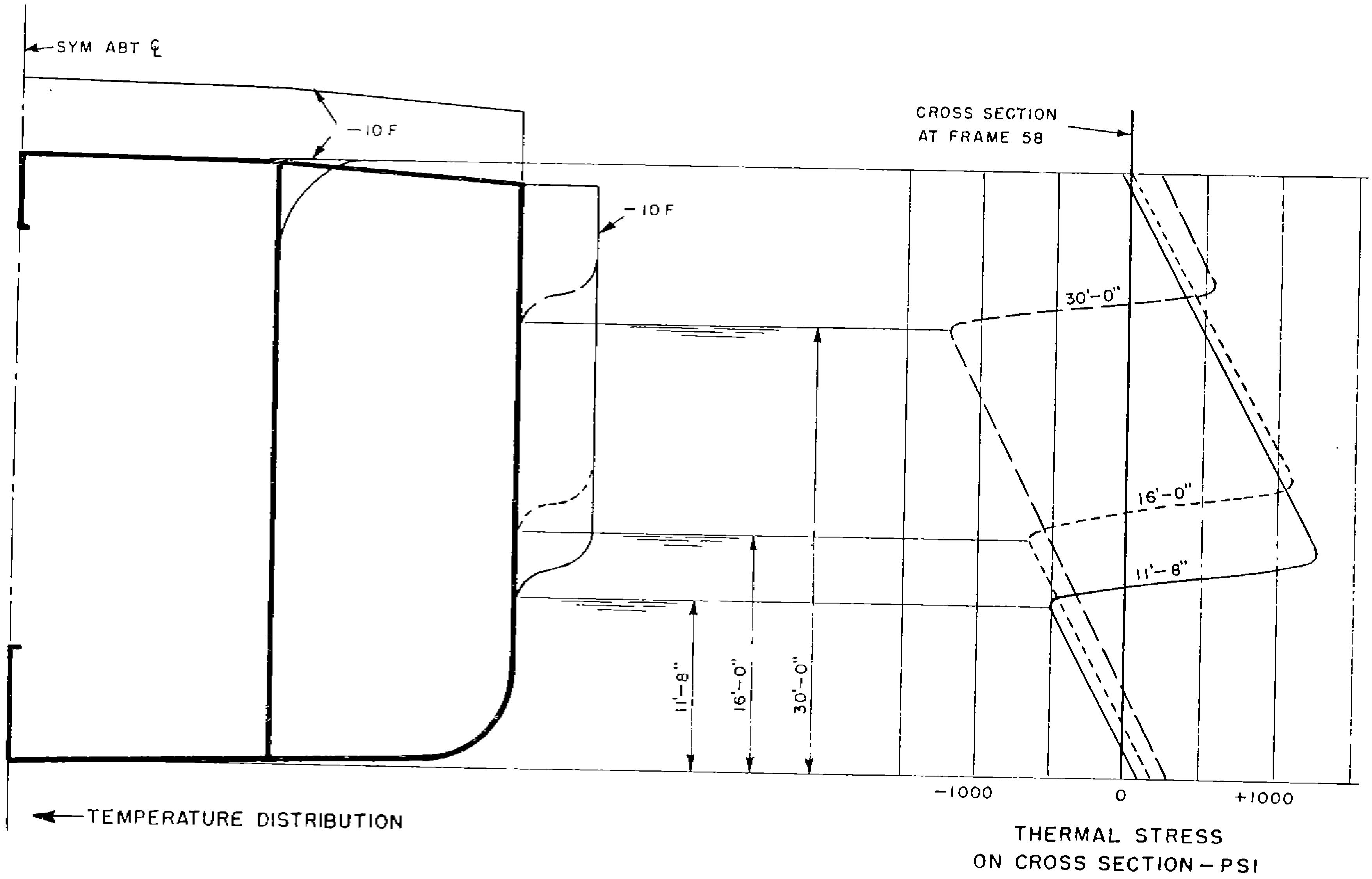


Fig. 4. Computed Thermal Stresses in Shell and Deck Plating of T2 Tanker for Different Drafts. Frame 58. $T_W - T_A = 10°$ F. Longitudinal Bulkheads at 0° F.

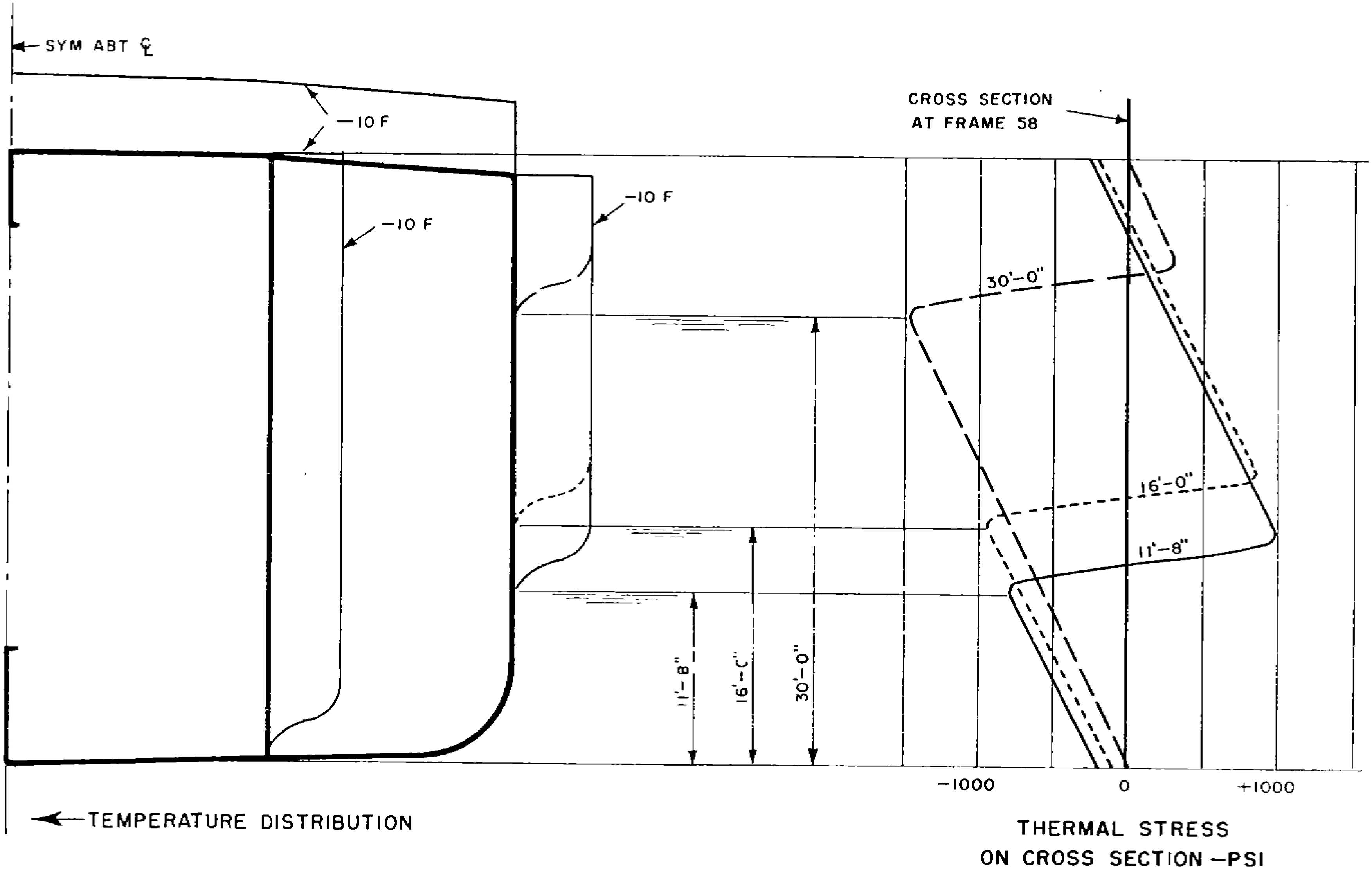


Fig. 5. Computed Thermal Stresses in Shell and Deck Plating of T2 Tanker for Different Drafts. Frame 58. $T_W - T_A = 10^\circ$ F. Longitudinal Bulkheads at -10° F.

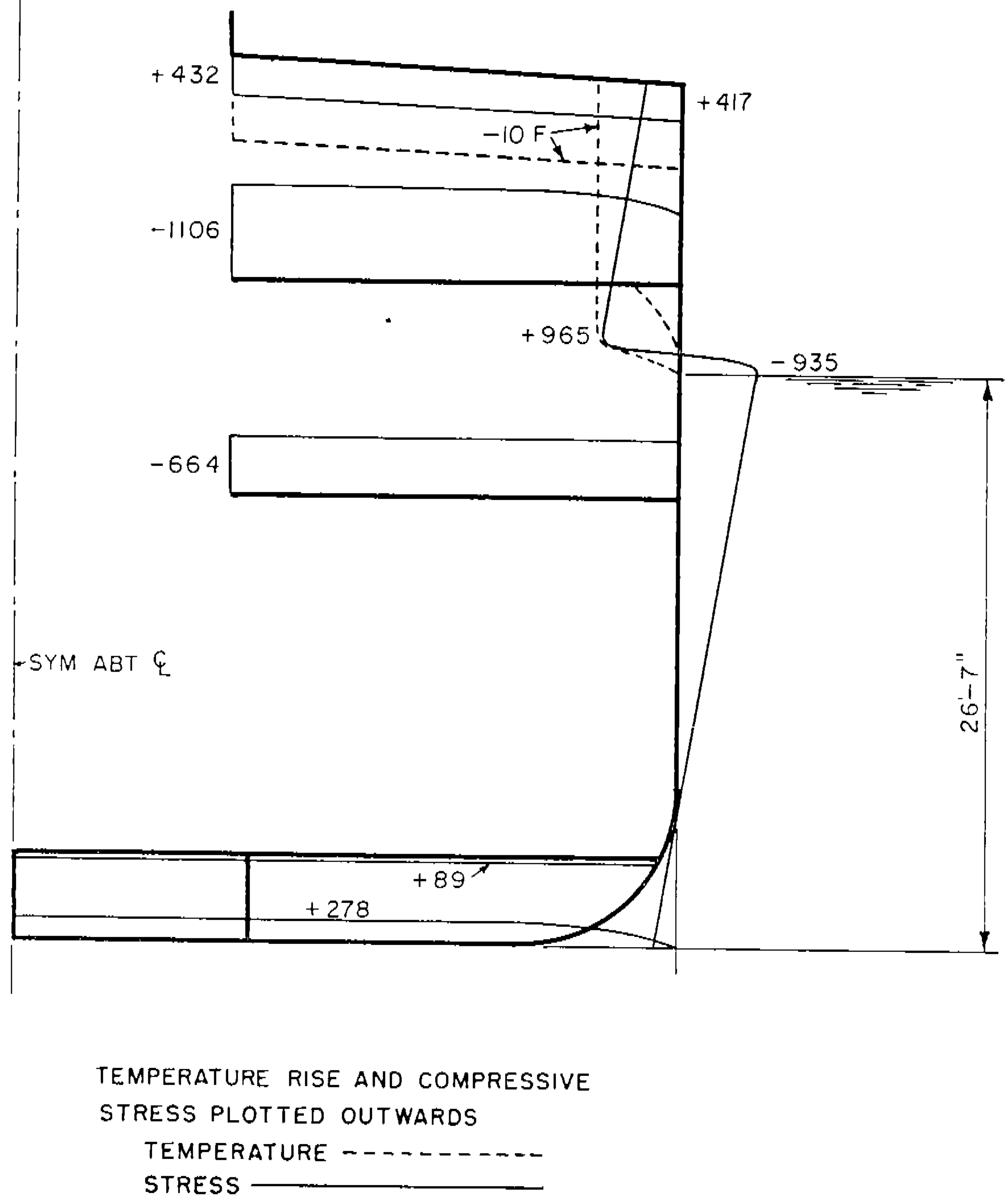


Fig. 6. Computed Thermal Stresses in C2 Dry Cargo Ship at Frame 85. $T_W - T_A = 10°$ F.

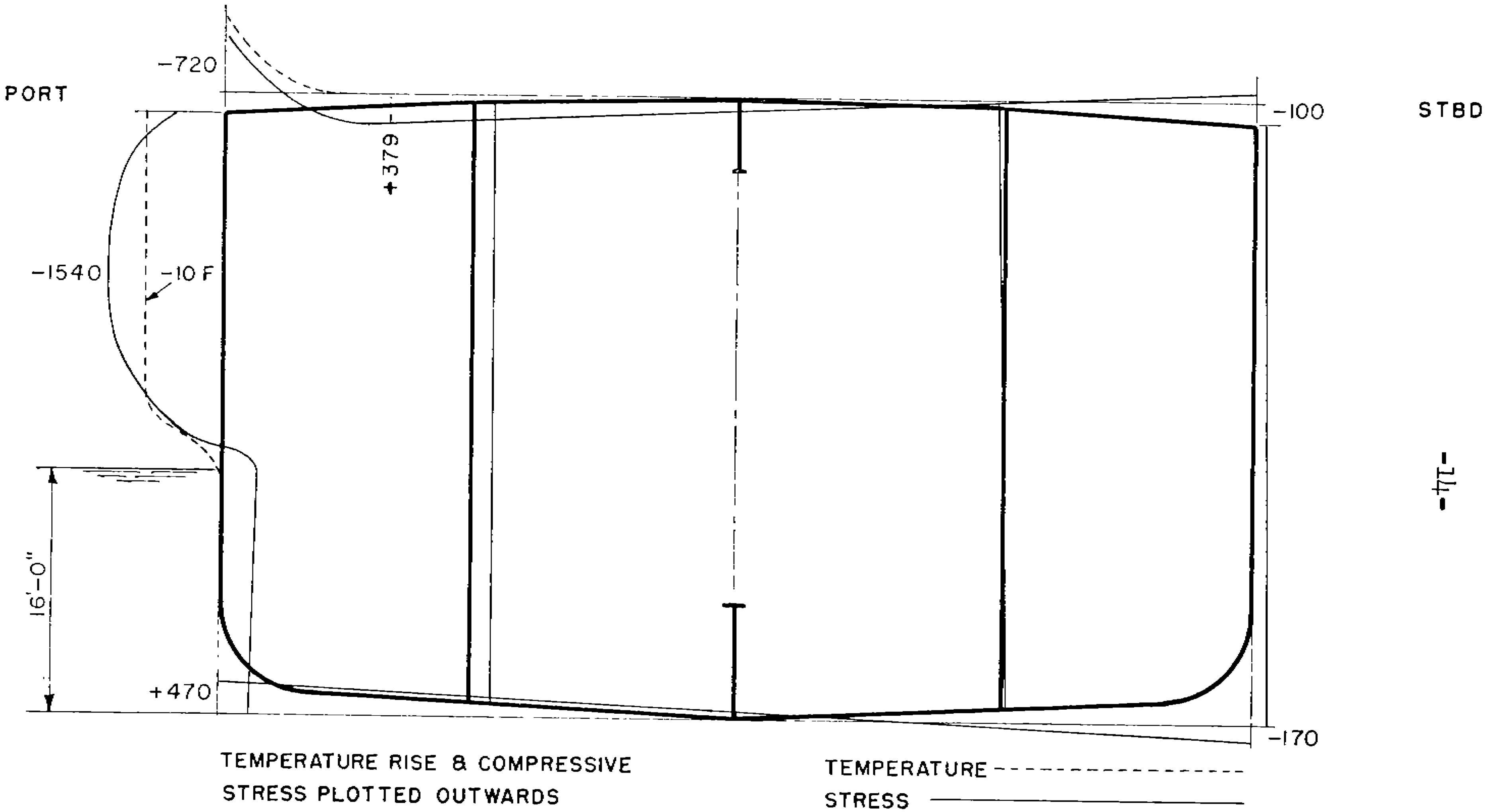


Fig. 7. Computed Thermal Stresses in T2 Tanker at Frame 59. Sun on Port Side.

the waterline was at one temperature, and the main deck and side shell plating above the waterline were essentially at a lower temperature. Thermal stresses computed for several drafts and for the above conditions are shown in Figs. 2--6.

Fig. 2 gives the stresses at Frame 72 in a Liberty ship with the second deck at the same temperature as the water, and Fig. 3, the stresses with the second deck at the same temperature as the main deck. Frame 72 is 34 ft forward of midships. Similar plots are shown in Figs. 4 and 5 for the stresses in a T-2 tanker at Frame 58 (amidships) with the longitudinal bulkheads first at the water temperature and then at the temperature of the deck. The following observations may be made concerning these plots:

1. The thermal stresses in the main deck and bottom plating for the 10 F differential are relatively small.
2. The maximum tension stresses occur just above the waterline, and the maximum compression stresses, just below.
3. The maximum tension stresses range from 50 to 75 per cent of those corresponding to full restraint against thermal strain.
4. In Figs. 2, 4, and 5, the maximum tension stresses are developed at the smallest draft, while the

stresses in the deck and bottom plating are not greatly affected by the draft.

5. In Fig. 3, where the second deck is at the same temperature as the main deck, the maximum tension stresses occur at intermediate drafts.
6. The effect of having the longitudinal bulkheads of the T-2 tanker at different temperatures was a small change in the values of the thermal stresses (see Figs. 4 and 5).

The thermal stresses for a C-2 dry-cargo ship with the 'tween decks at water temperature are plotted in Fig. 6 and are similar in pattern to those for the Liberty ship in Fig. 2.

Ships have suffered severe fractures when the early morning rays of the sun were directed at the side of the vessel but did not strike the main deck. Thermal stresses for a T-2 tanker under such conditions of insolation are shown in Fig. 7. The maximum tension stresses occur in the vicinity of the bilge and in the main deck, in each case on the side of the hull toward the sun. At these two locations they are approximately 25 and 20 per cent, respectively, of the stresses for full restraint of thermal strain. The appreciable amount of energy stored in the relatively warmer side shell can be seen.

The temperature distribution in Fig. 2 is such a common one that the variable coefficients for Hurst's equation(3) have been plotted in Fig. 8 for the Liberty ship at various drafts.

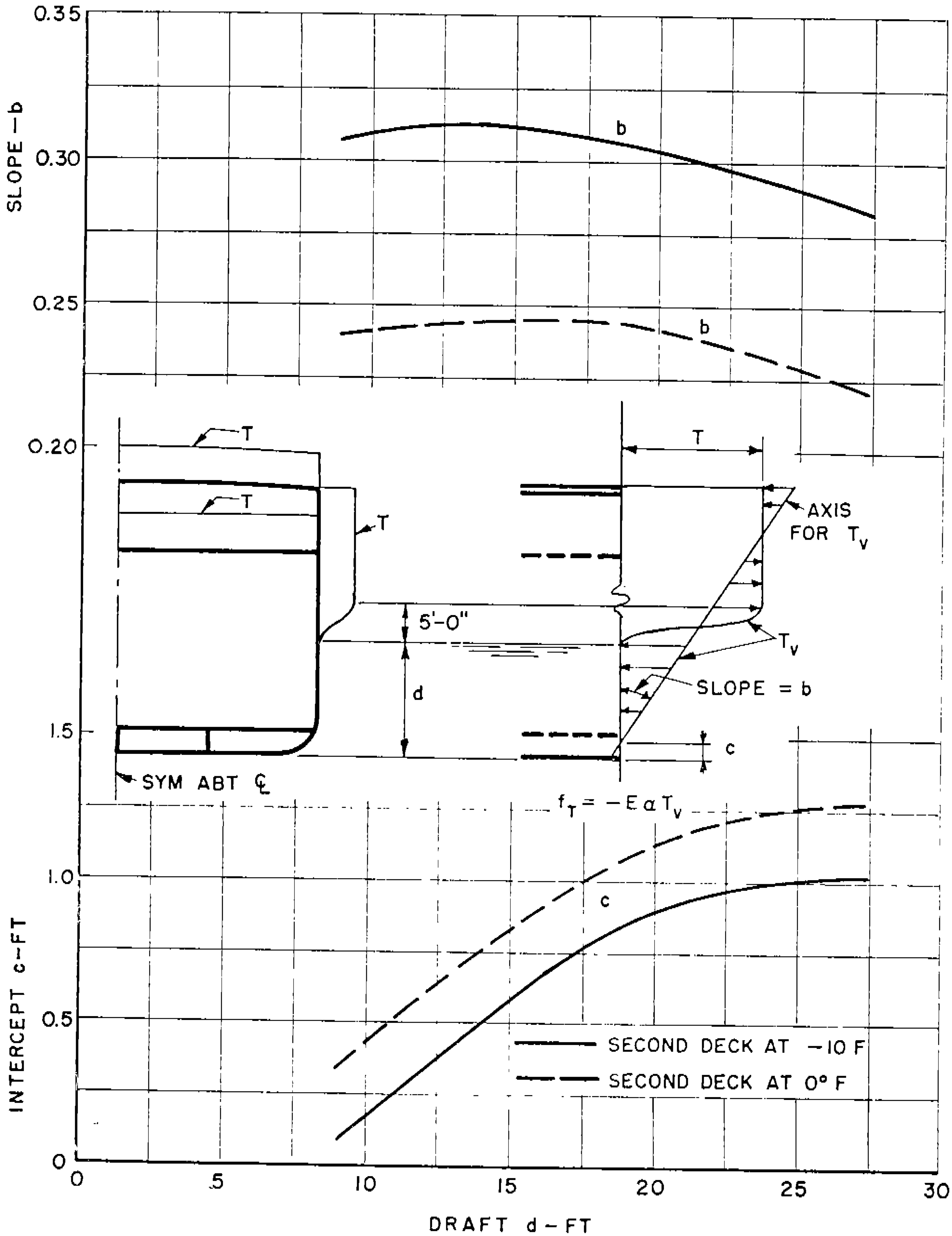


Fig. 8. Constants for Computing Thermal Stresses by Hurst's Method for A Given Temperature Distribution at Frame 72 of Liberty Ship.

V. TEMPERATURE EFFECTS OBSERVED IN SHIPS

1. Observations on Ships Heated by the Sun's Rays. The first reference to the deflections caused in ships by thermal strain was made by Smith[45], who found that a temperature differential of 7 F between the bottom and deck of the 500-ft collier "Neptune" produced a maximum deflection of about one inch in the hull. One of the discussers of his paper stated that the thermal deflections of a floating dry dock were suspected of being greater than those caused by docking a ship.

The first theoretical analysis of hull deflections was made by Suyehiro and Inokuty[1] in 1916. Their temperature measurements were crudely made, and no satisfactory results were obtained from the anslysis of them. They did conclude, however, that thermal deflections were large enough to merit serious consideration in the design of a large ship.

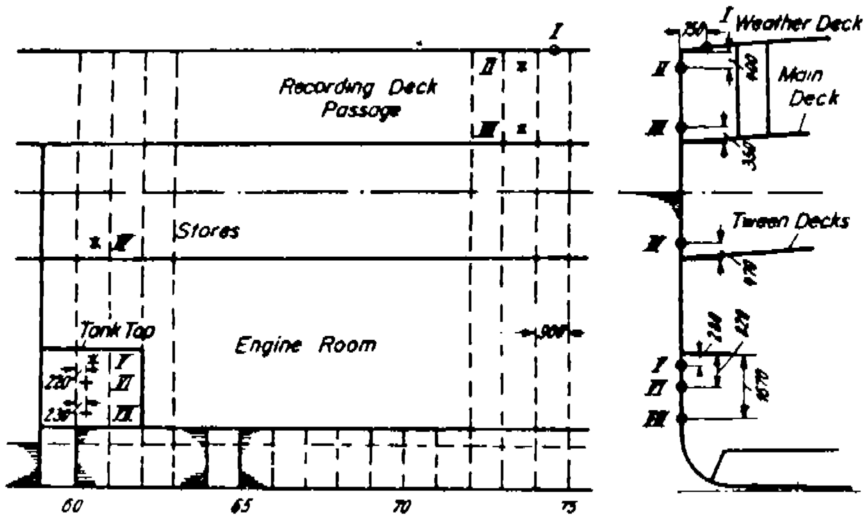
In 1915 Everett[46] reported a 1.7-in. deflection in a 388-ft cargo ship as a result of a 50 F differential between the deck and water temperatures which occurred between times 0430 and 1330.

Burtner and Tingey[2] reported in 1927 that a maximum deflection of 2.76 in. was found in a car float on a windy day when the sun shone intermittently and the air temperature varied between 36 and 42 F. The deck temperature increased from 35 to 60 F. The deflection was computed and found to be in good agreement with the observed value. They also mentioned a car float in dry dock which lifted several inches clear of the midship keel blocks when the sun shone on the deck.

Cross(47) in 1928 observed a 5 1/2-in. deflection in a 600-ft Great Lakes freighter between 0700 and 1900. The air temperature was 70 F in the morning and 85 F in the afternoon. The water temperature was around 72 F. Bennett(48) found that the fore and aft drafts of Great Lakes freighters were increased as much as six inches by the hogging deflections resulting from thermal strain.

Limited observations of the temperature distribution and the corresponding strains were made on the German riveted dry-cargo vessel M. S. "Duisburg"(49). This ship was transversely framed with double-bottom construction as shown in Fig. 9, its length being approximately 450 ft between perpendiculars. The temperatures and elongations of the shell plating were measured on the port side at the points shown in this figure. It should be noted that Station I was located within the deckhouse and was sheltered from the sun.

The observations were made on April 1 when the ship was two days out of Rotterdam. The readings were begun at 0700 with the sun on the port side of the vessel, the side on which the gages were located. The maximum temperature was reached at 1100 when the weather turned foggy. The air temperature ranged from 48 to 53 F, and the water temperature was 44 F during this period.



Arrangement of Strain Gages

All the instruments are inboard on the port side, and are, with the exception of VI and VII, placed midway between frames

Fig.9. Observations on M.S. DUISBERG.

The stations located below the waterline and on the weather deck showed such small thermal strains that their values were not computed. In the side shell above the waterline, a maximum temperature of 104 F was found at Station II, or a rise of 46 F, and a compression stress of 2400 psi. The same temperature increase occurred at Station III, and the corresponding compression stress was 5300 psi. This portion of the side shell, restrained above by the weather deck and below by the main deck and the part of the hull below the waterline, developed compression stresses of appreciable magnitude when warmed by the sun. The longitudinal deflection of the hull resulting from these thermal strains was not measured.

In 1946 Howe, Boodberg, and O'Brien(5) completed the most extensive observations made to date of temperature gradients and thermal stresses in ships. Tests were made on four ships. Typical temperatures found in the Liberty ship S. S. "William Sharon" are shown in Fig. 10. Here may be seen both the diurnal temperature fluctuation and the variation in temperature distribution on a cross section of the hull as the position of the sun changed. The pattern of the temperature change was unsymmetrical about the vertical centerline of the cross section at all times except in the middle of the night. The temperature differences between points on the hull and the water as computed from these data are shown in Fig. 11. The maximum difference in temperature

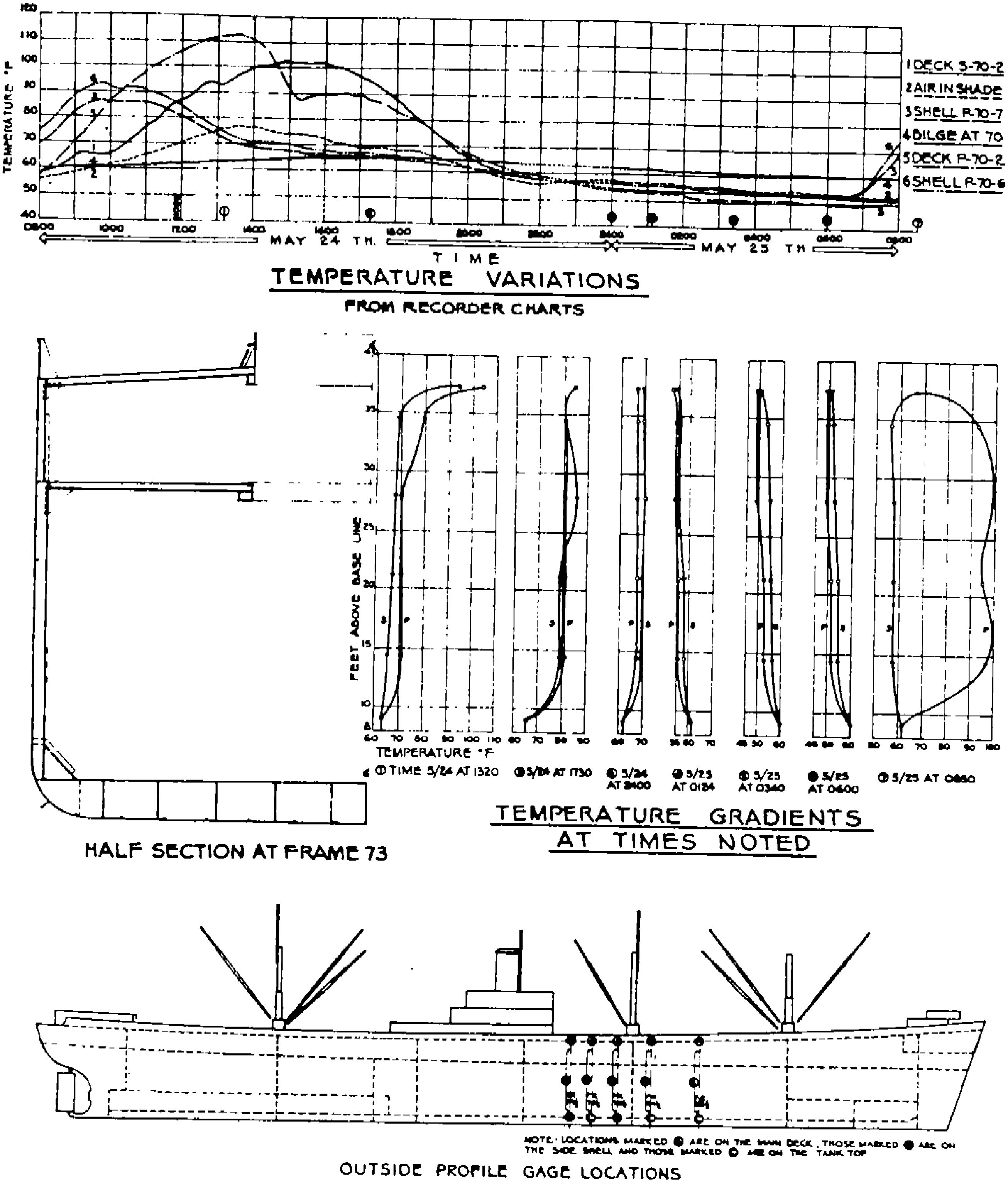
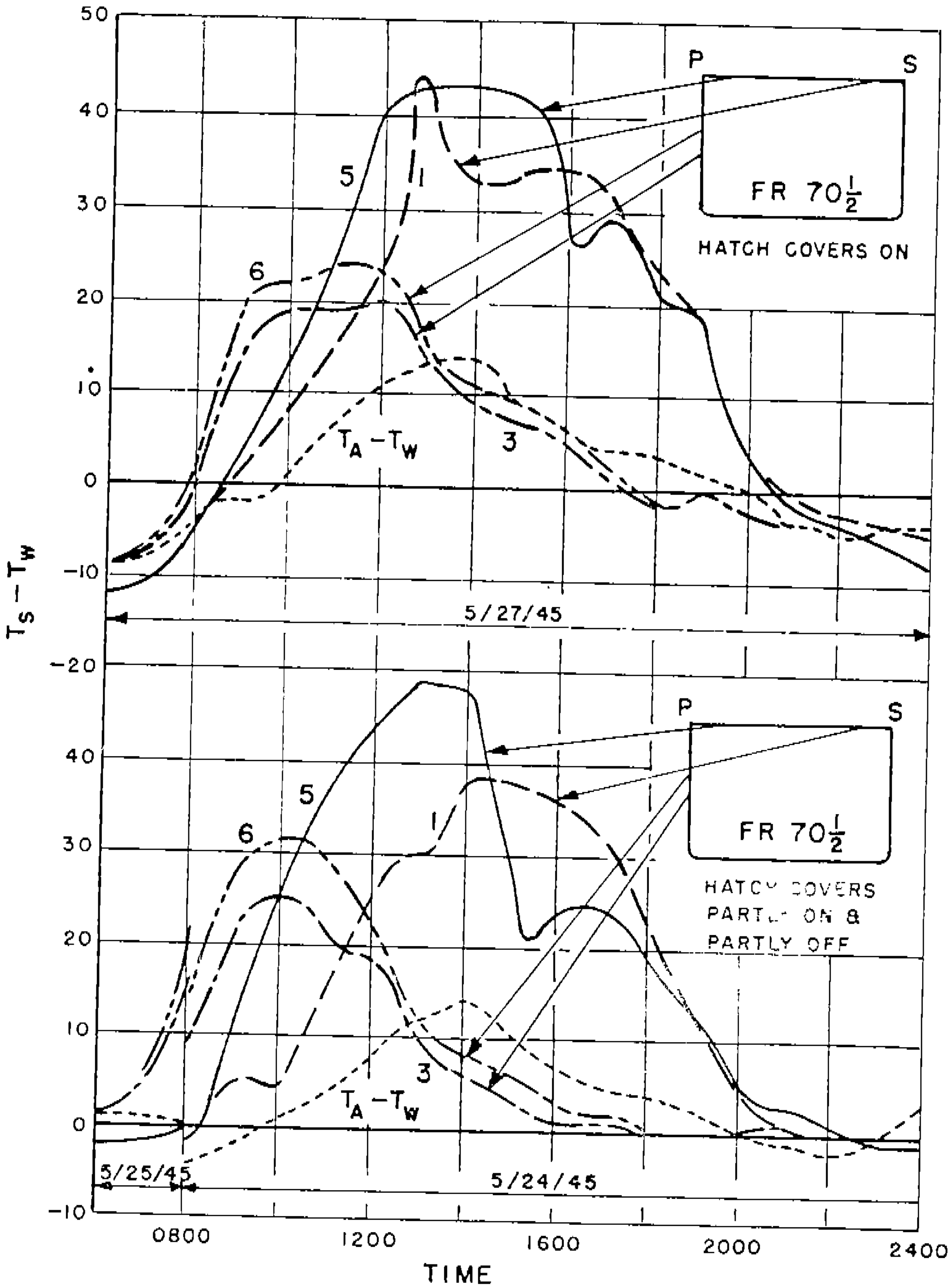


Fig. 10. TEMPERATURES MEASURED IN S.S. WILLIAM SHARON.



HEADING: SOUTH
SUNRISE: 0553
SUNSET: 2022

SKY CONDITIONS: HIGH FOG & CLOUDS
REL. HUMIDITY DURING PERIOD: 50–90%

Fig. 11. Difference between Temperatures of Hull and Water for S.S. WILLIAM SHARON.

between the main deck plating and the bottom plating was 48 F, while between the side shell plating receiving the morning sun and the bottom plating, it was 32 F. The heading of the ship was south. These observations were made in late May when the maximum air temperature was 78 F, the sky was obscured by high fog and clouds, and the relative humidity ranged from 50 to 90 per cent. Under these conditions the insolation was far from being as intense as would be found on a clear day when higher temperatures could be expected in the hull.

The phenomenon of nocturnal radiation is discussed in Appendix D, and an example of it appears in the diurnal temperature variation at the top of Fig. 10. The temperature of the deck around the hours of 2400 to 0400 was 5 to 7 F below the air temperature. Under clear skies and low humidity this difference would have been larger.

Thermal biaxial stresses in the S. S. "William Sharon" and in a C-2 refrigerated ship, the S. S. "Golden Rocket," were computed. Unfortunately, in these computations the last term in Eqs. (c) on page 8 of this report was neglected and all the computed stresses are in error. The writer hopes that the stresses can be correctly computed, as these data represent the most extensive investigation to date.

Bassett[50] measured the diurnal temperature gradients amidships in an LST vessel; these data are shown in Fig. 12.

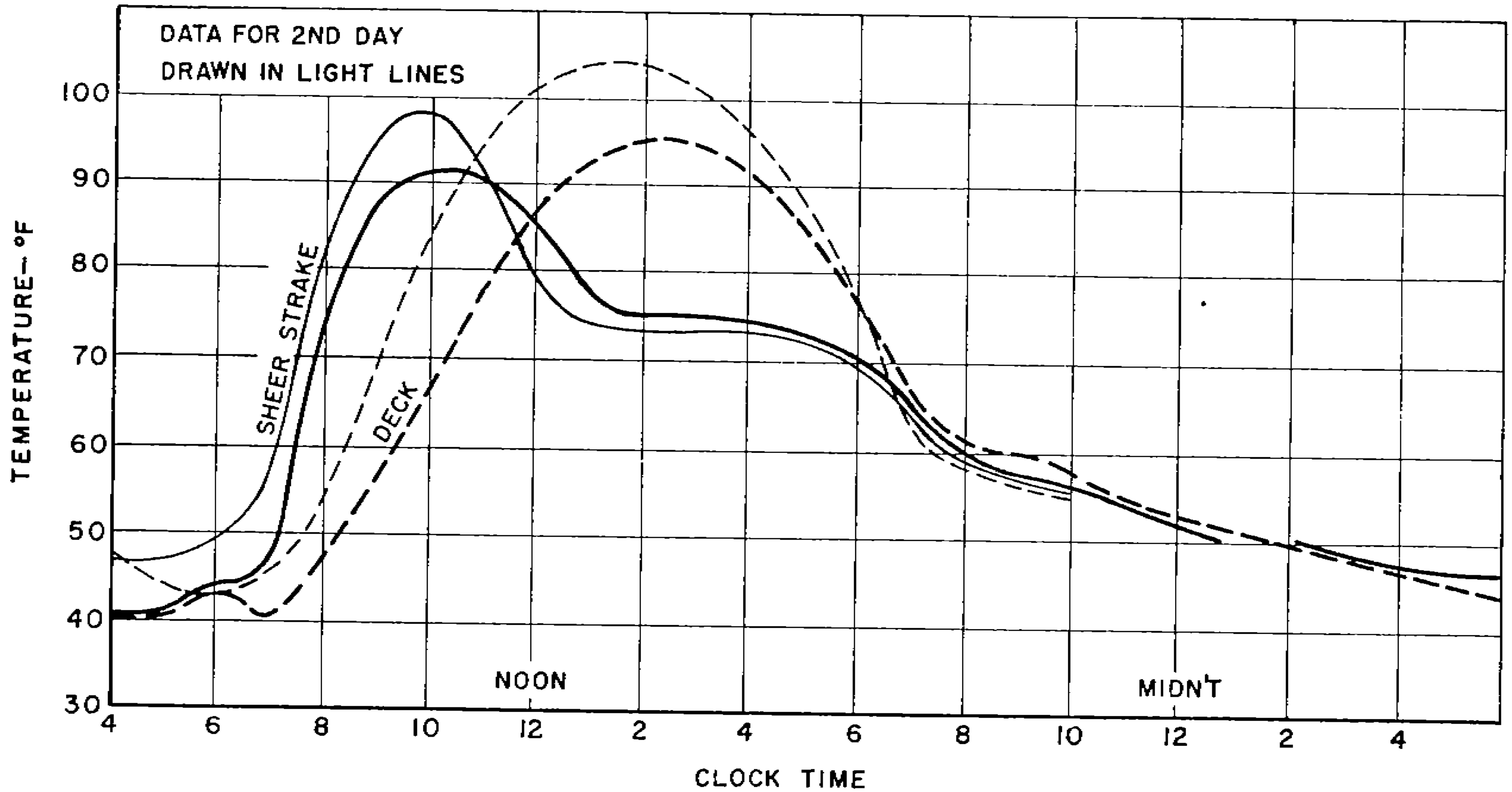


Fig. 12. Temperatures of Deck Plate and Sheer Strake of LST at Port Gunwale over Period of One Day.

The heading of the ship was south. During the day the temperatures of the deck and the side shell were always different except around noon. The same pattern of variation may be seen in Figs. 10 and 11.

Thermal stresses were also computed in these tests. Uniaxial stress conditions were assumed, but in the computations the last term in Eq. (b) on page   was neglected, and the calculated stresses are therefore in error. However, the writer scaled the necessary data from the plate to compute the correct thermal stresses which are shown in Figs. 13 and 14. These figures show the diurnal variation in thermal stress. The weather conditions from a weather station some fifteen miles away are also given. Compression stresses of 11,000 psi were developed in the main deck and side shell and temperature gradients as high as 73 F in the side shell, although the air temperature did not exceed 71 F and the humidity was at all times above 30 per cent. The tests were made in early April. The tension stresses in the hull were relatively small. Thermal stresses approaching 100 per cent of those for full restraint of thermal strain were developed in these tests.

It should be pointed out that the draft at the gaged cross section of the hull was 4 ft, 7 in., and the molded depth 25 ft, 2 in. The ratio of the draft to the molded depth amidships in these tests was about half of that for a cargo ship

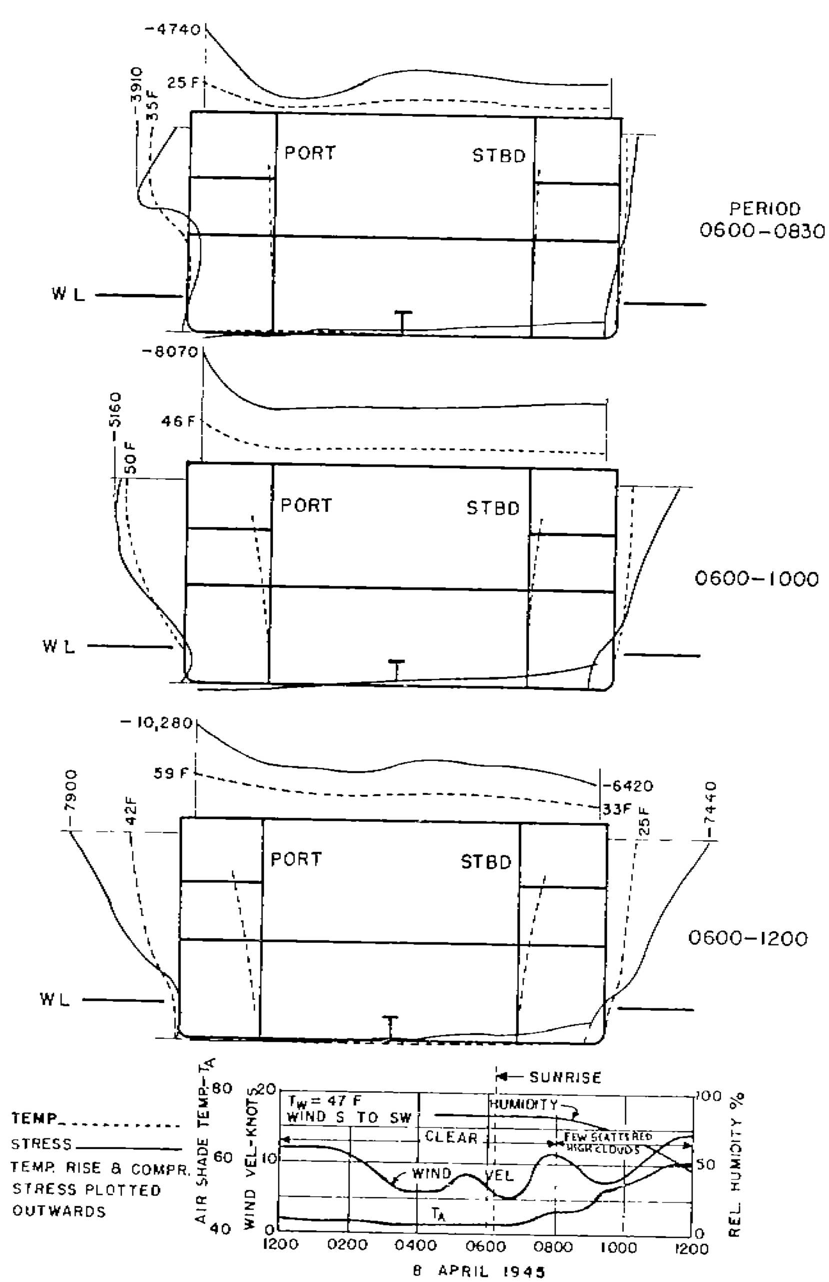


Fig. 13. Temperatures and Thermal Stresses Observed in LST-1075 at Frame 23-1/2. Heading of Ship, South.

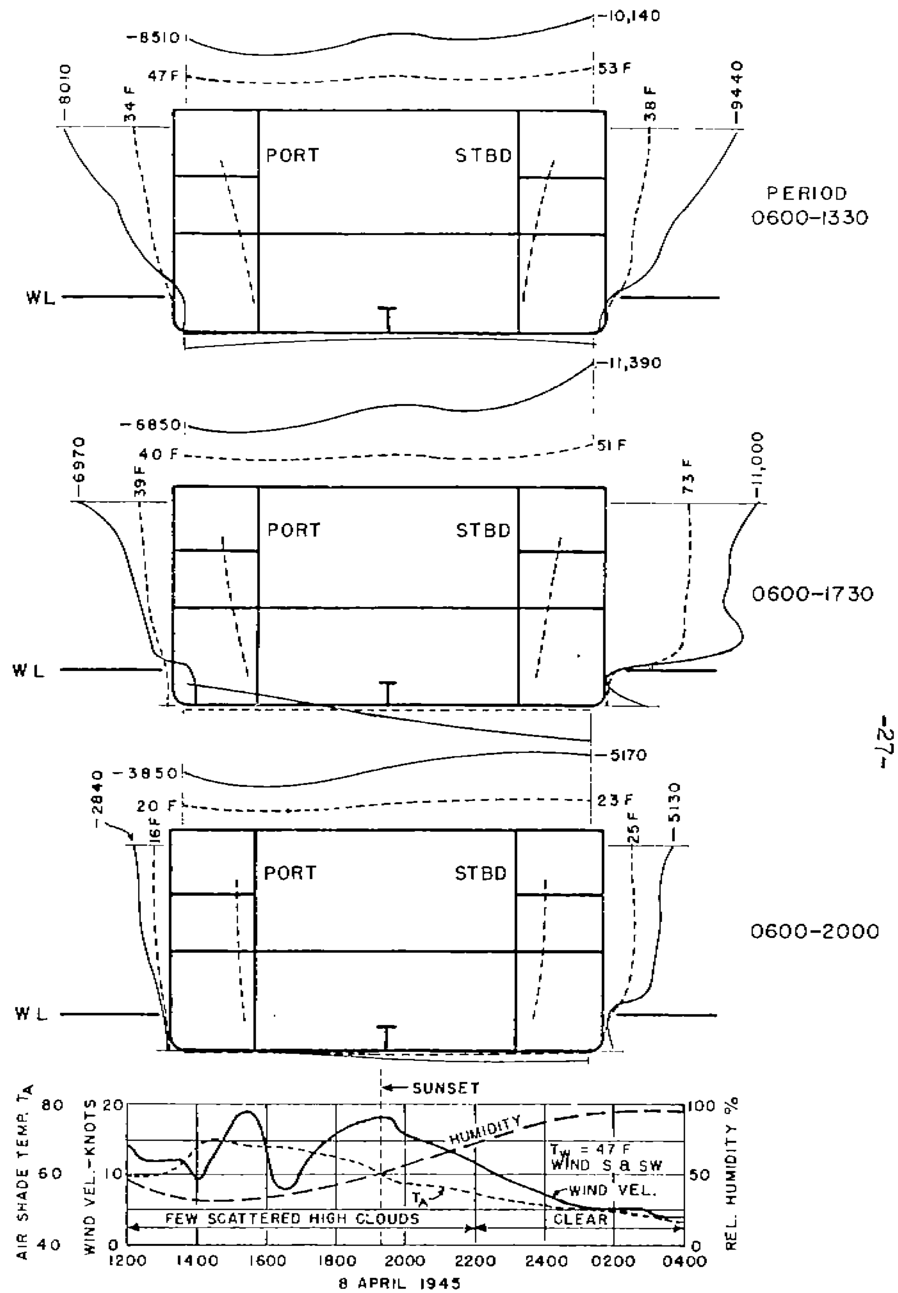


Fig. 14. Temperatures and Thermal Stresses Observed in LST-1075 at Frame 23-1/2. Heading of Ship, South.

in ballast condition. Thus the results of this test are not typical of those which might be found under service conditions.

The tests on the M. S. DUISBERG, the S. S. WILLIAM SHARON, and the LST were made in either April or May. In the first two, atmospheric conditions reduced the intensity of insolation. In all three cases there were not present the very clear skies and low humidity which have accompanied some still-water failures of ships on cold mid-winter days. With the data of Fig. D-1, Appendix D, in mind, it would be plausible to conclude that higher temperatures and thermal stresses in the main deck might be found in the side shell plating at midday in the summer and on very clear winter mornings.

From these ship tests it is possible to picture the temperature distribution to be expected in a ship's hull. At all times the shell plating below water attained the water temperature up to a level within one or two feet of the waterline. At night the temperature of the portion of the side shell plating more than four or five feet above the waterline was the same as that of the air, while the temperature of the deck was lower than the air temperature as a result of nocturnal radiation. During the day the temperatures of the above-water hull structure were related to the position of the sun and the heading of the ship. These observations are useful for one who wishes to develop a typical temperature distribution to be used for computing thermal stresses in a ship's hull.

During the course of extensive hogging and sagging tests on the 460-ft tanker M. V. NEVERITA[51], some observations of hull temperatures were made and thermal stresses computed. However, the number of gaging stations was not sufficient to give an adequate picture of the temperature distribution on the cross section. The ship lay approximately in a north-south direction.

The maximum hogging deflections during a warming up and cooling down cycle appear in Fig. 15. The hysteresis in this curve was undoubtedly the result of the slower temperature change in the two longitudinal bulkheads. The observed maximum deflection (hog) between 0930 and 1500 was 1.28 in., and the computed deflection 1.88 in., the discrepancy between the observed and the computed deflections being attributed by the investigators to the sheltering effect of the midships deckhouse on the temperatures below it, as well as its stiffening effect upon the hull. Neither of these factors would appear to account for all the difference between the figures of 1.28 and 1.88 in. The lack of adequate temperature data on which to base the computations would seem to be an important factor.

The effect upon the thermal stress distribution of the 4-ft diameter expansion trunks located on the deck was evident in some of the plots in this report[51]. The magnitude of the thermal stresses increased as the opening was approached.

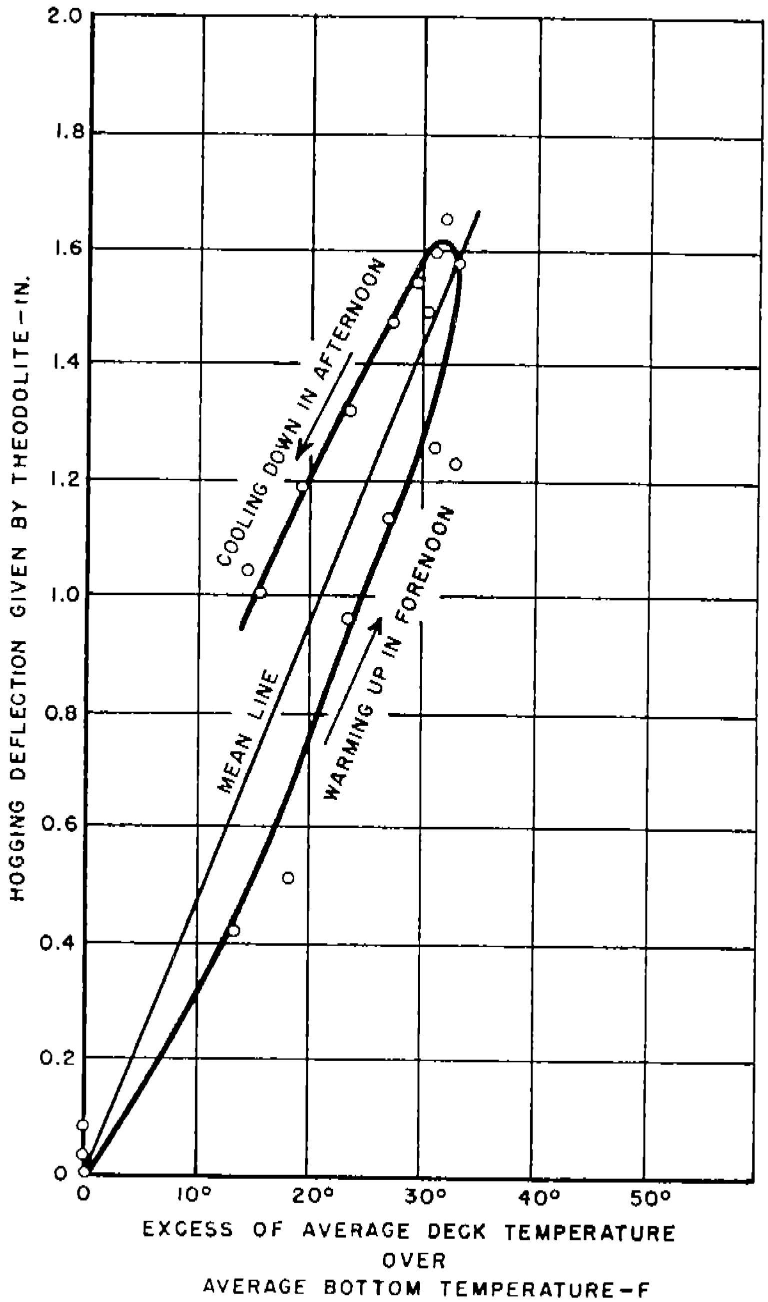
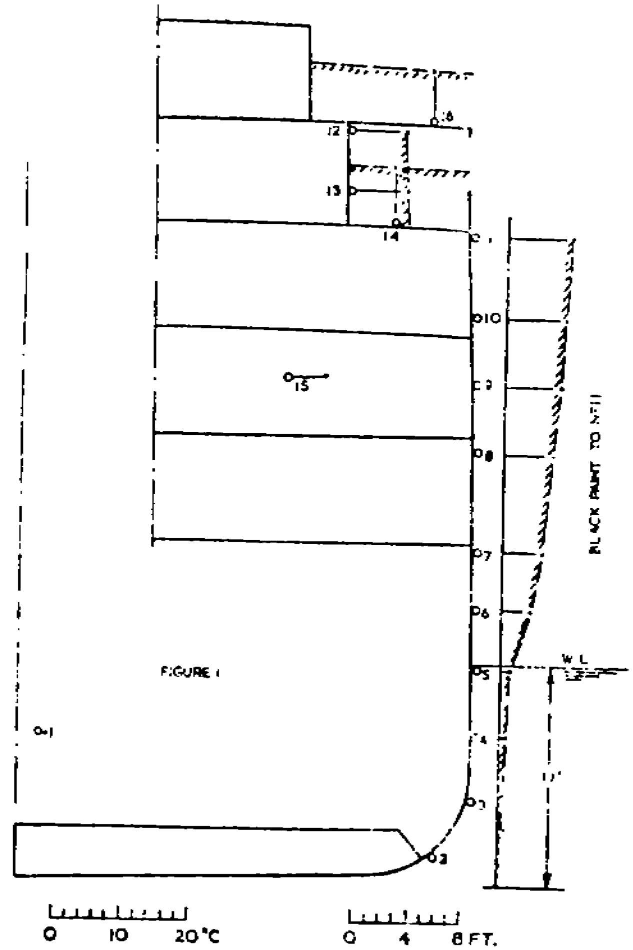


Fig. 15. Hogging Deflections in M.V. NEVERITA Caused by Temperature Change.

Unfortunately, no gages were located in the immediate vicinity of these trunks.

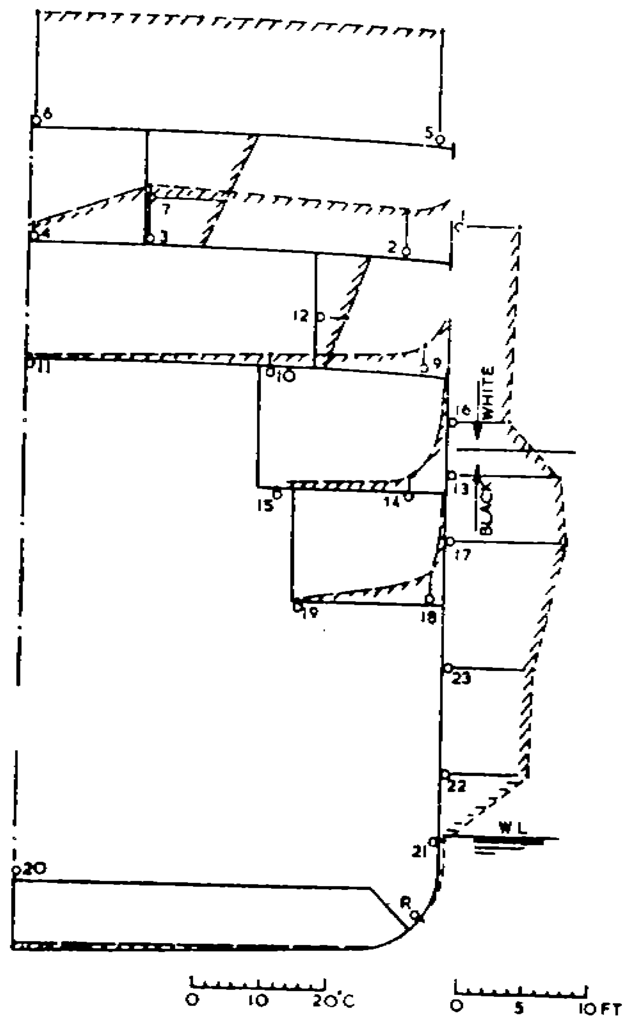
Fig. 16 shows the temperature gradients in three ships as measured by Corlett[4]. The observations for Ships 1 and 3 are similar to those reported by other investigators. However, the effect of the color of the paint upon the temperatures was the primary object in the case of Ship 2. At the junction of the white and black paint, the temperature changed 15 F in a distance of only three feet, this change being about 45 per cent of the maximum temperature difference.

Temperature gradients were investigated in the 416-ft riveted ship S. S. CLAN ALPINE by the Admiralty Ship Welding Committee[6]. The general arrangement of this vessel and the gaging stations are shown in Fig. 17. This vessel is similar in construction to the American Liberty class ship. The temperature gradients and the thermal stresses computed by Hurst's method[3] appear in Fig. 18. The temperatures were measured at fifty points on the cross section at Frame 90 just forward of the midship deckhouse. The shapes of the temperature and thermal stress gradients are similar to those found by other investigators. However, it should be noted that cloudy weather prevailed and the air temperature was below that of the water. The maximum temperature differential developed in this test was only 7.5 F and the maximum tension thermal stress around 700 psi in the second deck.



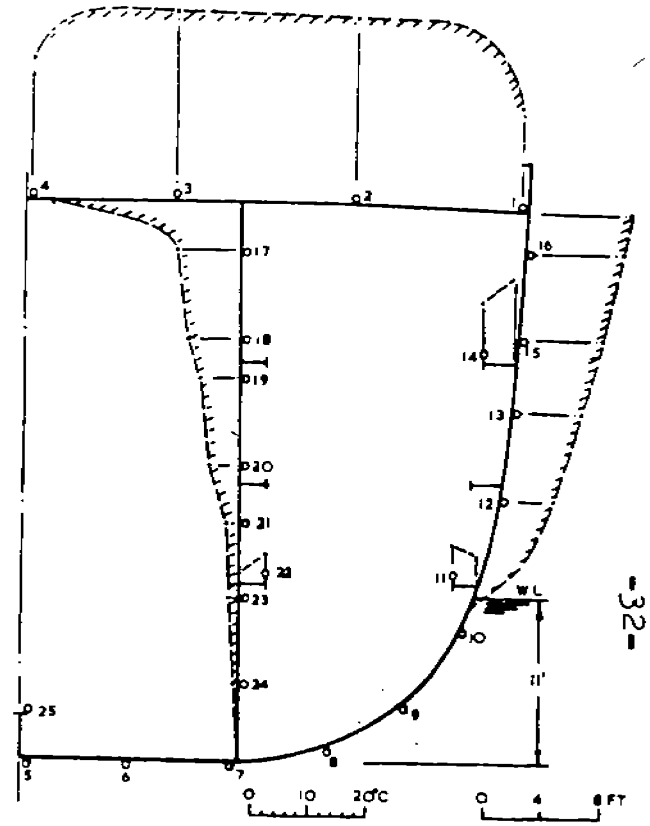
SHIP 1

Dimensions		*Conditions*	
L.o.a.	545 ft	Cloud	5/10
Beam	66 ft	Water temperature	61·5° F.
Depth	43 ft. 6 in. (to shelter deck)	Air temperature (shade)	68·0° F.
Test section amidships			



SHIP 2

Dimensions		*Conditions*	
L.o.a.	448 ft	Cloud	0/10
Beam	61·75 ft	Time	Noon
Depth (to upper deck)	34·75 ft	Water temperature	66·0° F.
Test section amidships.		Ambient shade temperature	72·5° F.
		Black bulb sun temperature	84·5° F.
		White bulb sun temperature	76·0° F.



SHIP 3. TEST 1

Dimensions		*Conditions*	
L.b.p.	515 ft	Cloud	0/10
Breadth	69·5 ft.	Time	12.30 G.M.T.
Depth	39·5 ft.	Sun on port beam.	
Test section	152 ft from A.P.	Water temperature	66·0 F.
		Shade temperature	91·5° F.

Fig. 16. Temperature Gradients in Three Ships as Observed by Corlett.

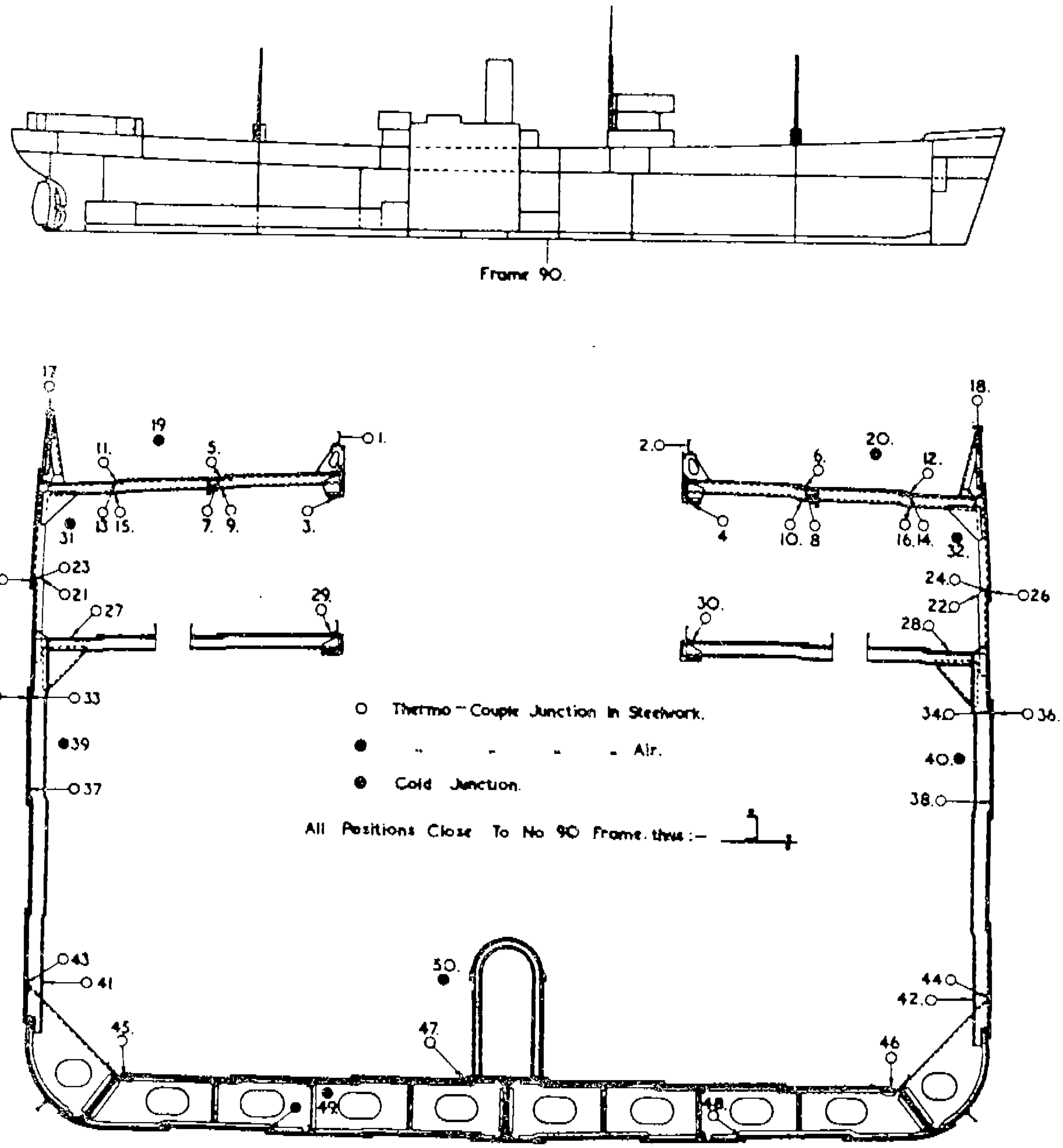


Fig. 17. General Arrangement of S.S. CLAN ALPINE
and Location of Thermocouples.

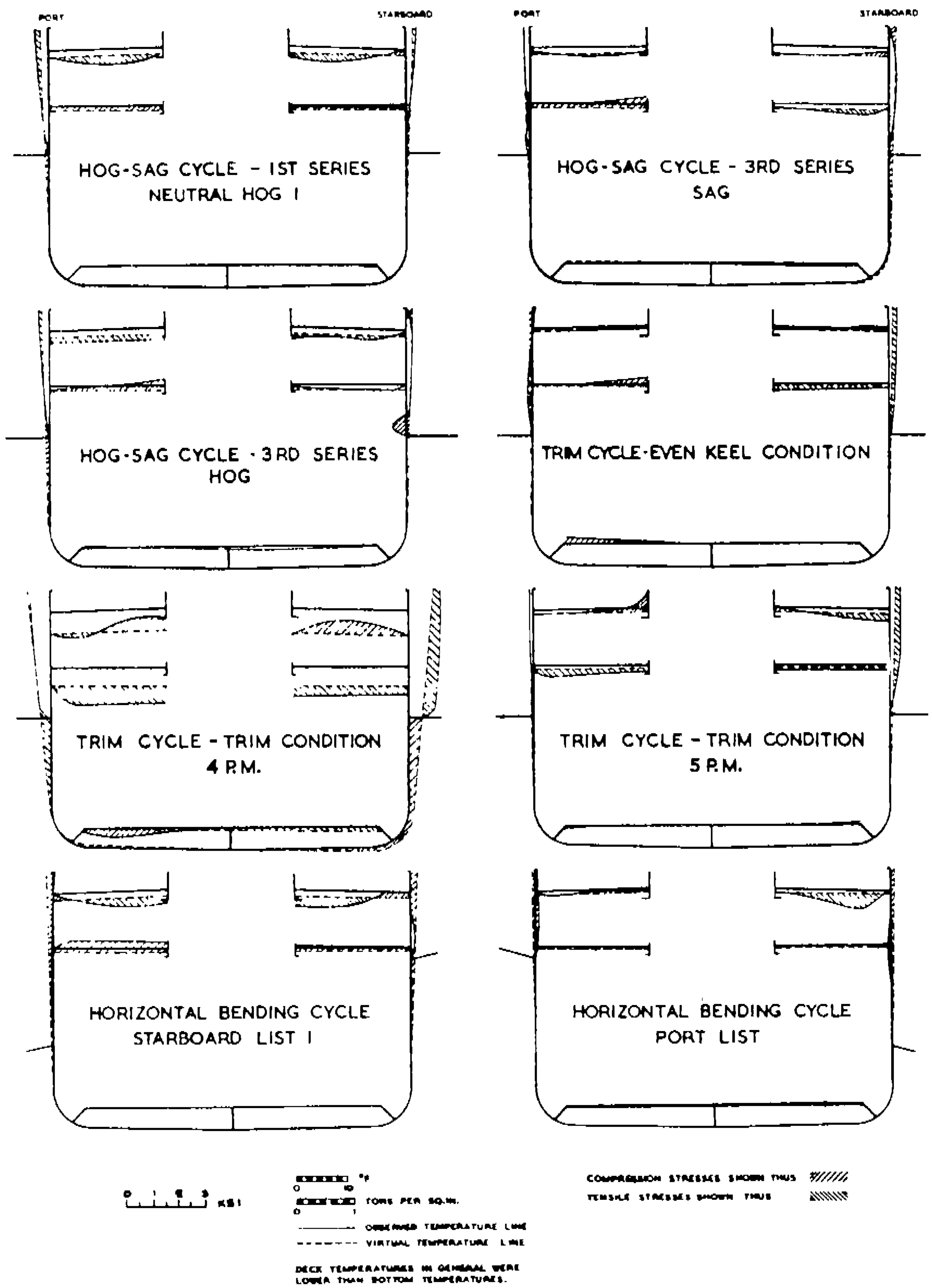


Fig. 18. Thermal Stress Patterns Developed in S.S. CLAN ALPINE Near Frame 90. Maximum Temperature Differential, 7.5 F.

During structural tests on the Liberty Ship S. S. PHILIP SCHUYLER, Vasta[52] observed the effect of temperature change on hull girder deflections shown in Fig. 19. An increase of 12 F in <u>air</u> temperature produced a hogging deflection of one inch. The water temperature was constant at 70 F. The air temperature just above the deck plating was frequently found to be as high as 116 F. Temperatures of the hull plating were not measured.

Strain measurements were made at a point six inches outboard from the hatch corner. An interesting observation was that the observed thermal strains were greater in the athwartships direction than in the fore-and-aft direction. If the deck plating is assumed to have had the same temperature as the air just above it, namely 116 F, the change in strains at this point between 1500 and 2300 would correspond to thermal stresses of about 6600 psi in the fore-and-aft direction and 2200 psi in the athwarthships direction. While the observed thermal strains were larger in the athwarthships than in the fore-and-aft direction, the magnitudes of the thermal stresses were in the reverse order.

On the S. S. OCEAN VULCAN[54], a dry-cargo vessel and a welded sister ship of the S. S. CLAN ALPINE, a maximum thermal stress of 700 psi was developed by a temperature difference between bottom and deck plating of 4 F. The observations were

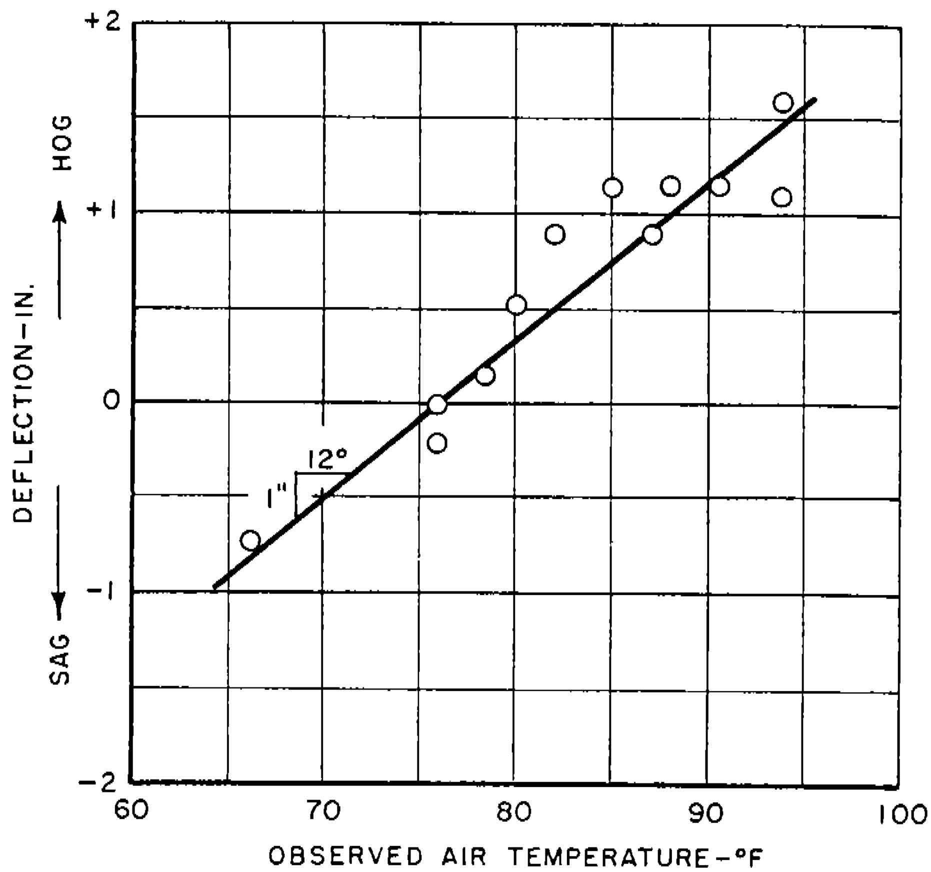


Fig.19. Comparison of Deflection of Hull Girder and Observed Air Temperature. Water Temperature, 70 F. S.S. PHILIP SCHUYLER. (Vasta)

made at Frame 84 just forward of the midship deckhouse. The conditions prevailing at the time of the test were not given in the report[54].

2. Observations on a Ship with Weather Conditions Unknown. Jasper[53] reported thermal stresses in a T-2 tanker at sea. These were observed at two stations, on the port and starboard stringer plates, 7 in. from the gunwale and amidships. This writer was unable to correlate the results of this investigation with those of previous investigations[5,10]. Moreover, the pattern of thermal stresses bore little resemblance to those shown in Figs. 10--14, inclusive. The greatest diurnal variations in thermal stresses which occurred in any 24-hr period were -10,900 psi at the gage on the port side and 1000 psi at the gage on the starboard side. These maximum stress variations occurred in the period prior to time 1500.

It is difficult to correlate these data with those of past investigations for the reasons which follow. The maximum air temperature was approximately 75 F; the minimum was not reported. The weather conditions and the heading of the ship during the time of the observations are not described. If the sun were out, it would have shown on the entire midship portion of the deck, no matter what the heading of the ship. For this condition, a difference as great as 10,000 psi between the port and starboard sides of the deck would not be expected, as Jasper[11] himself has shown. He computed thermal stresses for essentially this condition, using a maximum temperature difference in the hull of 70 F and obtained stresses at these points of -3700 psi and -1400 psi. On the other hand, if the sun were not out, the stress variation in the deck would be very small, as Figs. 4 and 5 indicate, regardless of the difference between the air and water temperatures. The writer is therefore of the opinion that the stresses reported are not of the magnitude of the nominal stresses which could be expected and either reflect the effect of stress concentration or include stresses which are not thermal in origin. He also expresses the hope that these data can either be substantiated or corrected by the investigator, as they are the only thermal stress data for a ship at sea over an extended period of time.

3. Observations on Refrigerated Ships. All but one of the observations just presented entailed atmospheric conditions where the air temperature was greater than the water temperature and the interior of the ship was free to seek its own temperature level. Howe, Boodberg, and O'Brien[5] report temperatures and thermal stresses developed in the C-2 refrigerated ship S. S. GOLDEN ROCKET when the hold temperature was reduced from 100 to 10 F. Unfortunately, the stresses were in error as previously noted. The heading of the ship was 17° true. With a temperature of 10 F in the holds, of about 63 F for the water, and approaching 70 F for the air, a maximum temperature of about 113 F was developed in the deck in mid-afternoon on

a very humid July day. In fact, the morning skies were overcast. The diurnal variation of temperature in the hull plating was very similar to that shown in Fig. 10. The tremendous temperature difference between 113 F in the main deck and 10 F in the second and third decks should be noted. The temperatures of the other portions of the hull girder lay between 63 and 113 F. These gradients would cause very large thermal stresses.

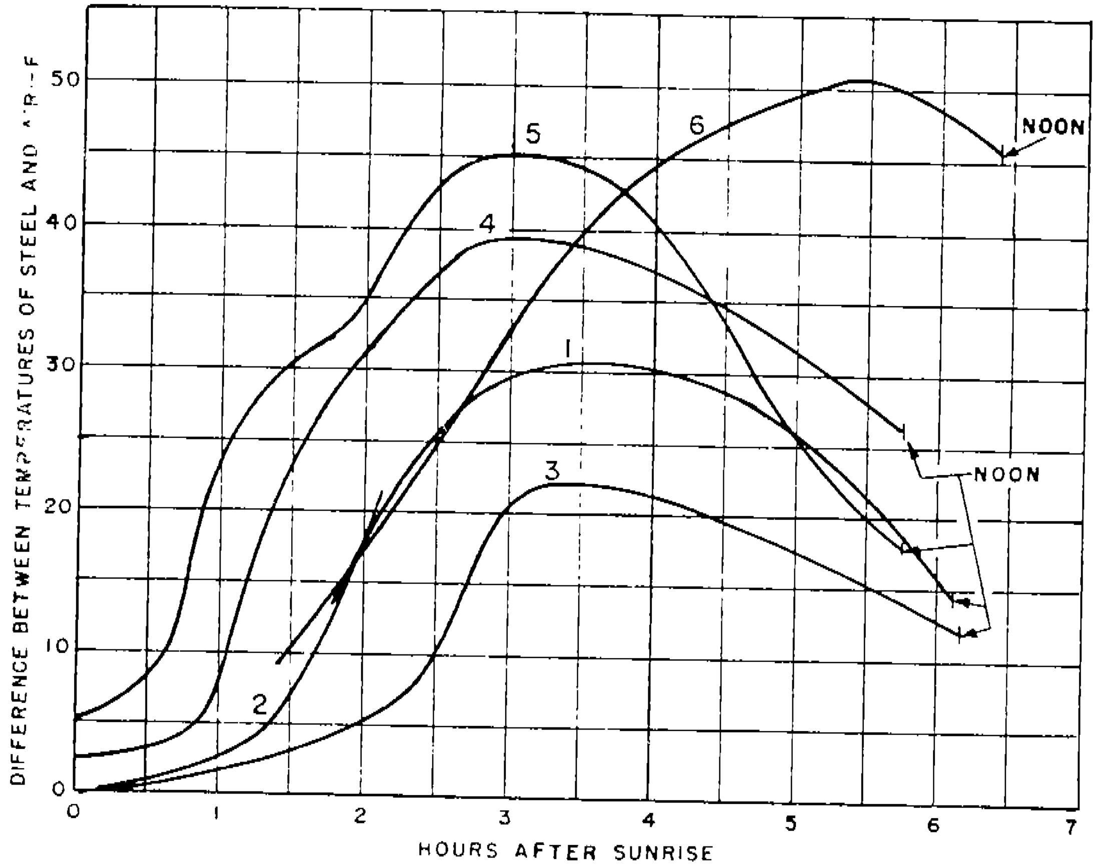
4. Summary of Maximum Temperatures and Thermal Stresses. Table I summarizes the maximum hull temperatures and thermal stresses found in the ship tests. All maxima occurred in the middle of the day. Most of the tests were made during the spring months. The amount of insolation ranged from a minimum under full cloud cover to maximums at Berkeley, California, and Wales, United Kingdom, in mid-summer. None of the observations were taken at times of very intense insolation. Therefore, the maximum temperature difference of 73 F between bottom and main deck plating is probably less than the maximum possible.

Since these tests were made to determine the effect of insolation, the maximum stresses were compression and occurred in the main deck or the side shell in or adjacent to the sheer strake. Thermal stresses of 5000 to 11,000 psi were found in five ships when the maximum temperature difference ranged from 46 to 73 F. These stresses are of too large a magnitude to be ignored.

Full-scale ship tests have not been made under the condition prevailing during many ship casualties: cloudy skies and air temperature below that of the water.

5. Effect of Insolation on Side of Vessel. A number of ships have sustained serious fractures in mid-winter when the early morning sun shone upon the side of the vessel. These failures will be discussed in a subsequent section of the report. However, at this point the data from a number of ship tests will be examined to see how rapidly the side of the vessel is heated by the morning sun.

The analysis presented in Fig. 20 was developed by determining the difference between the temperatures of the side shell plating and the air at intervals after sunrise. The table on this figure gives the conditions under which the data were observed. Fig. 20 would indicate that, when the sun had risen above the low-hanging fog on the horizon, the temperature of the side shell plating would exceed that of the air at a rate of 20 to 45 F per hour. These rates of heating are significant because in these tests there were present atmospheric conditions which would keep the amount of insolation below that prevailing on very clear winter days. Moreover, the sun would rise more slowly in the winter than in April and May and therefore strike a vertical surface at angles near normal incidence for a longer period of time. It would appear logical therefore to conclude



Curve No.	Ship	Date	Approx. Latitude	Approx. Heading of Ship	Location of Ship	Remarks
1	Sharon	5/24/45	38° N	S	At Dock)	
					)	High fog
2	Sharon	5/25/45	38° N	S	At Dock)	Side of ship
					)	partly shaded
3	Sharon	5/27/45	38° N	S	At Dock)	
4	LST	4/8/45	42° N	S	At Dock)	Scattered high
					)	clouds
5	LST	4/9/45	42° N	S	At Dock)	Side of ship
					)	partly shaded
6	Duisberg	4/1/39	52° N	W	At Sea)	Fog 6 hrs. after
					)	sunrise

Fig. 20. Observed Effect of Insolation on Side Shell Plating during Early Morning Hours.

that greater rates of heating could occur under clear skies on winter mornings.

6. Deflections of the Hull Girder Resulting from Insolation. Various investigators have attempted to relate the maximum hogging deflection of the hull girder to the maximum temperature difference between the main deck and bottom plating. A summary of their results appears in Table II.

The writer first applied Eq. (1) of Appendix A to these data and found that the temperature difference causing a 1-in. deflection was not related to the quantity L^2/D, where L is the length of ship and D its depth. Hurst[3] points out that the deflection of the hull girder may be computed directly from the "virtual temperature" distribution on the hull cross section, the portion of the temperature change which produces thermal strains, but no thermal stresses. The virtual temperature line must be computed from the temperature distribution on the cross section. It can be seen therefore that the deflection of each hull is an individual case and that it can be related to the length of ship and the molded depth in only a general way. Hurst[3] indicates that the equation for the deflected position of the hull is

$$y = \iint_{L=0}^{L=L} \frac{\alpha(T_{v,\,Top} - T_{v,\,Bot})}{D} \, dL \, dL. \qquad \text{(d)}$$

The virtual temperature S/T_V, Top and T_V, Bot. are those at the top and bottom of the beam.

It should be pointed out that thermal deflection curves are not usually smooth or almost symmetrical, as are those resulting from hogging or sagging tests. Fig. 21 shows the diurnal deflections of two dry cargo ships, the S. S. WILLIAM SHARON and the S. S. GOLDEN ROCKET[5]. The first had a heading of south and the second of 17° true. The shading of the midships deckhouse probably accounted for the irregular shape of the deflection curves in Fig. 21 and probably also for a part of the variation in deflections indicated in Table II. This surmise is strengthened by the smooth symmetrical deflection curves obtained for a bare hull with no deckhouse[55].

7. <u>Summary of Information on Temperature and Thermal Stress Gradients in Ships</u>. The temperature gradients found in a number of ships have been described. In many cases these were taken as an afterthought in connection with hogging and sagging or seaway tests and are inadequate to give a clear picture. All the observations but one took place when the air temperature was higher than the water temperature and solar radiation warmed the region of the hull exposed to it. No information was found where the air temperature was much lower than the water temperature and the sun was heavily blanketed by clouds. This latter weather condition has accompanied most brittle fractures in ships.

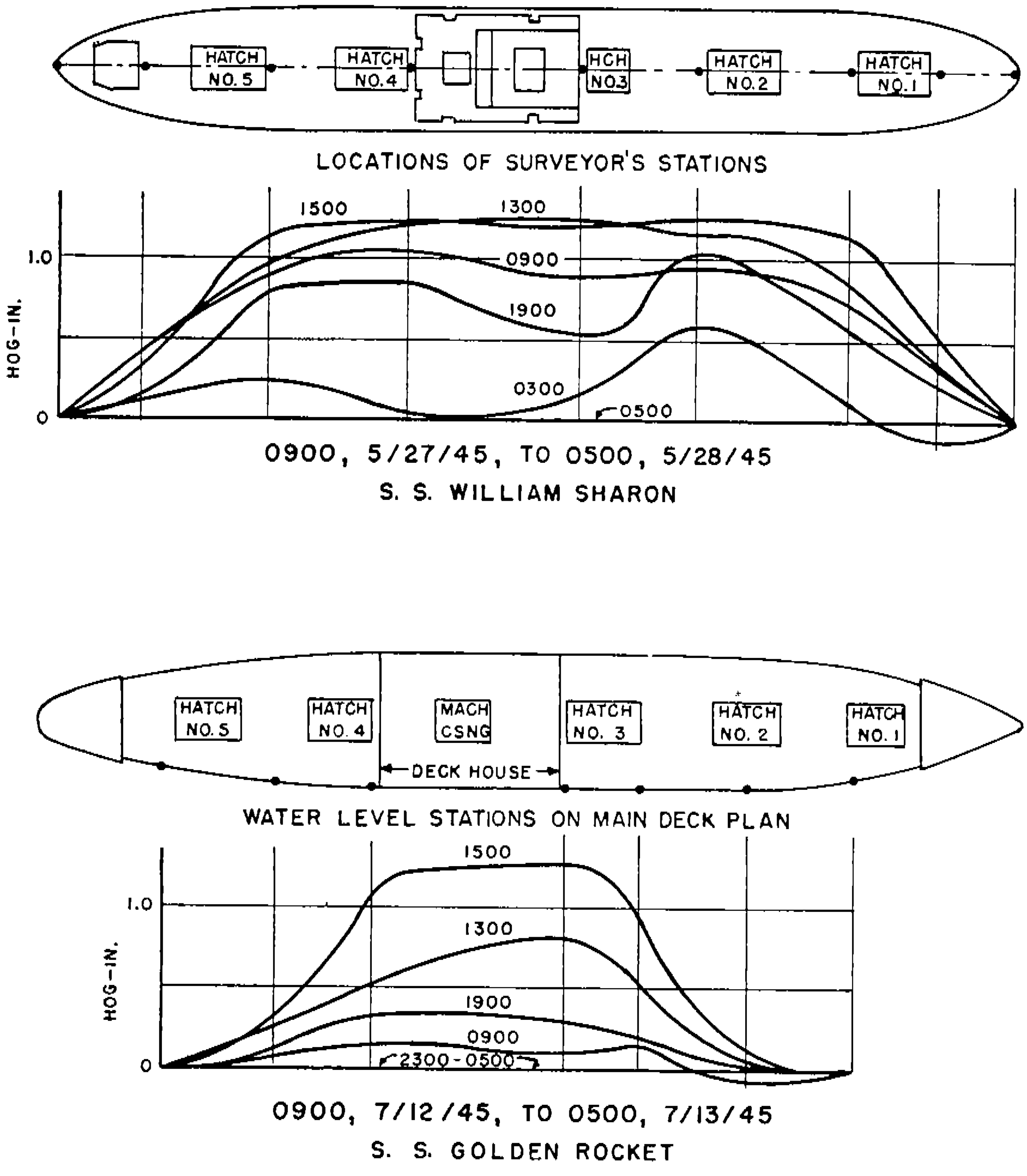


Fig. 21. Diurnal Deflections Observed in Two Ships (Howe, Boodberg, and O'Brien).

None of the investigators except Vasta[52] placed gages at points where stress concentration would be expected. Also, the thermal stresses were computed on the assumption that temperature change caused only fore-and-aft stresses. Thus the stresses reported are more likely to be equal to the nominal instead of the actual stresses.

The diurnal pattern of the temperatures and the thermal stresses as a result of solar radiation was clearly shown. Just after sunrise when the sun strikes the side shell of the ship on one side, the deck being shaded, the portion of the side shell above the water is restrained by the cooler deck above and the underwater shell plating below; and compression stresses which may be fairly high are developed. This condition tends to place the adjacent part of the deck in tension and to lock up energy which could be released to propagate a fracture across the deck if such a fracture were initiated by other causes. Examples of this type of failure were found among the ship casualties.

As the sun's rays strike the deck, it expands and develops compression stresses with tension stresses appearing in the upper side shell strakes. As the sun is about to set, the stresses are similar to those occurring just after sunrise except for being reversed from port to starboard. Moreover, because the deck is relatively warm, the stresses in the side shell are much lower than those in the early morning. The lack of symmetry in the temperature distribution at all times except in the middle of the night would of itself tend to increase the magnitude of the thermal stresses.

Most of the observations were made in the spring on hazy days when the temperature differential developed in the hull was not very great. The maximum of 73 F is probably smaller than is possible under severe solar radiation. The effect of black paint in intensifying the temperature differences as noted by Corlett(4) indicates that a spot of black paint or similar heat-absorbing material or a shaded spot is a potential stress raiser. The rapid cooling caused by shade is shown in Fig. D-3 of Appendix D.

The magnitudes of the thermal stresses appearing in Table I and those indicated by the stress distributions in Figs. 2--7 are appreciable. When it is realized that these are nominal stresses and that higher stresses would exist at points of stress concentration such as openings and right-angle junctions with other members, it would appear that thermal stresses can be large enough to merit earnest consideration in the design of a ship.

The high thermal stresses which would result from lowering the hold temperature in a refrigerated ship are indicated by the large temperature gradients found in the hull of a refrigerated ship.

The early investigators concluded that the thermal deflections of the hull of a cargo ship were not large enough to have any appreciable effect on the drafts of the ship, except in the case of Great Lakes ore carriers. Later observations would not appear to alter this conclusion.

VI. THERMAL STRESSES AND BRITTLE FRACTURE IN MERCHANT SHIPS

1. Sources and Nature of Information Used in Analysis. A number of reviews of brittle fracture in ships[40--43, 55, 57--62] have appeared. These are excellent sources of information which have been drawn upon heavily in this investigation of thermal stresses. The writer has also had the assistance of files of ship casualties[39] and conversations about particular failures and the problem in general with many persons. The results of the analysis of this information follow.

Reference will frequently be made to Appendix E, which contains a brief summary of the circumstances under which a number of ship casualties have occurred. These have been selected as cases where thermal stresses would appear to be an important factor. The material in this appendix has been developed from the sources just mentioned.

The four reports of casualties[40--43] list 250 Group I casualties. In less than half of this number, the writer found enough information to permit some sort of appraisal of the causes of the failure. About fifty cases were selected where thermal stresses would appear to be significant. Another ten cases, where less information was available, occurred under similar circumstances. It is interesting that in approximately 50 out of 125 cases, or around one-third to one-half of the sampling of cases with which the writer worked, circumstances prevailed which would produce thermal stresses of sufficient magnitude to be an important factor in the failure.

The larger part of the ship casualties have occurred under heavy weather. However, the term "heavy weather" is used to describe quite a range of intensities of wind and sea. Some of the failures were undoubtedly the result of heavy weather alone, but most of the so-called heavy weather failures would appear to entail other factors, one of which was thermal stresses.

2. Temperatures Prevailing at the Time of the Casualty. In the study of thermal stresses as related to ship failures, the investigator is faced with the fact that reduced air temperature is likely to increase the temperature difference $T_W - T_A$, but it also increases the tendency towards brittleness in the steel. The analysis in Fig. 22 was developed to study these two trends. All the ships covered by this analysis were built in or prior to 1945 and therefore were constructed of wartime steels. The data were found in References 40--43.

The upper plot in Fig. 22 gives the frequency of fracture at any air temperature for casualties of different severity.

The shapes of the curves for the Group I and combined Group II and III casualties are similar, but the curve for the former is displaced about 10 F lower on the temperature scale than that for the latter. When there is considered the fairly wide range of operating temperatures in which the wartime ship steels of shell plating thickness could exhibit brittleness, this 10 F difference does not appear to be of great significance. It would seem that air temperature was not the only important factor in determining the severity of the fracture.

The lower plot in Fig. 22 relates the temperature gradient to which the ships were subjected with the frequency of casualties of different severity. The Group II and III casualties were most frequent when the temperature gradient was close to zero. The Group I casualties were most frequent when the air temperature was lower than that of the water by around 8 F. This difference may seem small until it is realized that temperature gradients of 20 F or more are rather infrequent in ships at sea. As cracks usually occur at points of potential danger, it is more often the length of the crack rather than its location in the structure which determines the classification of the casualty. The presence of a temperature gradient, and therefore thermal stresses, would appear to support the conclusion that thermal stresses tend to encourage the propagation of a fracture and increase its severity.

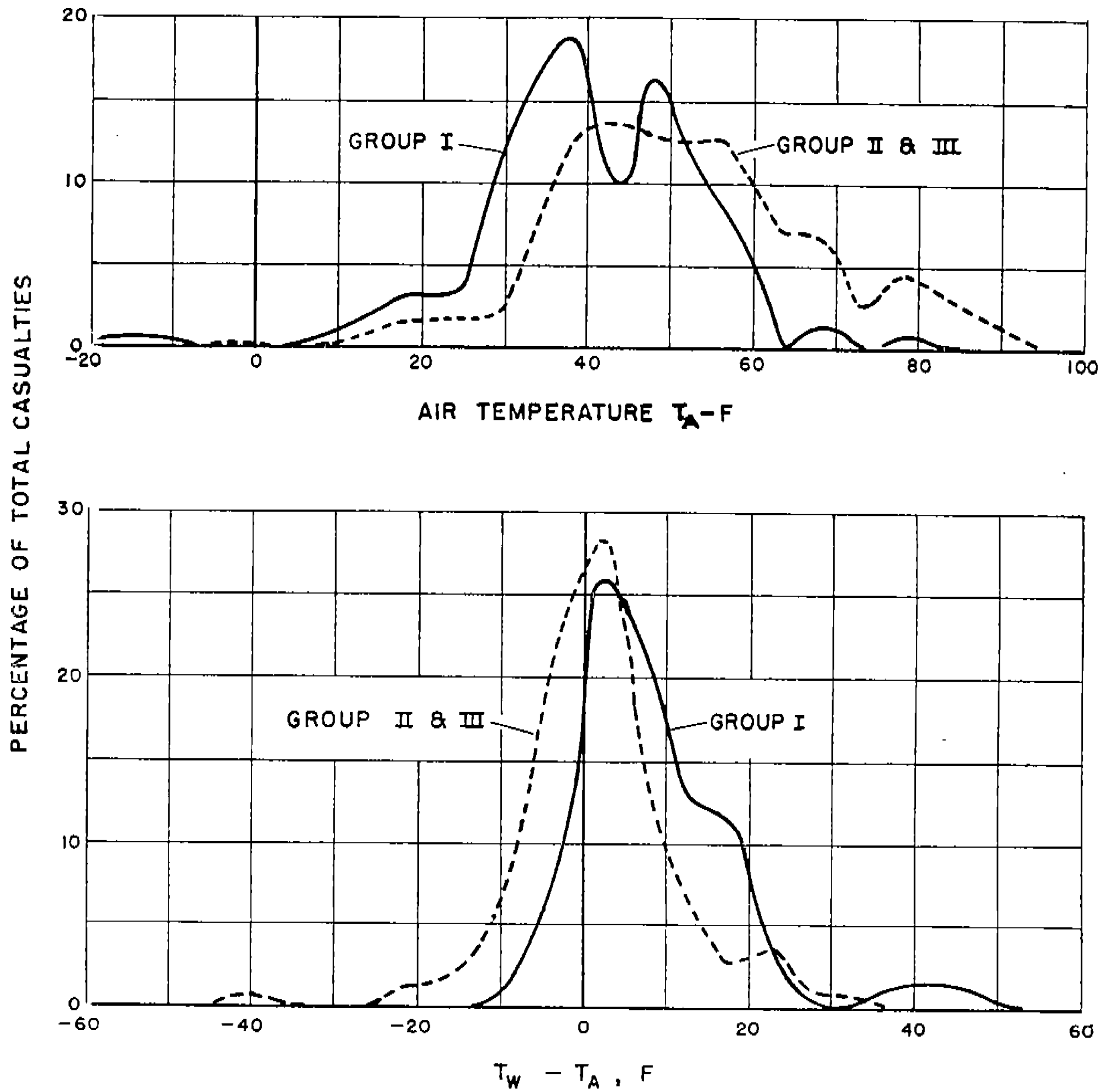


Fig. 22. Air Temperature and Temperature Gradient at Time of Fracture. 122 Group I Casualties through March, 1952. 334 Group II and III Casualties through July, 1945.

The thermal stresses in Figs. 2--6, when combined with bending stresses of the same sign, would tend to maintain high stresses in the hull for some distance in from the extreme fibers in bending. When this combination of stress is tension, the conditions would be present for continuation of propagation of a fracture.

Tables V and VI list cases of Group I fractures for which temperature data were available.

Temperatures of the air and water are ordinarily logged every four hours. The water temperatures recorded in the casualty lists[39--43] were sometimes higher than the location of the ship and the prevailing sea water temperature[68] would indicate as the probable one. In some cases this difference can be attributed to the variation between the actual sea and water temperatures and the long-time average reported in the isothermal charts. The reported temperature was probably the one observed at the latest four-hour interval preceding the time of the castualty.

3. Classification of Thermal Stress Effects in Connection with Ship Casualties. The role of thermal stresses in connection with brittle fracture is not entirely clear. However, there is a fairly large number of low-temperature casualties where they appear to have played a significant part in the initiation and propagation of the fracture. The circumstances attending these casualties can be classified as follows:

1. Localized artificially induced temperature change.

   A. Heating of fuel oil in the double bottom of transversely framed ships.

   B. Heating of liquid cargo in tankers.

   C. Cleaning with boiling water of liquid cargo spaces in tankers.

   D. Refrigeration of cargo spaces in dry-cargo ships.

   E. Loading or discharging of liquid cargo or water ballast.

2. Rapid change in water temperature.

3. Rapid change in air temperature.

4. Temperature of air well below that of water.

5. Sunshine on the side of the vessel only in northern latitudes on winter mornings.

6. Combinations of any of above five circumstances.

7. Heavy weather coupled with any of above conditions.

Examples of these various types will be discussed.

4. <u>Ship Casualties Associated with Localized Artificially Induced Temperature Change</u>. A fairly large number of Group I and II casualties have developed shortly after or during the heating of fuel oil or liquid cargo or the washing with hot water of tanks in tankers. Since other conditions surrounding the ship often remained constant, the inference would appear to be that thermal stresses raised the total stress level to the point of failure.

A Liberty ship[65], Casualty No. 147, was entering Schelde River in Belgium from the somewhat warmer waters of the North Sea and developed fractures in the shell plating around both bilges and into the tank top on the starboard side in the way of No. 5 deep tanks. Oil was being heated in these tanks for discharge.

Heating of oil to 115--120 F in the double bottom of the Victory ship sustaining Casualty No. 229* resulted in a 66-ft fracture across the bottom plating in the way of the heated tank. The fracture occurred shortly after the ship had gotten under way. While at the pier, the water around the heated area was probably also warmed, but when the ship was in motion, it moved into colder water and the temperature gradient in the hull was increased.

Casualty No. 244* and Casualty B* occurred under similar circumstances as described in Appendix E.

The heating of oil cargo was a circumstance present in the case of fifteen Group I casualties in tankers. The temperature of the oil usually falls in the range of 90--135 F. Since the temperature of the wing tanks is fifteen to twenty degrees lower than that of the center tanks, thermal stresses are induced in the hull because of this difference as well as

*Casualty numbers or letters followed by an asterisk are those for which the circumstances surrounding the failure are given in Appendix E.

by the large differences between the oil, water, and air temperatures. The temperature in the wing tanks being lower than that in the center tanks would tend to put tension stresses in the shell in the region of the bilges. It is in this location that most fractures have occurred in tankers. These combine with the horizontal and vertical bending stresses in the bilge area. In a loaded tanker, the stresses in the bottom caused by vertical bending are usually tensile.

Casualty Nos. 118 and 225* in light weather and Nos. 77* and 239* in heavy weather are typical cases of the above kind of failure where the air and water temperatures were fairly constant for the period preceding the fracture. Casualty Nos. 110, 226*, and 232* in light weather and Nos. 108, 112*, 189*, 205, 233*, and 238* in heavy weather took place with the additional circumstance of changing water temperature. Since the combination of heating oil and changing water temperature was found to be so frequent a circumstance in the failure of tankers, it will be more fully discussed in a later section.

One of the effects of heating oil is to cause the longitudinal framing in the hull to attain a different temperature from that of the shell to which it is attached. The effect of this temperature difference is illustrated by the fourteen cracked longitudinals found in the vessel suffering Casualty No. 233*.

Three Group I casualties in tankers, Nos. 48, 90*, and 211, occurred while cleaning cargo tanks with hot water. Water at

210 F was being used when Casualty No. 90* occurred, and frequent mention of this temperature was found in other records. The recommended wash water temperature[67] in only 165--185 F. It is also recommended[67] that adjacent tanks be washed one after the other so that the heat from one helps to warm and adjacent one, that the tanks be pumped steadily so as to keep the bottom as free as possible of the slops, and that the cleaning be done at sea where the slops can be pumped overboard. These three factors--the intense heating of one part of the hull, the pumping of the tanks which permits the bottom plating to be chilled, and the greater cooling effect of the water moving past the hull when the ship is at sea--combine to increase the temperature gradients in the hull.

The large temperature gradients set up in the hull of a refrigerated ship were demonstrated by full-scale tests[5] described in a previous section of this report. Acker[55] has compared the locations of the fractures in C-2 cargo and C-2 refrigerated ships. A summary of his study is shown in Fig. 23. The absence of cracks in the second deck of cargo vessels and their prevalence in this deck in refrigerated vessels is easily explained by the low temperature at which this deck is held. Since the surrounding hull structure is insulated and is considerably warmer, this deck must contain high tension stresses. On the other hand, the tension stresses in the second deck would work to place the surrounding hull structure in compression.

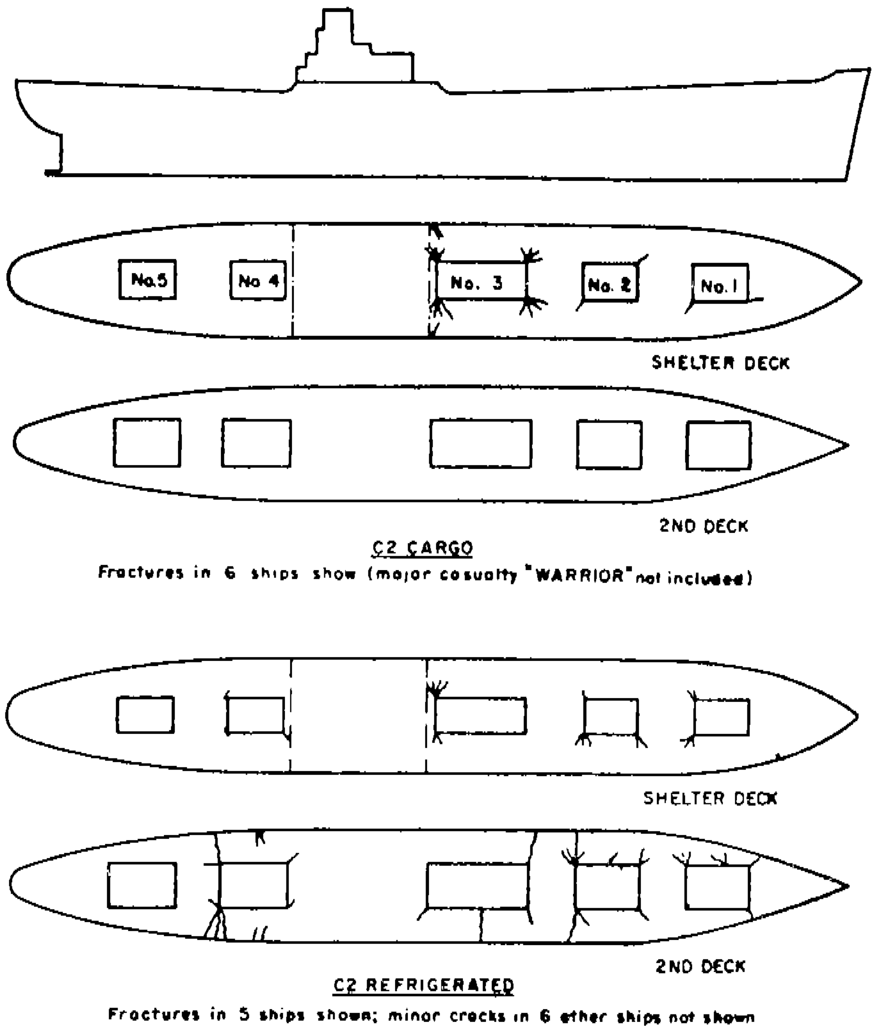


Fig. 23. Location of Deck Fractures in C2 Cargo and C2 Refrigerated Ships.

Only two Group I casualties, Nos. 158* and 244*, were found in refrigerated ships, and one, No. 8*, in the way of a refrigerated space. Other factors seemed to be important in these failures, and the temperature gradients produced by refrigeration of lesser significance. However, the continual occurrence of minor fractures in the 'tween decks as shown in the record of Casualty No. 158* was found to be duplicated in the cases of a number of other ships. It would seem that thermal stresses have been an aggravating factor in refrigerated ships rather than a danger.

The discharging or loading of heated cargo oil or the taking on of water ballast were connected with seven casualties. Group II casualties occurred in two tankers loading oil and one unloading oil; and Group I casualties, Nos. 123* and 124*, occurred in two tankers unloading oil. Taking on water ballast just preceded two Group I casualties, Nos. 25* and 240. In the latter the fracture occurred in the tank adjacent to the ballasted tank.

5. Ship Casualties Occurring after A Rapid Change in Water Temperature. A rapid change in water temperature was found to be associated with more casualties than any other type of temperature gradient. It was found that the geographical location of the ships at the time of failure was frequently in a region where the surface water temperature changed considerably over a relatively short distance.

One such region is the confluence of the warmer Gulf Stream and the colder coastal waters along the Atlantic Coast of the United States and Canada in the midwinter months. Ships sailing across the Atlantic or on route to coastal ports from the Caribbean Sea experience this change in temperature. Table III lists the temperatures experienced on a trans-Atlantic voyage by the ship sustaining Casualty No. 171*. The rapid rise in temperature upon entering the Gulf Stream on January 11 on the eastward voyage and leaving it on February 9, the day before the failure, are shown by this table. Two ships, those sustaining Casualty Nos. 110 and 232*, reported drops of water temperature of 21 F in the four hours and 27 F in the six hours just preceding failure while leaving the Gulf Stream.

A plot of the location of ships sustaining Group I casualties was made, and thirty-seven were found to have occurred in this area. The locations of these ships, the mean surface water isotherms, and the harbor water temperatures for the month of January are shown in Fig. 24. Since this area of the world's oceans is the only frequently navigated region where a change of 25 F in water temperature takes place in two to three hundred miles and because ship failures in all other ocean areas occurred in random locations, this belt of ship failures would appear to be closely linked with this unusual and large change in water temperature. Table IV gives pertinent information on the casualties noted on Fig. 24 and includes fifteen tankers and twenty-two dry-cargo vessels.

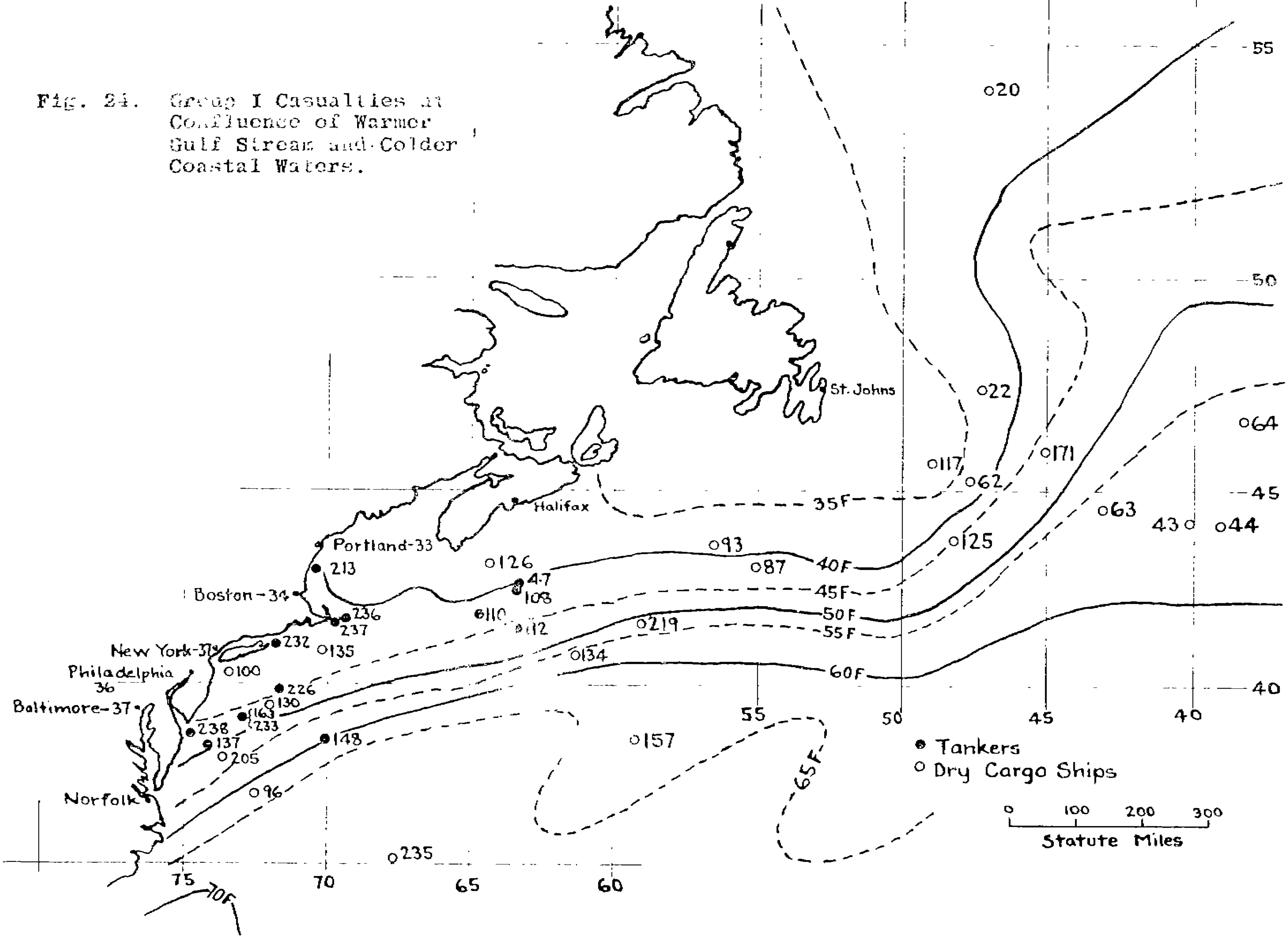


Fig. 24. Group I Casualties at Confluence of Warmer Gulf Stream and Colder Coastal Waters.

The combination of heating cargo oil and experiencing a drop in water temperature was a common cause of failure in fully loaded tankers. Such failures include Casualty Nos. 110, 226*, and 232* in light weather and Nos. 108, 112*, 163*, 205, 233*, and 238* in heavy weather. No data were found to indicate how many of the other tankers listed in Table IV were heating cargo oil also. Most of the American tankers sailing the Atlantic load oil in the Caribbean Sea area, follow the warm Gulf Stream waters northward to a point near their destination, and then cross from the warm waters into the cold coastal waters in a rather short period of time.

Other fully loaded tankers suffering failures in this area included Casualty Nos. 47, 137*, 148, 213, 236*, and 237*. The last two were cases of ships that broke in two. It is interesting that no Group I casualties were found in tankers traveling southward in ballast in this region.

Besides the Liberty ships sustaining failures at the edge of the Gulf Stream, others which failed in coastal waters include Casualty Nos. 2 and 7 near Cape Horn, 18 off Norway, 34 and 35 off East Greenland, 31 approaching Tasmania, and 39 and 45 off the Aleutian Islands.

The rapid change in water temperature occurring when a ship enters or leaves a harbor or river mouth has also been a significant factor in ship failures. Casualty No. 128* occurred to a T-2 tanker entering Boston Harbor, No. 49 to an outbound Liberty ship at the mouth of the James River estuary, No. 24 to an outbound Liberty ship five miles out of Dutch Harbor, Alaska, No. 209 to a tanker at the mouth of the St. Lawrence River, and No. 239* just outside of Golden Gate. Two T-2 tankers, those suffering casualty Nos. 212* and 227*, were just entering the mouth of the Columbia River. In the latter case the river temperature was reported to be 10 F lower than that of the ocean.

6. Ship Casualties Occurring after A Rapid Change in Air Temperature. Rapid change in air temperature was associated with Casualty Nos. 13*, 15, 95*, and 101* which occurred under falling air temperatures in ships moored or anchored in still water, and Nos. 137* and 187* in heavy weather. The drop in air temperature ranged from 15 to 35 F.

7. Insolation on the Side of the Vessel. Three failures of ships were found where the fracture occurred shortly after the sun had risen and shone on the side of the ship. All of these failures took place during the winter on clear days in New York or Boston. In all instances the fracture was originated near the gunwale of the ship on the side opposite that warmed by the sun. Casualty Nos. 16* and 17* occurred on the same morning in New York to two Liberty ships, and No. 155* to a T-2 tanker[63] which broke in two in Boston (see Fig. 25).

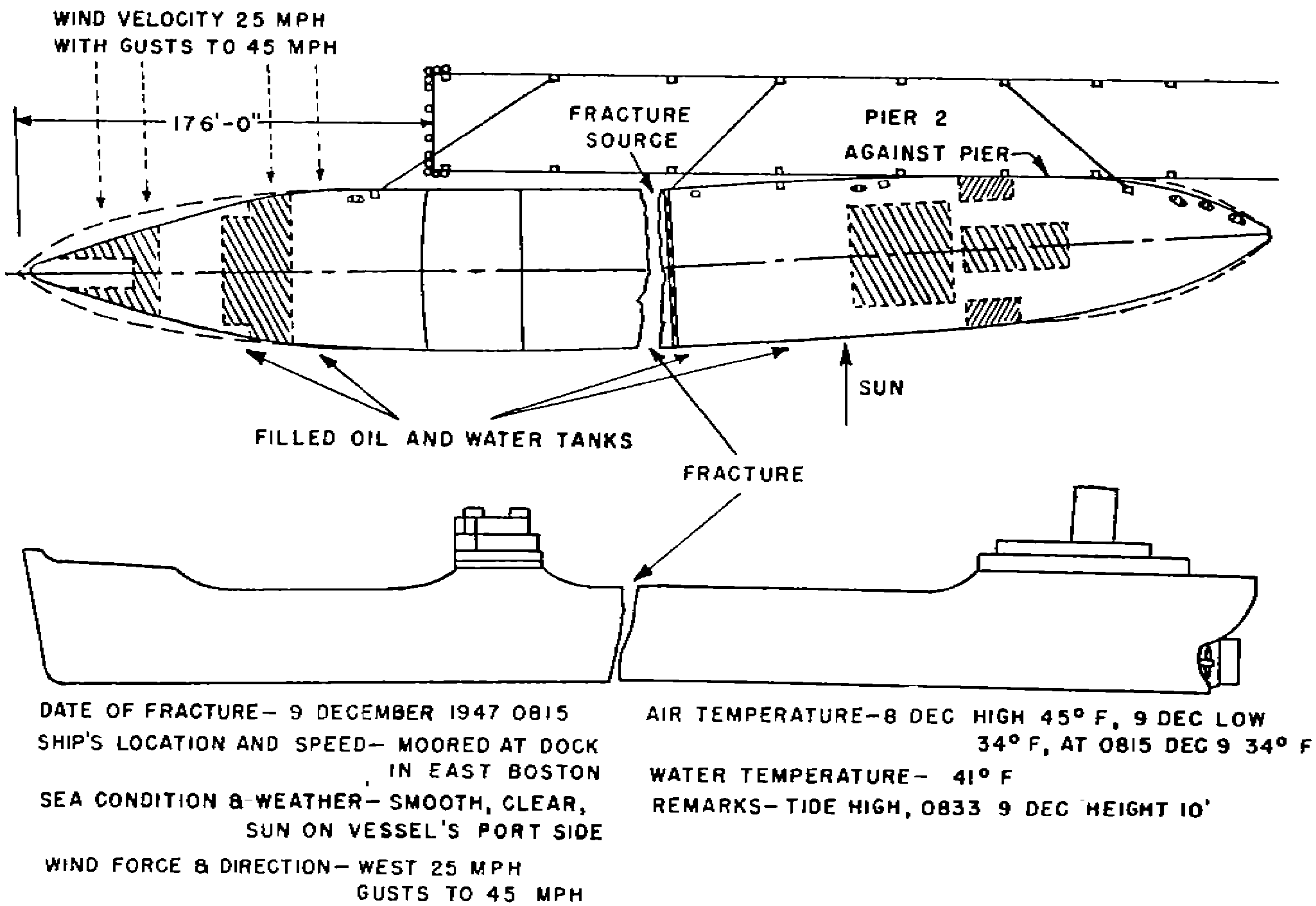


Fig. 25. Conditions Surrounding the Brittle Fracture for Casualty No. 155.

The observations in Fig. 20 indicate how quickly the side of a ship can be heated.

The conditions under which Casualty No. 155* occurred are interesting. The vessel was loaded forward and aft in a manner which placed the midships deck in tension. The hull girder was also bent horizontally by the combined wind forces and moorage in a manner which developed tension stresses amidships in the starboard side shell. The combined effect of the vertical and horizontal bending moments produced the maximum tension stresses at the starboard gunwale where the brittle fracture had its source in a crater in the weld joining a chock bracket to the deck. However, the fracture traveled across the deck and completely down both sides of the ship. The tanks in the vicinity of the fracture were empty.

The possible contribution of the energy locked up in the hull by thermal stresses in the sun-warmed port side shell in propagating the fracture should be considered. Fig. 25 indicates that the fracture occurred at 0815 and that the water temperature was 41 F and the air temperature 34 F. The data in Fig. 20 indicate that the port side shell may have attained a temperature of 80 F. Figs. 4 and 7 show that the thermal stresses in the deck for the above conditions would be small, but the compression stress in the side warmed by the sun might approach 6000 psi. The writer suggests the following explanation of this failure.

This compression stress would cause this region to store energy in the manner of a compressed spring, the colder deck and bottom of the ship supplying the restraints which would prevent the expansion of the side shell. It is likely that the symmetrical nature of the fracture, which was initiated at the starboard gunwale and traveled across the deck and down both sides of the vessel, was made possible by the energy stored up as a result of the thermal stresses in the port side shell. This conjecture does not ignore the fact that the hogging moment produced by the loading of the ship was also a factor in producing a symmetrical fracture.

8. Location of Fractures Involving Thermal Stresses. Figs. 2--6 indicate that tension thermal stresses of appreciable magnitude are developed in the side shell of the ship when the skies are cloudy and the air temperature is lower than that of the water, while the thermal stresses in the deck are low in magnitude. The combination of this thermal stress distribution with the bending stresses resulting from a hogging moment would tend to initiate and propagate fractures in the vicinity of the gunwale. The analysis in Fig. 26 was made to determine whether the location of the origin of the fracture was dependent upon the temperature difference $T_W - T_A$. This figure indicates that, as this difference increased, the incidence of fracture origin in the vicinity of the gunwale increased sharply. The casualties listed in Table V were used for this analysis.

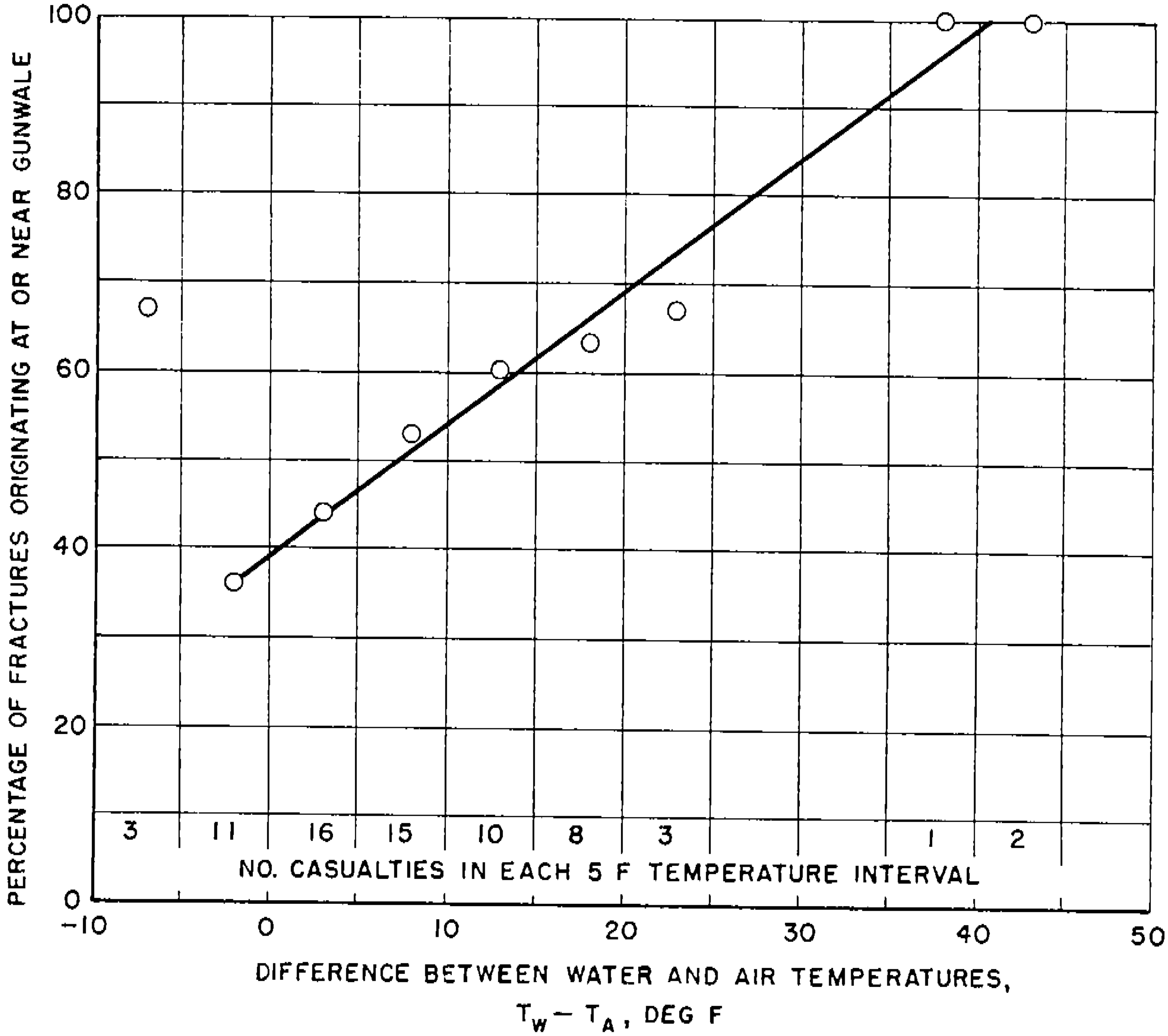


Fig. 26. Analysis of Group I Casualties where Fracture Originated Either at Hatch Corner or at or Near Gunwale.

9. Summary. This section of the report has presented ship casualties in which thermal stresses appeared to be an important factor. Usually other factors also played a part in the failure.

Still-water failures occurred under falling air temperatures when the difference between the temperatures of the water and the air ranged from 15 to 35 F and all other conditions remained constant. Heavy weather reduced the temperature difference necessary to produce failure. Decreasing water temperature was also the cause of a number of failures and was an important factor in the failure of tankers. Localized thermal stresses from heating fuel or cargo oil, washing tanks in tankers, refrigerating the holds, or loading or discharging heated cargo oil also were found to have contributed to failure. The rising sun shining on the side of a vessel in northern latitudes in mid-winter was associated with three still-water failures. About one-third to one-half of the casualties for which the writer found sufficient information to make an analysis appeared to involve thermal stresses to a significant degree.

VII. RECOMMENDED TESTING PROCEDURE FOR OBSERVING TEMPERATURE EFFECTS IN SHIPS

1. General Comments. The writer has formed the following opinions about the testing procedure to be used in full-scale tests of ships for the purpose of observing thermal effects.

Two types of vessels should be tested: the transversely framed dry-cargo ship and the longitudinally framed tanker. For the first tests the heading of the ship should be kept at approximately 90° to the azimuth of the sun at sunrise, and the tests should extend over a period embracing the months of July through December or December through June. The ship should be located so that no surrounding structures will shade it and so that there are about 1000 feet of open water on either side. The water temperature should not vary more than 5 F in any one day.

Thermocouples and strain gages should be installed on four cross sections of the ship spaced within the middle half of the length of the vessel. A minimum of thirty gaging stations on each cross section is necessary. The gages should not be covered by boxes or other coverings which would produce a shaded spot. The gage readings should be recorded continuously along with the observations of the air temperatures in the shade and in the cargo spaces and the insolation on surfaces parallel to the deck and to the two sides of the ship. The deflections of the hull at seven or more stations along the length should be read at hourly intervals.

Weather data should include hourly observations of the relative humidity, cloud conditions, and wind velocity and direction.

Careful observations of miscellaneous conditions affecting the readings include such items as shaded areas of the hull, wave height, and tides. A competent engineer should be in attendance throughout 24-hour periods on a sufficient number of days to obtain a complete picture of the diurnal and seasonal variations.

The observations should be taken in such a manner that apparent anomalies in the data can be explained. Fancy gaging arrangements which electrically combine the readings of more than one gage should be avoided, as one bad gage can nullify the readings of the other gages.

The shortcoming of previous tests has been the failure to take enough data to provide a reasonable explanation of the nature of the experimental observations.

Model testing has been only moderately successful in the field of thermal stresses. If the dimensions of the prototype are N times those of the model, the temperatures generated in the model must be N^2 times those in the prototype[70]. The very steep gradients necessary in the model because of the above fact can usually be maintained in only a transient state of heating. The best model would be one made of a material with a low coefficient of thermal conductivity. Such a model may therefore be impractical.

VIII. CONCLUSION

The most important finding of this investigation was the observation that conditions which would produce thermal stresses of moderate to severe intensity were present in the case of one-third to one-half of the sample of ship failures studied. Since this sample was entirely random, it is possible that many other failures, were their full story known, would be found to be connected with thermal stresses in some manner.

The writer feels that consideration should be given to further improvement in the design of structural details and in the operating procedures for tankers. Thermal stress failures may occur in locations where the load stresses are small, as well as in other locations where load stresses are large. Large temperature differences producing appreciable thermal stresses in critical regions of the hull can be caused by heating cargo oil and cleaning empty tanks. Some attention to a better design of the arrangement for heating fuel oil in the double bottom of a transversely framed ship also appears desirable.

While the number of severe casualties in refrigerated ships is very small, here too further consideration of the design of structural details could reduce the number of minor fractures which are always potential origins of a serious casualty.

IX. ACKNOWLEDGMENTS

This investigation has been guided by the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council and was sponsored by the Ship Structure Committee. Dr. Finn Jonassen, formerly Technical Director of the Committee on Ship Structural Design, was most helpful during the early stages of this investigation. Dean L. E. Grinter, Chairman; Mr. Fred C. Bailey, formerly Assistant Technical Director; and Dr. David K. Felbeck, Executive Director of this committee, have continued the guidance of this research.

The writer also expresses his gratitude to Captain C. P. Murphy, USCG; Mr. J. B. Robertson, Jr.; and Mr. W. C. McAuley of the U. S. Coast Guard; Dr. Morgan L. Williams of the National Bureau of Standards; Mr. D. P. Brown and Mr. Mathew Letich of the American Bureau of Shipping; Mr. Harold G. Acker of the Bethelehem Steel Company; and Dr. D. Vasarhelyi of the University of Washington for their suggestions and willing assistance.

X. LIST OF SYMBOLS

The symbols used in this report are defined as follows:

A	Area.
c	Half the width of plate.
D	Depth of the beam.
E	Modulus of elasticity.
G	Modulus of rigidity $= \frac{E}{2(1 + \nu)}$.
I	Moment of inertia.
L	Total length.
R	Radius of curvature in bending.
t	Thickness
T	Temperature change
T_o	A uniform temperature
x, y, z	Rectangular coordinates: x along length of member, y across breadth, z across depth or thickness.
u, v, w	Components of displacement in x, y, and z directions, respectively.
α	Thermal coefficient of expansion.
δ	Vertical deflection.
ν	Poisson's ratio.
λ	Lame's constant $= \frac{\nu E}{(1 + \nu)(1 - 2\nu)}$.
ϵ	Unit elongation.
γ	Unit shearing strain.
σ	Normal stress.
τ	Shearing stress.

Subscript i denotes property at the element i.

Subscripts x, y, z denote property in the direction of the respective axes.

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TABLE I

MAXIMUM TEMPERATURE DIFFERENCE AND THERMAL STRESSES IN HULLS UNDER INSOLATION

Vessel and Reference	Max. Air Temp. F	Fraction of Possible Sunshine	Temp. Range in Hull Below W. L. F	Temp. Range in Hull Max. above W. L.	Max. Temp. Difference F	Location of Max. Temp.	Max. Thermal Stress: Stress psi	Max. Thermal Stress: Location
405'x54'x31' Cargo (46,56)	78	3/10	--	--	50	Deck		
360'x40'x12' Car Float (2)	42	Overcast	--	60	--	Deck		
450' Dry Cargo (49)	--	Misty	50	104	54	Side Shell	-5300	Sheer Strake
455'x63'x38' Victory (5)	56	10/10	49	102	53	Deck		
441'x57'x37' Liberty (5)	69	Overcast	63	109	46	Deck	-7500	Deck
459'x63'x41' C-2 Cargo (5)	68	Clear	63	113	50	Deck	+2700 -8000	Sheer Strake Sheer Strake
305' LST (50)	71	Clear	57	130	73	Deck	-11390	Sheer Strake
485'x59x34' Tanker (51)	--	Overcast	--	--	33	Deck	-2900	Side Shell
545'x68'x44' Passenger (4)	68	5/10	62	80	18	Sheer Strake		
448'x62'x35' Passenger (4)	73	10/10	66	100	34	Side Shell		
515'x69'x39' Tanker (4)	92	10/10	66	127	61	Deck	+4200 -2500	Long. Bulkhead Deck

TABLE I (cont.)

MAXIMUM TEMPERATURE DIFFERENCE AND THERMAL STRESSES IN HULLS UNDER INSOLATION

Vessel and Reference	Max. Air Temp. F	Fraction of Possible Sunshine	Temp. Range in Hull: Below W. L. F	Temp. Range in Hull: Max. above W. L.	Max. Temp. Difference F	Location of Max. Temp.	Max. Thermal Stress: Stress psi	Max. Thermal Stress: Location
515'x69'x39' Tanker (4)	91	10/10	66	116	50	Deck		
441'x57'x37' Liberty (52)	--	--	70	116	46	Deck	-6600	Deck
441'x57'x37' Liberty (6)	Below Water	Cloudy	--	--	8	Deck	+700	Second Deck
441'x57'x37' Liberty (54)	--	Cloudy	--	--	4	Deck	-700	Deck

TABLE II

MAXIMUM HOGGING DEFLECTIONS UNDER INSOLATION

Vessel and Reference	Fraction of Possible Sunshine	Max. Temp. Difference in Hull F	Temp. Diff. to Cause One Inch Deflection F
520' x 65' x 28' Collier (45)		--	7
405' x 54' x 31' Cargo (46,56)	3/10	40	27
388' Cargo Ship (46)	--	50	29
485' x 59' x 34' Tanker (51)	Overcast	33	21
441' x 57' x 37' Liberty (5)	Overcast	46	37
459' x 63' x 41' C-2 Cargo (5)	Clear	50	39

TABLE III

VARIATIONS IN TEMPERATURE EXPERIENCED BY CASUALTY NO. 171 ON TRANS-ATLANTIC VOYAGE

New York to Le Havre

Date	Hour	Air	Water
1/10/48	0400	34	45
	0800	34	46
	1200	35	44
	1600	27	44
	2000	24	44
	2400	24	46
1/11/48	0400	25	48
	0800	27	46
	1200	32	66
	1600	33	66
	2000	32	66
	2400	29	57
1/12/48	0400	30	58
	0800	30	54
	1200	41	63
	1600	42	69
	2000	40	66
	2400	43	63
1/13/48	0400	46	64
	0800	46	64
	1200	54	64
	1600	52	60
	2000	52	56
	2400	50	62
1/14/48	0400	54	66
	0800	54	72
	1200	54	57
	1600	52	56
	2000	54	60
	2400	50	55
1/15/48	0400	52	62
	0800	52	62
	1200	58	64
	1600	58	62
	2000	58	60
	2400	57	60
1/16/48	0400	57	60
	0800	57	60
	1200	64	60
	1600	58	61
	2000	57	60
	2400	56	62
1/17/48	0400	57	60
	0800	56	58
	1200	60	57
	1600	54	60
	2000	52	58
	2400	52	57
1/18/48	0400	50	58
	0800	50	56
	1200	53	57
	1600	54	56
	2000	51	56
	2400	51	57
1/19/48	0400	50	56
	0800	50	56
	1200	44	55
	1600	53	56
	2000	51	56
	2400	51	57
1/20/48	0400	53	56
	0800	54	55
	1200	53	56
	1600	55	56
	2000	54	56
	2400	57	54
1/21/48	0400	55	54
	0800	56	54
	1200	53	54
	1600	52	54
	2000	49	52
	2400	48	52
1/22/48	0400	50	52
	0800	50	52
	1200	49	52
	1600	48	52
	2000	47	50
	2400	47	50
1/23/48	0400	42	57
	0800	40	--
	1200	40	--
	1600	At Dock	

Data from log of ship. Casualty No. 171.

TABLE III (Cont.)

VARIATIONS IN TEMPERATURE EXPERIENCED
BY CASUALTY NO. 171 ON TRANS-ATLANTIC VOYAGE

Le Havre to Point of Failure 400 Miles

East of St. Johns, Newfoundland

Date	Hour	Air	Water
1/31/48	1200	56	--
	1600	53	--
	2000	50	--
	2400	52	50
2/1/48	0400	53	52
	0800	53	52
	1200	52	52
	1600	53	52
	2000	52	52
	2400	49	52
2/2/48	0400	56	52
	0800	56	52
	1200	56	52
	1600	55	54
	2000	54	54
	2400	52	54
2/3/48	0400	52	54
	0800	53	54
	1200	51	54
	1600	51	53
	2000	50	52
	2400	50	52
2/4/48	0400	50	53
	0800	51	53
	1200	52	54
	1600	52	54
	2000	52	54
	2400	52	53
2/5/48	0400	54	54
	0800	54	54
	1200	54	54
	1600	53	53
	2000	53	55
	2400	52	54
2/6/48	0400	51	53
	0800	52	53
	1200	52	54
	1600	54	53
	2000	53	53
	2400	53	52
2/7/48	0400	52	51
	0800	52	51
	1200	52	54
	1600	46	54
	2000	44	48
	2400	44	54
2/8/48	0400	44	54
	0800	43	52
	1200	44	54
	1600	41	54
	2000	39	54
	2400	36	54
2/9/48	0400	36	44
	0800	42	40
	1200	45	48
	1600	33	39
	2000	30	42
	2400	28	42
2/10/48	0400	27	42
	0600	27	42
		(Fracture)	
	0800	--	--
	1200	--	--
	1600	--	--
	2000	33	52
	2400	32	52

TABLE IV
GROUP I CASUALTIES ALONG THE CONFLUENCE OF THE GULF STREAM WITH COASTAL WATERS

Casualty No.	Type	Casualty Date	Lat. N Deg.-Min.	Long. W Deg.-Min.	Course Deg.	Temperature Air F	Temperature Water F	Temperature Oil F	Wind	Drafts Ft.-In.	Remarks
						Tankers					
47	T2	12/11/43	150 mi. S. Halifax		Inbound	32	35	Crude	6	29-6/32-6	
108	Not M.C.	3/8/45	168 mi. S. Halifax		010	30	47	110-114	5	29-3/30-5	
110	Not M.C.	3/17/45	41-50	64-48	014	40	37	95	3	29-7/30-1	10 F drop in T_A, 21 F drop in T_W in 4 hr.
112	Not M.C.	5/11/45	41-25	63-25	045	43	42	108	5-6	30-11/31-6	
137	T2	3/19/46	38-17	74-11	Inbound	46	48		7	Loaded	Drop of 30 F in T_A
148	T2	2/5/47	43-31	70-05	290	33	40		4-6	28-6/30-7	Off Portland, Me.
163	T2	3/19/46	39-00	73-00	336	48	50	100	5-6	28-11/30-11	Venezuela to N. Y.
205	T2	2/27/50	37-53	73-38	N	32	56	100-112	8	30-2/30-2	Panama to N. Y.
213	T2	1/24/51	42-57	70-35	333	46	43		6	29-6/28-8	Off Massachusetts
226	T2	1/4/52	100 mi. S.Block Is.		N'ly	40	59	120	4	29-3/29-8	T_W falling
232	500'	1/23/52	N.E. Block Is.		Inbound	50	42	114-129	4	29-4/29-4	Drop of 27 F in T_W
233	T2	2/11/52	39-00	72-59	347	38	49	100-118	7-8	29-10/29-10	100 mi.E. of Cape May
236	T2	2/18/52	41-38	69-20	340	35	41		8-9	30-0/30-0	Broke in two
237	T2	2/18/52	41-36	69-51	Inbound	35	41	Not Htg.	10	29-3	Broke in two
238	T2	2/-/52	38-33	74-50	346	44	55	Htg.	6-7	29-3/31-1	Off Cape May

TABLE IV (cont.)
GROUP I CASUALTIES ALONG THE CONFLUENCE OF THE GULF STREAM WITH COASTAL WATERS

Casualty No.	Type	Casualty Date	Lat. N Deg.-Min.	Long. W Deg.-Min.	Course Deg.	Temperature Air F	Temperature Water F	Temperature Oil F	Wind	Drafts Ft.-In.	Remarks
					Dry Cargo Ships						
20	EC2	3/5/43	54	47	W'ly	22	38		7	14'/22'	
22	EC2	3/14/43	230 mi. E. St. Johns		E'ly	32	30		Light	22-3/28-6	
43	EC2	12/11/43	44-10	40-04	270	--	--		5	18'/20'	
44	EC2	12/11/43	44-01	38-57	W'ly	60	64		8-10	11-4/21-7	
62	EC2	1/9/44	300 mi. ESE Cape Race		W'ly	50	68		8-10	13-0/21-0	
63	EC2	1/9/44	44-30	43-01	W'ly	34	50		6-9	7-0/21-0	
64	EC2	1/9/44	46-40	38-15	W'ly	44	54		6	11-0/20-0	
80	EC2	2/1/44	48-30	35-45	W'ly	52	50		8-10	12-10/21-6	T_W noted as variant
87	EC2	2/20/44	43	55	W'ly	20			6	Ballasted	
93	EC2	3/4/44	43-30	56-30	W by S	20	40		8-12	13-0/21-5	
96	EC2	3/15/44	36-54	72-37	Outbound	50	70		4	28-7/28-7	Off Norfolk, Va.
100	EC2	12/16/44	96 mi. SE Ambrose Channel		SE	47	52		5	27-1/30-5	8 F in T_A, 4 F in T_W f_{Deck}=18,000 psi tons
117	EC2	11/8/45	45-38	48-54	287	37	42		7-8	26-10/27-5	
125	EC2	1/15/46	43-38	48-10	238	30	42		10	13-8/19-6	Snowing
126	EC2	1/19/46	43-06	64-25	27	30	43		2		
130	EC2	2/1/46	39-20	72-07	310	48	68		6-7	10-6/16-6	

TABLE IV (cont.)
GROUP I CASUALTIES ALONG THE CONFLUENCE OF THE GULF STREAM WITH COASTAL WATERS

Casualty No.	Type	Casualty Date	Lat. N. Deg.-Min.	Long. W Deg.-Min.	Course Deg.	Temperature Air F	Temperature Water F	Temperature Oil F	Wind	Drafts Ft.-In.	Remarks
					Dry Cargo Ships (cont.)						
134	EC2	12/13/46	40-40	61-20	270	36	60		9	10-9/19-2	
135	EC2	2/22/46	550 mi. E of N.Y.		270	28	37		8-10	13-0/19-3	
157	EC2	12/9/47	38-22	59-21	283	64	70		6	7-6/15-6	
171	EC2	2/10/48	46	45	235	28	42		8-9	8'/16'	Drop in T_W
219	EC2	11/27/51	41-31	59-03	230	60	68		10-12	12'/18'	
235	EC2	2/18/52	35-07	67-38	275	62	66		9	9-8/19-2	

TABLE V
BRITTLE FRACTURES ABOVE WATERLINE

Temperatures - F			Origin of Fracture			Casualty No.	Type of Vessel	Vessel Launched	Sea	Wind Force	Drafts	
T_W-T_A	T_W	T_A	Hatch Corner	Elsewhere in Deck	Gunwale						Fwd.	Aft
-9	47	56	X			70	EC2	1943	Heavy	--	13-6	20-6
-9	51	60			X	180	C4	1943	Normal	3	15-6	22-5
-6	38	44			X	18	EC2	1942	Heavy	9-10	25-10	27-9
-4	53	57			X	114	C1B	1943	Normal	5	26-3	27-0
-3	52	55	X			59	C3	1942	Heavy	6	24-10	29-8
-3	61	58			X	116	EC2	1943	Heavy	7-10	24-7	27-11
-2	30	32	X			22	EC2	1943	Calm	--	22-3	28-6
-2	50	52	X			80	EC2	1942	Heavy	8-10	12-10	21-6
-2	36	38	X			158	C2	1942	Rough	3	16-11	23-2
-1	75	76			X	52	EC2	1943	Normal	4	23-10	26-6
-1	49	50	X			81	EC2	1942	Heavy	9	11-10	21-2
0	45	45			X	41	EC2	1942	Heavy	9-10	11-0	20-0
0	48	48	X			151	C1M	1945	Heavy	--	Ballasted	
0	51	51	X			224	C1B	1944	Heavy	12	Light	
1	35	34			X	55	EC2	1943	Heavy	7-8	Ballasted	
1	42	41		X		69	EC2	1942	Heavy	8-9	24-10	25-9
1	47	46	X			76	EC2	1942	Heavy	8-6	14-1	20-1
1	35	34			X	95	EC2	1943	Calm	--	19-4	24-6
1	52	51	X			242	EC2	1942	Rough	4-7	7-0	16-6
2	34	32			X	83	EC2	1942	Calm	2	8-5	15-0
2	52	50		X		115	Z-ET1	1943	Heavy	9	28-9	28-10
0-6	40-46	40			X	8	EC2	1942	Heavy	5	6-6	15-8
4	34	30	X			23	EC2	1942	Heavy	9	25-11	26-1
4	64	60	X			44	EC2	1943	Heavy	8-10	11-6	19-6
4	54	50	X			82	EC2	1943	Heavy	9-11	13-3	19-8
4	42	38	X			84	EC2	1943	Heavy	6	26-7	25-11
4	54	50			X	86	EC2	1942	Heavy	8	8-4	18-4
4	64	60	X			208	C3	1943	Heavy	12	Unknown	
5	45	50			X	99	Z-ET1	1943	Heavy	9	26-0	28-0
5	42	37		X		117	EC2	1944	Heavy	7-8	26-10	27-5
5	60	55			X	119	T2	1944	Calm	1	1-0	19-10

TABLE V (Cont.)
BRITTLE FRACTURES ABOVE WATERLINE

Temperatures - F			Origin of Fracture			Casualty No.	Type of Vessel	Vessel Launched	Sea	Wind Force	Drafts	
T_W-T_A	T_W	T_A	Hatch Corner	Elsewhere in Deck	Gunwale						Fwd.	Aft
5	54	49	X			154	C2	1942	Heavy	--	6-5	19-7
5	65	60	X			235	EC2	1943	Heavy	--	Loaded	
6	60	54		X		221	VC-2	1944	Heavy	--	Unknown	
9-5	45-47	36-42			X	35	EC2	1942	Heavy	7	13-6	19-6
7	54	47	X			75	EC2	1943	Heavy	5-7	23-4	26-10
9-5	48-52	39-47			X	100	EC2	1943	Normal	5	27-1	30-5
7	41	34			X	155	T2	1944	Calm	4	14-0	18-0
7	52	45	X			223	C2	1944	--	--	Unknown	
8	46	38		X		36	EC2	1942	Heavy	10	Mean	16-0
8	50	42	X			56	EC2	1942	Heavy	7-8	11-8	21-0
8	50	42			X	71	EC2	1942	Heavy	8	Ballasted	
8	48	40	X			72	EC2	1943	Heavy	8	9-6	21-0
8	68	60		X		219	EC2	1944	--	--	Unknown	
9	45	36			X	89	EC2	1943	Heavy	11-12	20-0	25-3
13-6	62-64	49-58			X	109	EC2	1942	--	--	Unknown	
9	63	54		X		121	EC2	1943	Heavy	6-7	Ballasted	
9	49	40			X	159	EC2	1943	Heavy	10	Loaded	
9	52	43	X			230	Cargo	1944	--	--	Unknown	
10	32	42	X			4	EC2	1942	Heavy	9	7-1	18-0
10	34	24			X	19	EC2	1942	Heavy	8	27-0	27-3
10	54	44	X			64	EC2	1943	Heavy	6	11-0	20-0
11	63	52			X	85	EC2	1943	Heavy	7-8	24-0	29-0
11	45	34			X	144	C1A	1944	Heavy	--	8-9	18-8
11	57	46	X			153	C2	1943	Heavy	6	15-1	17-7
12	42	30		X		125	EC2	1942	Heavy	10	13-8	19-6
15-9	66-69	51-60			X	104	EC2	1943	Normal	--	Loaded	
13	42	29	X			45	EC2	1942	Heavy	10	11-6	19-6
13	51	38	X			65	EC2	1942	Heavy	8-9	12-5	20-3
13	43	30		X		126	EC2	1943	Calm	--	22-7	24-6
15	48	33	X			27	EC2	1943	Heavy	--	Ballasted	
15	47	32			X	103	C2	1943	Normal	4	26-8	27-8

TABLE V (cont.)
BRITTLE FRACTURES ABOVE WATERLINE

Temperatures - F			Origin of Fracture			Casualty No.	Type of Vessel	Vessel Launched	Sea	Wind Force	Drafts	
$T_W - T_A$	T_W	T_A	Hatch Corner	Elsewhere in Deck	Gunwale						Fwd.	Aft
20-10	42	22-32			X	102	EC2	1942	Heavy	6-7	19-4	25-0
15	41	26		X		135	EC2	1942	Heavy	10	Ballasted	
15	42	27			X	171	EC2	1942	Heavy	10	8-0	16-0
16	38	22	X			20	EC2	1942	Heavy	9	14-0	22-0
16	50	34		X		63	EC2	1943	Heavy	6-9	7-0	21-0
17	42	25			X	1	Not MC	1942	Heavy	7	12-3	21-8
18	68	50		X		62	EC2	1943	Heavy	8-10	13-0	21-0
19	35	16			X	90	T2	1943	Normal	4	4-7	15-11
19	37	17-20			X	24	EC2	1942	Heavy	9	Ballasted	
20	58	38	X			66	EC2	1943	Heavy	8	12-0	21-6
20	40	20			X	92	EC2	1943	Heavy	6-8	20-5	27-5
20	70	50	X			96	EC2	1943	Normal	4	28-7	28-7
20	68	48			X	130	EC2	1943	Heavy	6-8	Ballasted	
21	54	33	X			53	EC2	1943	Heavy	--	Ballasted	
22	72	50		X		157	EC2	1943	Heavy	10	Ballasted	
24	60	36			X	134	EC2	1943	Heavy	--	10-9	19-2
25	38	13			X	58	EC2	1942	Calm	1	24-0	25-2
25	56	31		X		146	EC2	1944	Heavy	10	8-6	19-6
38	37-40	0			X	183	C2	1942	Calm	8	15-11	22-5
43	33	-10			X	16	EC2	1942	Normal	4	22-10	26-5
43	78	35			X	187	VC2	1945	Rough	8	Light	
48	32	-16		X		101	C1	1944	Calm	--	1-11	14-0

TABLE VI
BRITTLE FRACTURES BELOW WATERLINE

Temperatures - F			Origin of Fracture			Casualty No.	Type of Vessel	Vessel Launched	Sea	Wind Force	Drafts	
T_W-T_A	T_W	T_A	Bilge	Bottom	Detail						Fwd.	Aft
-8	42	50	X		Faulty Butt Weld	122	EC2	1943	Calm	--	Loading	
-8	47	55	X		Butt Weld	240	Tanker	1941	Heavy	--	Ballast	
-3	37	40		X		110	Tanker	1943	Normal	3	29-7	30-1
-3	43	46	X		Bilge Keel	213	T2	1943	--	--	Loaded	
-1	42	43		X	Butt Weld	112	Tanker	1943	Heavy	5-6	30-11	31-6
0	36	36		X		128	T2	1945	Calm	3-4	28-8	30-8
0	40	40	X			138	T2	1944	Heavy	2-3	Loaded	
1	38	37	X			106	T2	1942	--	--	28-10	30-4
3	53	50		X		118	T2	1943	Heavy	4-5	29-2	32-5
4	58	54	X		Bilge Keel	178	T2	1944	Rough	5	25-0	26-8
4	74	70	X		Butt Welds	204	T2	1945	Normal	5-6	29-3	31-3
4-6	41-43	37		X		129	T2	1944	Heavy	--	Loaded	
5	42	37	X		End Long.	207	T2	1944	Heavy	5	Ballasted	
5	52	47	X		Butt Weld	239	T2	1944	Heavy	--	--	--
5	75	70	X		End Long.	247	Tanker	1938	Heavy	--	Loaded	
6	41	35		X	End Long.	236	T2	1945	Heavy	--	Loaded	
7	45	38	X			148	T2	1942	Heavy	--	Loaded	
13	45	32	X		--	47	T2	1943	Heavy	6	29-6	32-6
14	62	48	X		Bilge Keel Weld	120	EC2	1942	Heavy	--	12-6	20-0
17	47	30	X		Bilge Keel Weld	108	Tanker	1941	Normal	5	29-3	30-5
20	45	25	X		Bilge Keel Weld	123	T2	1944	Calm	--	25-0	27-0
24	56	32		X	Butt Weld	205	T2	1943	Heavy	--	Loaded	
28	36	8	X		Bilge Keel Weld	124	T2	1943	Calm	3-4	22-4	25-6

APPENDIX A

THEORETICAL TREATMENTS OF THERMAL STRESSES*

1. Introduction. This section will present theoretical solutions which may be applied to problems of thermal stresses as they occur in ships. In most cases these solutions produce nominal rather than actual stresses. A list of symbols used in the equations is given in the list under Section X. The references may be found in the bibliography, Section XI.

2. Thermal Stresses and Deflections in Bars and Box Structures. Consider a homogeneous beam of uniform EI with a linear temperature distribution along the depth of the cross section and uniform in the width as shown in Fig. A-1. Also assume that this temperature distribution is the same at every section of the beam and that the beam is free from external restraints. In Fig. A-1 the temperature increases linearly from zero at the bottom to T at the top fiber. This temperature distribution can be expressed as the sum of the temperature distributions shown in parts (b) and (c). The temperature distribution (b) will give a uniform elongation of the beam proportional to the magnitude of (b). For (c) the elongation or contraction of each fiber is proportional to the distance from the centroidal axis. This deformation will produce bending in the bar. Thus a linear temperature distribution gives

*The references in this appendix were reviewed by Mr. S. P. Chhabra, graduate student in the Department of Civil Engineering, University of Washington.

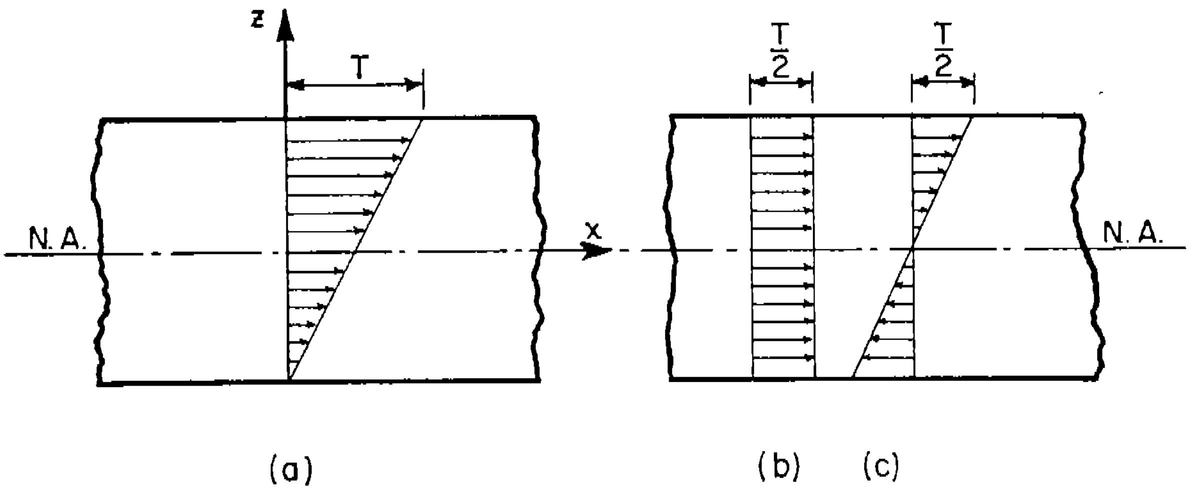
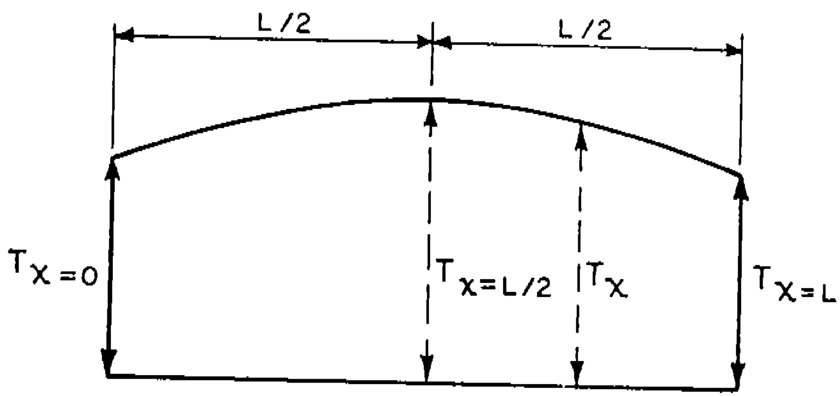


Fig. A-1. Linear Temperature Distribution in Bar.



$$T_X = T_{X=L/2} - \left[T_{X=L/2} - T_{X=0}\right]\frac{4X^2}{L^2}$$

$$T_{X=0} = T_{X=L}$$

Fig. A-2. Linear Temperature Distribution on Cross Section of Bar with Magnitudes Varying Parabolically Along the Length elongation and bending without any stresses. The amount of the deflection due to bending was first expressed as a special case to a more general solution by Suyehiro and Inokuty[1] as

$$\delta_{L/2} = \frac{\alpha T L^2}{8D}. \tag{1}$$

The curvature R in this case is constant, and the bar bends in a circular arc. This same relation was later derived by Burtner and Tingey[2] and Hurst[3].

When the temperature is linear at every cross section but varies parabolically along the length as shown in Fig. A-2, the following relation was given by Hurst[3] for the maximum deflection at $x = \frac{L}{2}$:

$$\delta_{L/2} = \frac{\alpha L^2}{48D}(5T_{x=L/2} + T_{x=0}), \tag{2}$$

where the parabolic temperature distribution over the length of the bar is

$$T_x = T_{x=L/2} - (T_{x=L/2} - T_{x=0})\frac{4x^2}{L^2}. \tag{3}$$

Eq. 2 was derived by Hurst[3] from the general geometrical relation

$$\delta = \int_0^L \int_0^x \frac{1}{R}\,dx\,dx. \tag{4}$$

When the temperature distribution on the cross section is non-linear, then in addition to deformations, internal or thermal stresses exist in the bar. Suyehiro and Inokuty[1] derive an expression for the deflection in this general case by using the argument that both the resultant force and the resultant couple of the stresses on a cross section vanish:

$$\delta_x = \int_0^x \int_0^x \frac{S}{I}\, dxdx - \frac{x}{L} \int_0^L \int_0^x \frac{S}{I}\, dxdx \qquad (5)$$

where

$$S = \int_{-z}^{+z} T(z)\, z\, dA, \qquad (6)$$

and $T(z)$ is the temperature distribution expressed as a function of z.

The special case for a step-function temperature distribution is analyzed by Suyehiro and Inokuty[1]. The deflection for one degree F for three different ships having this step-function distribution constant along their length was calculated, but the authors did not have any experimental data to check their results.

The value of Hurst's work[3] is that he systematically organized the information on this subject developed by the previous investigators. His derivation makes the following assumptions:

1. The coefficient of thermal expansion and the modulus of elasticity are constant within the temperature range considered.
2. The vertical temperature distribution is the same across the breadth of the ship.

3. Cross sections originally plane and normal remain so after temperature change and deflection.
4. After change of temperature the resultant of the induced forces is zero.
5. After change of temperature the resultant moment of the induced forces is zero.

To comply with the assumption in (3) above, a virtual temperature line is drawn as shown in Fig. A-3 to define a linear temperature distribution from which the longitudinal extension and the stress-free bending deflection can be calculated. The equation for the virtual temperature line is derived by imposing the assumptions in (4) and (5) above. The bending deflection is found by the general Eq. 1. The induced thermal stress is proportional to the difference between the actual temperature curve and the virtual temperature line. It is interesting that the induced stresses do not contribute to the deflection or the longitudinal extension of the bar. The validity of assumption (3) above has been verified by Corlett[4] and Howe, Boodberg, and O'Brien[5].

Hurst illustrates this procedure in his paper by finding the stresses and deflections in three types of standard beam sections for three temperature distributions. An extension of Hurst's method to include the case of the completely unsymmetrical temperature distribution on the cross section is given in Ref. 6.

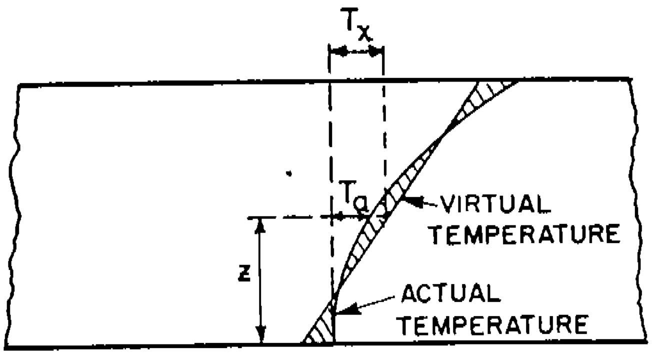


Fig. A-3. Actual and Virtual Temperature Lines Assumed by Hurst.

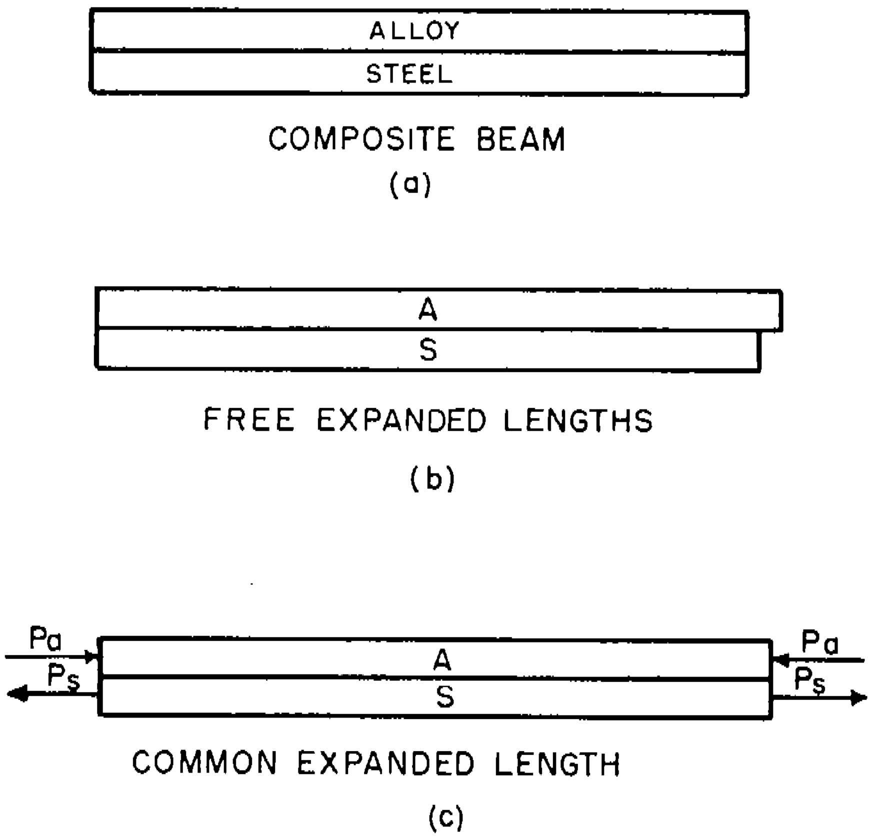


Fig. A-4. Corlett's Method of Finding Thermal Stresses.

An example problem showing the application of Hurst's method appears in Appendix C.

Timoshenko and Goodier[7] treat the thermal stress problem as one of boundary-force type. A thin rectangular plate or bar of uniform thickness is first assumed to be completely restrained at the two ends and the stresses found. The forces on the boundary due to the restraint against thermal expansion are calculated. Since the boundaries are actually free, the next step is to apply the calculated boundary forces in the reverse direction on the free plate and compute a second set of stresses. Then the final thermal stresses at any point in the plate are the sum of these two stresses. The stresses resulting from the removal of the restraints can be considered as made up of two parts: first, direct stress, and second, bending if the temperature distribution is not symmetrical about the longitudinal axis of the plate. The following equation is derived:

$$\sigma_x = \alpha E \left[- T + \frac{1}{2c} \int_{-c}^{+c} T dy + \frac{3y}{2c^3} \int_{-c}^{+c} T y dy \right] . \qquad (7)$$

The first two terms in this equation represent the direct stress, part from the restraint and part from its release, and the last term the bending stress. The same procedure is also applied to thick plates with the modifications necessary because the latter is not a plane stress problem. This procedure can be applied to beams and girders as well.

Corlett[4] presented the first comprehensive study of thermal stresses in a composite ship. The ship is analyzed as a long beam. Moreover, the transverse deformation of the hull is recognized, and each section is considered as a rigid frame fixed at its vertical centerline. In the theoretical analysis stresses are divided into longitudinal stresses due to beam action and transverse stresses due to rigid frame action. These two sets of stresses are assumed to be independent of one another. The following assumptions are made:

1. The thermal coefficients of expansion and moduli of elasticity are constant over the range of temperature considered.
2. Cross sections plane before deformation remain plane after deformation.
3. The forces and moments of the thermal stresses on a cross section are self-equilibrating.
4. Compound beam theory is valid.

The assumptions in 1--3 above are the same as those made by Hurst[3].

Corlett's method of handling the longitudinal stresses will be described first. Fig. A-4 shows the steps used in applying this method. Consider a compound beam made of different materials. At a cross section the free expanded length of an element can be determined. In order to satisfy the assumption in (2) above, the elements must be strained until they fit together. The difference between the two elongations gives the stress in the element. Using the argument that the total force on the cross section must be zero, the restrained elongation of each element can be found, from which the induced thermal stresses can be computed. In addition, these forces will produce bending moments which will in turn result in stresses and deflections which must be combined with those previously found.

Transverse stresses are induced in a composite ship because of the differences in elongation of the decks, floors and other horizontal members. The bending moments are found by using the moment distribution method[8,9] as used in rigid frames where there is settling of the foundations. In this analysis the hull section is replaced by an equivalent structure of horizontal and vertical members with the vertical centerline of the hull cross section as the fixed plane. From the bending moments thus found, the stresses can be calculated.

An example problem showing the application of Corlett's method appears in Appendix C.

In addition, this paper describes experiments on a simplified model hull. The check between the theoretical and the experimental values of the longitudinal thermal stresses was found to be very good. The most important finding of this model study was a verification of the hypothesis that plane cross sections before deformation remain plane after deformation, even though the temperature distribution is nonlinear and therefore thermal stresses are present.

Mar and Engel[10] considered transient thermal stresses in a one-cell box beam. Eq. 7 was broken down into the following three summations:

$$
\begin{aligned}
(\sigma_{x,1})_i &= -E\,\alpha T_i, \\
(\sigma_{x,2})_i &= \frac{1}{A}\sum_{i=1}^{n} E\,\alpha A_i\,T_i, \\
(\sigma_{x,3})_i &= \frac{Z_i}{I_y}\sum_{i=1}^{n} E\,\alpha A_i Z_i\,T_i.
\end{aligned}
\tag{8}
$$

The first summation represents the direct stress resulting from complete restraint against longitudinal expansion; the second, the direct stress from the release of the axial restraining end forces; and the third, the bending stress, the release of the restraining end couples. They correspond respectively to the first, second, and third terms in Eq. 7.

These investigators also treat the problem of stresses in the transverse direction. It is assumed that the temperature distribution is symmetrical about the vertical centerline of the box and constant along the length. The transverse stresses causing the distortion of the cross section are calculated by using the concept of elastic center and superposition.

Mar and Engel also handle the box beam structure by applying the differential equations of equilibrium and stress-strain relations for the three-dimensional case of temperature distribution as given by Timoshenko and Goodier[7]:

$$(\lambda + G)\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + G\nabla^2 u - \frac{E\alpha}{1-2\nu}\frac{\partial T}{\partial x} = 0$$

$$(\lambda + G)\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + G\nabla^2 v - \frac{E\alpha}{1-2\nu}\frac{\partial T}{\partial y} = 0 \qquad (9a)$$

$$(\lambda + G)\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + G\nabla^2 w - \frac{E\alpha}{1-2\nu}\frac{\partial T}{\partial z} = 0$$

The stress-strain relations are

$$\epsilon_x = \frac{1}{E}\left[\sigma_x - \nu(\sigma_y + \sigma_z)\right] + \alpha\Delta T,$$

$$\epsilon_y = \frac{1}{E}\left[\sigma_y - \nu(\sigma_x + \sigma_z)\right] + \alpha\Delta T,$$

$$\epsilon_z = \frac{1}{E}\left[\sigma_z - \nu(\sigma_x + \sigma_y)\right] + \alpha\Delta T,$$

$$\gamma_{xy} = \frac{1}{G}\tau_{xy},$$

$$\gamma_{yz} = \frac{1}{G}\tau_{yz}, \qquad (9b)$$

$$\gamma_{xz} = \frac{1}{G}\tau_{xz}.$$

The principle of minimum energy is used to solve these equations. The following assumptions are made:

1. The cross sectional shape is preserved by closely spaced diaphragms.
2. The temperature is constant through the thickness of the shell.

Mar and Engel applied their two methods to determine the stresses and deflections in a box cantilever beam. Heat was applied to one face of this box, and the temperature distribution and thermal stresses were determined. In this analysis this distribution was assumed to hold for all cross sections of the box. It was symmetrical about the vertical axis of the cross section and nonlinear through the depth. The theoretical and experimentally determined stresses were found to be in only fair agreement. This discrepancy was attributed to buckling of the skin. At the same time it was found that the transverse stresses resulting from the distortion of the cross section of the box were very small.

Jasper[(11)] has also used the equations (Eq. 7) of Timoshenki and Goodier[(7)]. He gives a very clear explanation of the method and its application to the hull of a ship.

Goodman and Russell[(12)] applied Eqs. 8 to a built-up beam of I-shape. In addition, they derived equations which assume temperature-dependent values of Young's modulus and the coefficient of thermal expansion. Good agreement was obtained between the theoretical and the experimental results.

Wise and Andersen[13] studied the thermal stresses in a box beam consisting of stringers and shell plating. The following assumptions were made:

1. The thermal strain varies linearly with temperature.
2. The elastic properties of the material do not change with temperature.
3. The thin shell carries the shearing stresses only while the stringers carry the bending and direct stresses.
4. The displacements of the structure are small compared to its dimensions.
5. The beam is stiffened by rigid diaphragms spaced infinitely close to prevent any deformation of the cross sections of the box.

The basic approach in calculating the stresses is the same as that of Timoshenko and Goodier[7] in deriving Eq. 7. Shear-lag equations are written which include the effect of temperature deformation.

Three box beams were tested to verify the method, and poor agreement was found between the experimental values of the stresses and those computed by theory. The failure to obtain a check was attributed to buckling of the shell and to participation of the shell in carrying the bending and direct stresses. The investigators expressed the opinion that some of the shell area should have been converted into hypothetical stringers to represent better the temperature distribution.

Heldenfels has presented four different solutions applicable to panels and box beams, three of which are considered here. The equations are too lengthy to include in this report, but the general approach of each method will be described.

For a rectangular panel or a box, Heldenfels[14] makes the assumption that the normal cross sections of the panel in one of its directions remain straight after deformation and that the normal cross sections of the box remain plane after deformation. A differential equation is derived from the equilibrium relations and the stress-strain relations and solved with due consideration to the boundary conditions.

The second is an elementary method[14] which is an extension of beam theory as given by Bruhn[15]. An example problem shows its application to a wing section.

The third method[16] employs a numerical procedure to compute the stresses by the equations developed in his first method[14]. A nonuniform temperature distribution is assumed. A matrix iteration process is used to provide an easy approximate solution. An example problem is presented. This particular method appears to have considerable merit.

Timoshenko[17] considers thermal stresses in cylindrical shells. If a cylindrical shell has no external restraints and is subjected to a uniform temperature distribution, no thermal stresses are developed. However, if the end cross sections of the shell are supported or clamped in a manner which prevents a change in the diameter of the shell at the support points, reactive bending moments and shears exist which can be calculated. In a transversely bulkheaded ship, similar stresses would be developed in the vicinity of the junction of the bulkhead with the side and bottom shell and the deck.

He also considers the case(17) where a temperature gradient exists along the length of the cylinder which has no external restraints. The shell is divided into rings, and an external radial pressure is applied to each ring to make it fit the adjacent rings. This distribution of pressure is then applied to the entire cylinder in the reverse direction, and the thermal stresses are computed by the superposition of the two solutions. In general principle this method is the same as that proposed by Timoshenko and Goodier(7) for bars.

3. Thermal Stresses in a Plate of Uniform Thickness. Timoshenko and Goodier(7) give a general equation for the plane strain problem in the form of an Airy stress function which is as follows:

$$\nabla^4 \phi = -\frac{\alpha E}{1 - \nu} \nabla^2 T, \tag{10}$$

where the stresses are found from the stress function ϕ. The required stress function should satisfy the above equation and give a normal boundary stress of

$$\frac{ET}{1 - 2\nu}. \tag{11}$$

Heldenfels, Richard, and Roberts[18] modified Eqs. 10 and 11 for the solution of a thin flat plate assumed to be in a state of plane stress. It was also assumed that the properties of the material did not change with temperature. The modified form of the equation is

$$\nabla^4 \phi = - E\alpha\nabla^2 T. \qquad (12)$$

The temperature distribution was assumed constant through the plate thickness and varying over the plate surface as follows:

$$T = T_0 + X(x)\ Y(y), \qquad (13)$$

where T_0 is a uniform temperature. Since the exact solution of this equation is in the form of an infinite series, an approximate solution is found by assuming that the stress function can be expressed as

$$\phi = f(x)\ g(y). \qquad (14)$$

The problem is solved by selecting an appropriate function g and then using the principle of minimum complimentary energy to determine a function f that gives the best approximation of the exact solution. The degree of approximation is dependent upon the function g selected.

An actual experiment on a plate with a nonuniform temperature distribution was carried out, and the agreement between the theoretical and the test results was within ±5 per cent of the maximum stress except at one point.

Gossard, Seide, and Roberts[19] deal with the subject of the thermal buckling of plates under a bisymmetrical nonuniform temperature distribution. The stress equations derived by Heldenfels and Roberts[18] are used together with the following equation[20] to obtain the critical temperature:

$$D\nabla^4 z = t(\sigma_x \frac{\partial^2 z}{\partial x^2} + \sigma_y \frac{\partial^2 z}{\partial y^2} + 2\tau_{xy} \frac{\partial^2 z}{\partial x \partial y}). \tag{15}$$

The critical temperature is found by choosing a buckle pattern symmetrical about the center of the plate and using the Raleigh-Ritz energy method of solution.

Tests were carried out on a rectangular plate with its two opposite edges on hinged supports and free longitudinal expansion of the plate permitted. Good agreement between the theoretical and experiment results was obtained.

4. Thermal Stresses in the Vicinity of a Heated Spot. Several solutions are given by Goodier[21] for the thermal stresses on the boundary of a heated spot.

If the heated spot is a rectangle of length 2a and width 2b, the maximum thermal stress occurs parallel to and on the side of the length 2a at a point adjacent to the corners of the spot. This stress is

$$\sigma = \frac{E\alpha T}{\pi}(\pi - \tan^{-1} \frac{a}{b}). \tag{16}$$

If the heated spot is an ellipse with major and minor semi-axes of a and b, respectively, the maximum thermal stress occurs tangential to the ellipse at the ends of the major axis and is

$$\sigma = \frac{E\alpha T}{1 + (\frac{b}{a})}. \qquad (17)$$

If the elliptical spot becomes quite slender (a much greater than b), the maximum stress approaches $E\alpha T$. If a is equal to b, the spot is circular, and the tangential stress on the boundary is $\frac{1}{2}E\alpha T$.

5. Miscellaneous Theoretical Solutions. Tsien[22] gives similarity laws for the stressing heated wings. It is shown that the differential equation for a heated plate with a large temperature gradient and for a similar plate at constant temperature can be made the same by a proper modification of the thickness and the loading of the isothermal plate. This fact enables the stresses in the heated plate to be calculated from the measured strains in the unheated plate by a series of relations called "similarity laws." The application of this analog theory to solid wings under aerodynamic heating is discussed in detail. In practice the method would be difficult to apply. The loading is a body force loading in the unheated analog wing and involves the application of a distributed three-dimensional loading.

Lessen[23] theoretically justified the study of thermal stresses by the use of models of the prototype structure. This reference is a brief summary of a paper to be published later.

Scaling transfigurations are applied to the equilibrium, stress-strain, and energy relationships written in tensor notation. The resulting dimensionless equations indicate that the effect of the scale factor is negligible and that a similarity of thermal stresses exists in bodies of similar geometry. This relation, which is sometimes taken for granted, is proved vigorously.

6. Summary of the Available Theoretical Solutions. The majority of the methods previously presented approach the determination of the thermal stresses and deflections in a bar or box beam in either of two ways. One group attacks the problem from the standpoint that the resultant force and bending moment on every cross section must equal zero. The second group uses the argument that thermal stresses in a free body can cause no forces on the boundaries of the body. The first group was spearheaded by Suyehiro and Inokuty[1], who were followed by Hurst[3] and Corlett[4]. The second group has used the method of Timoshenko and Goodier[7] and included Mar and Engel[10], Jasper[11], Wise and Andersen[13], and Goodman and Russell[12].

It is interesting that the first and earlier group was interested in the ship problem and most of the second in the aircraft problem. Hurst's method[3] in its present state can be applied to a beam of one material subjected to a temperature distribution on its cross sections with one axis of symmetry. Corlett[4] treated the more general case of more than one material with any temperature distribution. Both procedures are excellent and can be applied by one who is not conversant with the methods of theory of elasticity. They will produce results in terms of nominal stresses which are as good as the common methods of computing load stresses in terms of Mc/I or P/A.

The work of the second group has taken place since 1940 and is built upon the differential equation approach. The method of Mar and Engel[10] should give good results when applied to ships. The type of solution which assumes that the skin plating does not carry bending stress, but concentrates it in the stringers, such as that of Wise and Andersen[13], would give erroneous results for the hull of a ship. A number of hogging and sagging tests have clearly shown that the hull plating carries a major part of the bending stress.

Both groups make two assumptions: first, plane sections before deformation remain plane after deformation; second, the forces on a cross section are self-equilibrating. The second assumption is a fact, and the first was well substantiated by the model experiments of Corlett[4] and indirectly by the ship tests where computed and measured deflections were in fair agreement.

Corlett[4] and Mar and Engel[10] were the only investigators to consider the transverse stresses arising from the distortion of the cross sections of a box beam. Both found these stresses to be negligible.

The work of Lessen[23] makes possible model analysis of thermal stress problems.

APPENDIX B

THERMAL STRESSES ON THE BOUNDARY OF AN OPENING

The thermal stresses on the boundary of an opening were developed on the basis of the following conditions:

1. The rectangular plate is flat, infinite in extent, of uniform thickness, and has a centrally located opening.
2. The dimensions of the opening are small compared to the length and width of the plate, and the opening is symmetrical in shape about both rectangular axes of the plate.
3. The plate is thick enough so that it does not bend under stress.
4. The four edges of the plate parallel to the rectangular axes are fixed.

Greenspan[24] expresses the shape of an ovaloid hole in the parametric form,

$$x = p \cos \theta + r \cos 3\theta$$

$$y = q \sin \theta - r \sin 3\theta.$$

If the p and q dimensions are equal and r is negative, an approximate square with rounded corners results with sides parallel to the x and y coordinate axes. However, if r is positive, the coordinate axes become diagonals of the square. The width length of the square are $2(p + r)$. If p and q are unequal and r is zero, an exact ellipse results with its axes lying on the coordinate axes. If p and q are equal and r is zero, an exact circle results. The quantities p and q are measured in the x and y directions, respectively. In actual application the degree of approximation of the shape of a square opening with rounded corners is rather poor if r falls outside of the range of 0.10 to 0.20.

Greenspan's equation(24) when modified for the four conditions of this problem gives the following stress tangential to the opening,

$$\sigma_\theta = \frac{2S\left\{(p^2\sin^2\theta + q^2\cos^2\theta - 9r^2) - \dfrac{(p^2 - q^2)}{(p + q - 2r)}\left[(p - 3r)\sin^2\theta - (q - 3r)\cos^2\theta\right]\right\}}{\left\{(p^2 + 6rq)\sin^2\theta + (q^2 + 6rp)\cos^2\theta - 6r(p + q)\cos^2 2\theta + 9r^2\right\}}, \tag{19}$$

where S is the boundary stress on the plate. In this case,

$$S = \frac{E\alpha T}{1 - \nu}. \tag{20}$$

From Eqs. 19 and 20 can be developed the stress concentration factors for several shapes of openings. For the circular opening where $p = q$ and $r = 0$,

$$\sigma_\theta = 2S, \tag{21}$$

that is, the tangential stress around the opening is constant. For the elliptical opening, where $p \neq q$ and $r = 0$,

$$\sigma_\theta = S \left\{ 2 - \frac{2(p - q)(p \sin^2\theta - q \cos^2\theta)}{p^2 \sin^2\theta + q^2 \cos^2\theta} \right\} . \qquad (22)$$

The values for the square opening with rounded corners for which $p = q$ in Eq. 19 are plotted in Fig. B-1. Ovaloid openings have sides which are not quite straight and corners which are not quite circular. Therefore, the width of opening 2c and the corner radius R were measured from the plotted outline of the opening.

It may be seen in Fig. B-1 that the maximum thermal stress occurs at the corner of the opening for the assumed conditions. The value of the quantity, $\frac{E\alpha T}{(1 - \nu)}$, for a steel plate is 274 psi per degree F change in temperature. Thus, thermal stresses around an opening can be of considerable magnitude.

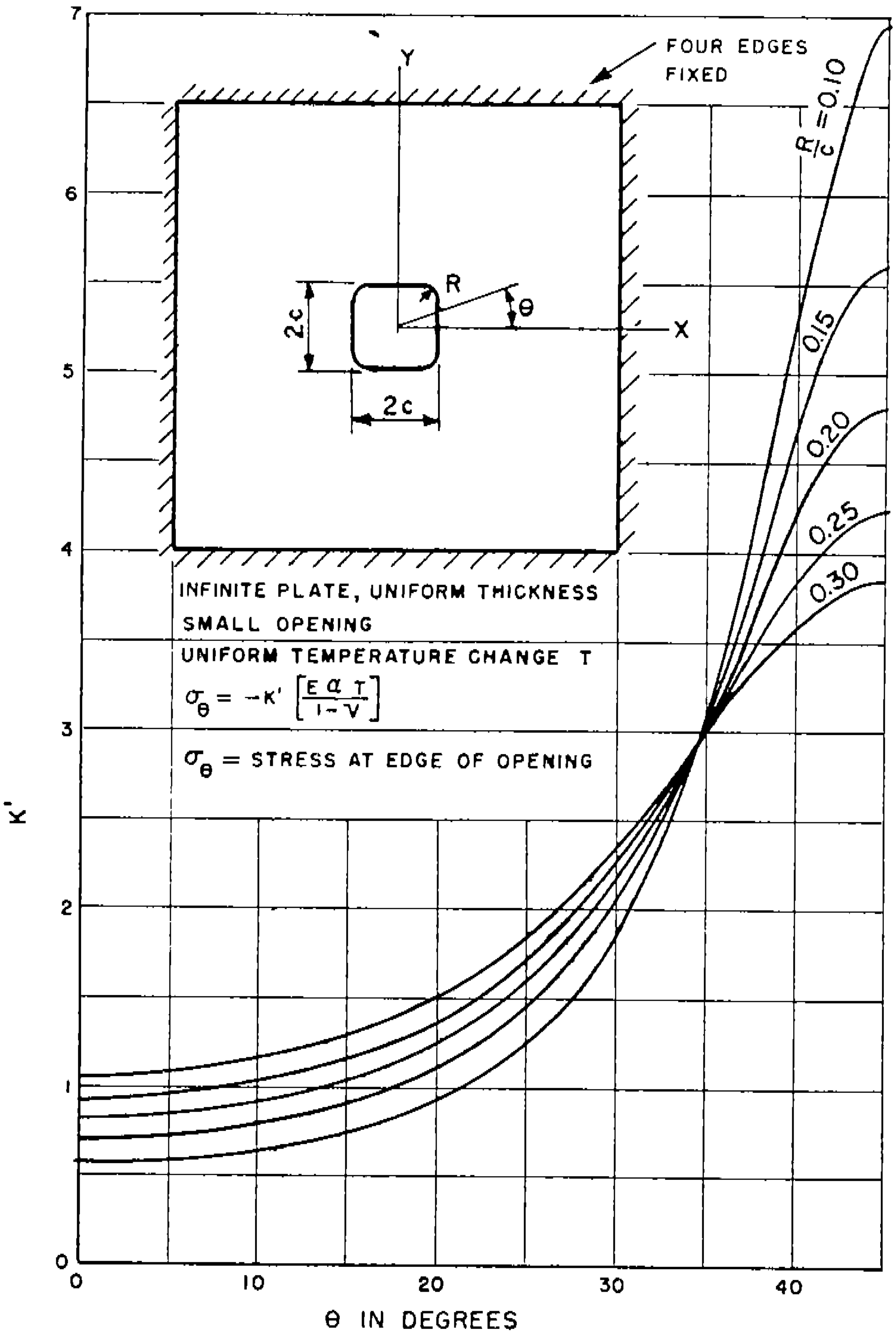


Fig.B-1. Thermal Stresses in Infinite Plate with All Four Edges Fixed and Small Square Opening with Rounded Corners. Uniform Temperature Change.

APPENDIX C

COMPUTATION OF THERMAL STRESSES IN SHIPS

1. Theoretical Methods for Computing Thermal Stresses. A brief review of the theoretical bases of several methods of computing thermal stresses in the hull of a ship is given in Appendix A. Example computation sheets for these methods appear in this appendix.

The three methods discussed hereafter result in the same form of computation, since their basic assumptions are that plane cross sections remain plane after thermal strain, that the forces on the cross section are self-equilibrating, and that the strains are in the elastic range of the material.

2. Hurst's Method[3,6]. The writer feels that Hurst's method requires less labor than the other methods for the case of a temperature distribution which is symmetrical about the vertical centerline of the hull cross section. It utilizes the keel line as the base line for the computation and therefore can use the dimensions and distances as developed by the naval architect for his moment of inertia calculations. Table C-I shows a typical calculation sheet for a symmetrical temperature distribution.

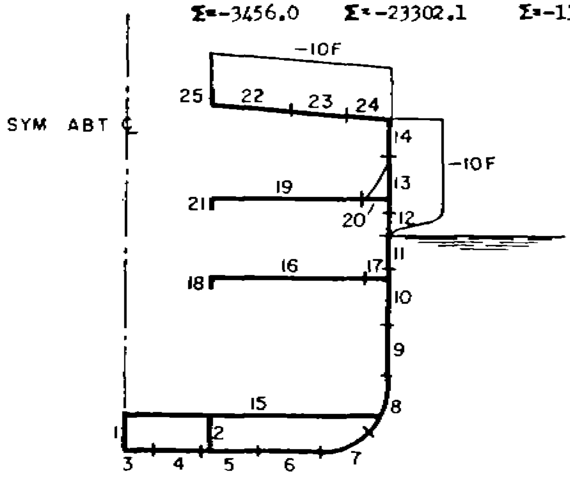
The temperature distribution which is unsymmetrical about both principal axes of the cross section can also be handled

TABLE C-I

C2 DRY CARGO SHIP. 26'-7" DRAFT

NO SUN. $T_w - T_A = -10$ F. FRAME 85

1 Increment	2 ΔA Sq. In.	3 y Ft.	4 T F	5 ΔAT Deg-in^2	6 ΔAy in^2-ft	7 $T\Delta Ay$ Deg-in^2-ft	8 y^2 ft^2	9 ΔAy^2 in^2-ft^2	10 by	11 T_v	12 $T_T = T - T_v$	13 $f_T = -197.5\ T_v$	14 $f_T \Delta A$	15 $f_T \Delta Ay$
1	13.52	2.2	0	0	29.7	0	4.84	65	-.49	+.92	-.92	+182	+2461	+5414
2	17.68	2.2	0	0	38.9	0	4.84	86	-.49	+.92	-.92	+182	+3218	+7080
3	20.65	0	0	0	0	0	0	0	0	+1.41	-1.41	+278	+5741	0
4	62.40	0	0	0	0	0	0	0	0	+1.41	-1.41	+278	+17347	0
5	62.40	0	0	0	0	0	0	0	0	+1.41	-1.41	+278	+17347	0
6	54.60	0	0	0	0	0	0	0	0	+1.41	-1.41	+278	+15179	0
7	54.60	1.2	0	0	65.5	0	1.44	79	-.27	+1.14	-1.14	+225	+12285	+14742
8	50.70	5.8	0	0	294.1	0	33.64	1706	-1.30	+.11	-.11	+22	+1115	+6467
9	53.76	12.1	0	0	650.5	0	146.41	7871	-2.71	-1.30	+1.30	-257	-13816	-167174
10	53.76	18.9	0	0	1016.1	0	357.21	19204	-4.23	-2.82	+2.82	-557	-29944	-565942
11	33.92	24.4	0	0	827.6	0	595.36	20195	-5.47	-4.06	+4.06	-802	-27204	-663778
12	19.84	27.9	-5.	-99.2	553.5	-2768	778.41	15444	-6.25	-4.84	-0.16	+32	+635	+17717
13	53.76	32.5	-10.	-537.6	1747.2	-17472	1056.25	56784	-7.28	-5.87	-4.13	+816	+43868	+1425710
14	40.32	38.4	-10.	-403.2	1548.3	-15483	1474.56	59454	-8.60	-7.19	-2.81	+555	+22378	+859315
15	191.88	4.3	0	0	825.1	0	18.49	3548	-.96	+.45	-.45	+89	+17077	+73431
16	64.80	21.3	0	0	1380.2	0	453.69	29399	-4.77	-3.36	+3.36	-664	-43027	-916475
17	18.00	21.3	0	0	383.4	0	453.69	8166	-4.77	-3.36	+3.36	-664	-11952	-254578
18	20.8	20.2	0	0	420.2	0	408.04	8487	-4.52	-3.11	+3.11	-614	-12771	-257974
19	74.37	31.3	0	0	2327.8	0	979.69	72860	-7.01	-5.60	+5.60	-1106	-82253	-2574519
20	20.40	31.3	-3.	-61.2	638.5	-1916	979.69	19986	-7.01	-5.60	+2.60	-514	-10486	-328212
21	27.4	30.0	0	0	822.0	0	900.00	29660	-6.72	-5.31	+5.31	-1049	-28743	-862290
22	66.03	41.7	-10.	-660.3	2687.4	-26874	1656.49	109378	-9.12	-7.71	-2.29	+452	+29846	+1214732
23	51.12	41.1	-10.	-511.2	2101.0	-21010	1689.21	86352	-9.21	-7.80	-2.20	+434	+22186	+911845
24	75.33	41.5	-10.	-753.3	3126.2	-31262	1722.25	129737	-9.30	-7.89	-2.11	+417	+31413	+1303640
25	43.0	42.3	-10.	-430.0	1818.9	-18189	1789.29	76939	-9.48	-8.07	-1.93	+381	+16383	+693001
	Σ=1245.04			Σ=-3456.0	Σ=-23302.1	Σ=-134974		Σ=750400					Σ=-1717	Σ=-57848



INCREMENTS OF CROSS SECTION

Solve Simultaneous Equations for b and c.

ΣCol. 5 − cΣCol. 2 − bΣCol. 6 = 0

ΣCol. 7 − cΣCol. 6 − bΣCol. 9 = 0

$-3456 - 1245c - 23{,}302b = 0$

$-134{,}974 - 23{,}302c - 750{,}400b = 0$

$b = -0.2237 \qquad c = 1.41$ ft.

Find Ordinates of Virtual Temperature Line

$T_v = c - by = 1.41 - 0.2237y$

$f_T = -E\alpha T_v$

by Hurst's method[6] and will result in a form of computation very similar to that in Table C-II.

3. Timoshenko's Method[7,11]. Timoshenko's method may be used for temperature distributions which are either symmetrical about one axis or unsymmetrical about both principal axes of the cross section. It is recommended for the latter case, and a sample computation appears in Table C-II.

4. Corlett's Method[4]. Table C-III outlines and shows an example of the application of Corlett's method.

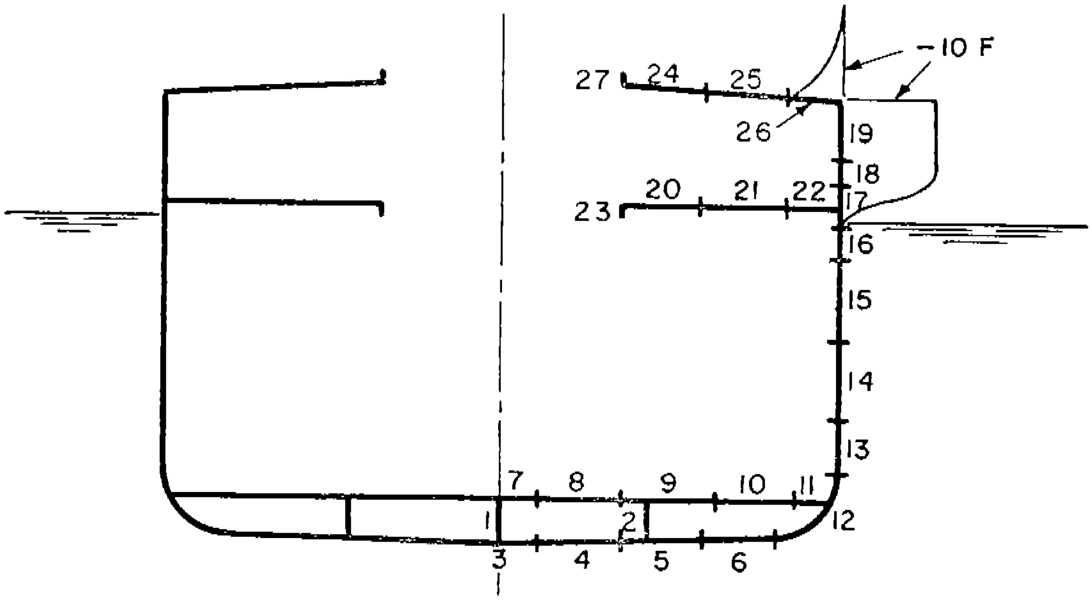
TABLE C-II

LIBERTY SHIP. 27'-7" DRAFT.

SUN ON STARBOARD SIDE. $T_S - T_W = 10$ F. FRAME 83.

1 Increment	2 ΔA Sq. In.	3 y Ft.	4 z Ft.	5 T F	6 $f_1 = -197.5T$ psi	7 $f_1 \Delta A$ lb.	8 $f_1 \Delta Ay$ lb-ft	9 $f_1 \Delta Az$ lb-ft	10 $f_1 + f_2$ psi	11 f_3 psi	12 f_4 psi	13 f_T psi	14 $f_T \Delta A$ lb	15 $f_T \Delta Ay$ lb-ft	16 $f_T \Delta Az$ lb-ft X 10^2
1	23.5	-15.1	0	0	0	0	0	0	+89	-94	0	-5	-115	+1750	0
2P	15.4	-15.0	-12.7	0	0	0	0	0	+89	-93	-68	-[illegible]	-1110	+16650	-14100
2S	15.4	-15.0	+12.7	0	0	0	0	0	+89	-93	+68	+64	+987	-14830	+1[illegible]530
3	52.8	-16.9	0	0	0	0	0	0	+89	-105	0	-16	-846	+14280	0
4P	56.3	-16.8	-6.2	0	0	0	0	0	+89	-104	-33	-48	-2700	+45350	+16730
4S	56.3	-16.8	+6.2	0	0	0	0	0	+89	-104	+33	+18	+1013	-17020	+6280
5P	56.3	-16.6	-13.5	0	0	0	0	0	+89	-103	-72	-86	-4840	+80500	+65400
5S	56.3	-16.6	+13.5	0	0	0	0	0	+89	-103	+72	+58	+3265	-54200	+44150
6P	56.3	-16.5	-20.8	0	0	0	0	0	+89	-102	-111	-124	-6990	+115400	+145600
6S	56.3	-16.5	+20.8	0	0	0	0	0	+89	-102	+111	+98	+5520	-91200	+114700
7	26.4	-13.3	0	0	0	0	0	0	+89	-83	0	+6	+158	-2102	0
8P	35.2	-13.3	-5.8	0	0	0	0	0	+89	-83	-31	-25	-880	+11700	+5100
8S	35.2	-13.3	+5.8	0	0	0	0	0	+89	-83	+31	+37	+1303	-17340	+7560
9P	35.2	-13.3	-12.5	0	0	0	0	0	+89	-83	-67	-61	-2146	+28570	+26830
9S	35.2	-13.3	+12.5	0	0	0	0	0	+89	-83	+67	+73	+2570	-34200	+32150
10P	35.2	-13.3	-19.2	0	0	0	0	0	+89	-83	-102	-96	-3380	+45000	+64900
10S	35.2	-13.3	+19.2	0	0	0	0	0	+89	-83	+102	+108	+3802	-51700	+74100
11P	35.6	-13.3	-25.2	0	0	0	0	0	+89	-83	-134	-128	-4510	+60000	+113300
11S	35.6	-13.3	+25.2	0	0	0	0	0	+89	-83	+134	+14[illegible]	+4930	-65700	+124200
12P	56.3	-12.9	-26.4	0	0	0	0	0	+89	-80	-141	-132	-7440	+96000	+196700
12S	56.3	-12.9	+26.4	0	0	0	0	0	+89	-80	+141	+150	+8460	-109[illegible]00	+2[illegible]3000
13P	41.3	-8.4	-28.5	0	0	0	0	0	+89	-52	-152	-115	-4760	+39930	+135500
13S	41.3	-8.4	+28.5	0	0	0	0	0	+89	-52	+152	+189	+7820	-65700	+223000
14P	50.5	-2.3	-28.5	0	0	0	0	0	+89	-14	-152	-77	-3890	+8960	-110800
14S	50.5	-2.3	+28.5	0	0	0	0	0	+89	-14	+152	+227	+11560	-26600	+329500
15P	50.5	+4.4	-28.5	0	0	0	0	0	+89	+27	-152	-36	-1817	-7990	+51800
15S	50.5	+4.4	+28.5	0	0	0	0	0	+89	+27	+152	+268	+13530	+59600	+386000
16P	22.0	+9.1	-28.5	0	0	0	0	0	+89	+57	-152	-6	-132	-1200	+3760
16S	22.0	+9.1	+28.5	0	0	0	0	0	+89	+57	+152	+298	+6560	+59600	+186700
17P	28.4	+13.4	-28.5	0	0	0	0	0	+89	+83	-152	+20	+568	+7620	-16180
17S	28.4	+13.4	+28.5	-5	-988	-28059	-375991	-799682	-899	+83	+152	-664	-18860	-252700	-538000
18P	10.5	+15.1	-28.5	0	0	0	0	0	+89	+94	-152	+31	+326	+4930	-9300
18S	10.5	+15.1	+28.5	-10	-1975	-20738	-313144	-591033	-1886	+94	+152	-1640	-17230	-260400	-492000
19P	45.5	+18.3	-28.5	0	0	0	0	0	+89	+114	-152	+51	+2320	+42500	-66200
19S	45.5	+18.3	+28.5	-10	-1975	-89862	-1644475	-2558000	-1886	+114	+152	-1620	-73700	-1350000	-2103000
20P	29.6	+11.7	-13.1	0	0	0	0	0	+89	+73	-70	+92	+2720	+31830	-35650
20S	29.6	+11.7	+13.1	0	0	0	0	0	+89	+73	+72	+234	+6930	+81200	+90900
21P	38.4	+11.7	-20.2	0	0	0	0	0	+89	+73	-108	+54	+2073	+24260	-41800
21S	38.4	+11.7	+20.2	0	0	0	0	0	+89	+73	+108	+270	+10360	+121200	+209300
22P	20.4	+11.7	-26.3	0	0	0	0	0	+89	+73	-140	+22	+449	+5270	-11840
22S	20.4	+11.7	+26.3	0	0	0	0	0	+89	+73	+140	+302	+6170	+72300	+162400
23P	23.8	+10.5	-10.4	0	0	0	0	0	+89	+65	-55	+99	+2360	+24800	-24570
23S	23.8	+10.5	+10.4	0	0	0	0	0	+89	+65	+55	+209	+4980	+52300	+51800
24P	41.2	+21.4	-12.4	0	0	0	0	0	+89	+133	-66	+156	+6430	+137700	-79800
24S	41.2	+21.4	+12.4	0	0	0	0	0	+89	+133	+66	+288	+11860	-254000	+147000
25P	60.3	+21.0	-18.4	0	0	0	0	0	+89	+130	-98	+121	+7300	+153300	-134400
25S	60.3	+21.0	+18.4	0	0	0	0	0	+89	+130	+98	+317	+19120	+402000	+352000
26P	55.4	+20.6	-25.2	0	0	0	0	0	+89	+128	-134	+83	+4550	+93800	-114700
26S	55.4	+20.6	+25.2	-3	-592	-32797	-675618	-827000	-503	+128	+134	-241	-13360	-275300	-336700
27P	11.4	+20.7	-10.2	0	0	0	0	0	+89	+129	-54	+164	+1870	+38800	-190800
27S	11.4	+20.7	+10.2	0	0	0	0	0	+89	+129	+54	+272	+3103	+64400	+316500
	$\Sigma = 1924.7$					$\Sigma = -171456$	$\Sigma = -3009228$	$\Sigma = -4775715$					$\Sigma = -3739$	$\Sigma = -401882$	$\Sigma = -400450$

TABLE C-II (Continued)



INCREMENTS OF CROSS SECTION

$$f_2 = \frac{-\text{Col. } 7}{\text{Col. } 2} = \frac{171,456}{1924.7} = 89 \text{ psi}$$

$$f_3 = \frac{-\text{Col. } 8}{I_{zz}} \times \text{Col. } 3 = \frac{3,009,228y}{484,000} = 6.22y$$

$$f_4 = \frac{-\text{Col. } 9}{I_{yy}} \times \text{Col. } 4 = \frac{4,775,715z}{896,000} = 5.33z$$

TABLE C-III

THERMAL STRESSES IN COMPOSITE SHIP BY CORLETT'S METHOD*

The ship used in this example was redesigned from the scantlings of an existing steel ship, the thickness of the light alloy plating, etc., giving the same longitudinal strength as the original ship. The geometrical properties are as follows:-

Moment of inertia of composite hull about neutral axis
$= 257{,}500$ in.^{2}ft.^{2}
Height of neutral axis above U.S.K. = 12.08 ft.

The gradient used was as shown in the figure and it was assumed that all horizontal material was at the same temperature at any level. In general it is not likely that this will be true except in the case of the bottom structure and in an open deck exposed to radiation.

The structure was divided into 2-ft. vertical elements, the decks being taken as elements in themselves. If there had been a gradient across the decks, they too would have been divided into elements.

The area of each element, together with the height y of its center of gravity and the temperature θ at that point is entered in tabular form and ϕ and the thermal bending moment derived as shown in the calculation below. This Table is drawn up in Fahrenheit units.

The expansion stress p_θ is then determined, knowing ϕ, from

$$p_\theta = E\alpha\left[\frac{\phi}{\alpha} - f(y)\right]$$

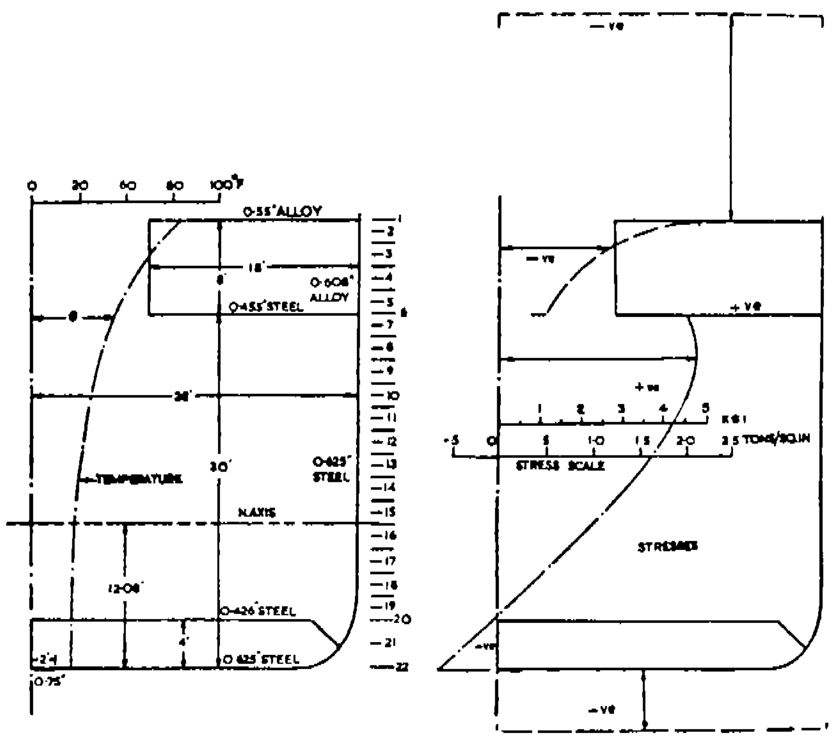
and entered in column 10.

The bending relief stress p_b is given by

$$p_b = \frac{\text{Thermal bending moment}}{\text{Relevant section modulus}}$$

and the total stress is given by the sum of the two.

Column 13 gives the final stress and a check is obtained in columns 14 and 15 by obtaining the total force on the section.



-CALCULATION FOR COMPOSITE FREIGHTER. L.O.A. 390 FT.

*The material in this table is quoted in Reference 4.

TABLE C-III (Continued)

THERMAL EXPANSION EFFECTS IN COMPOSITE SHIPS

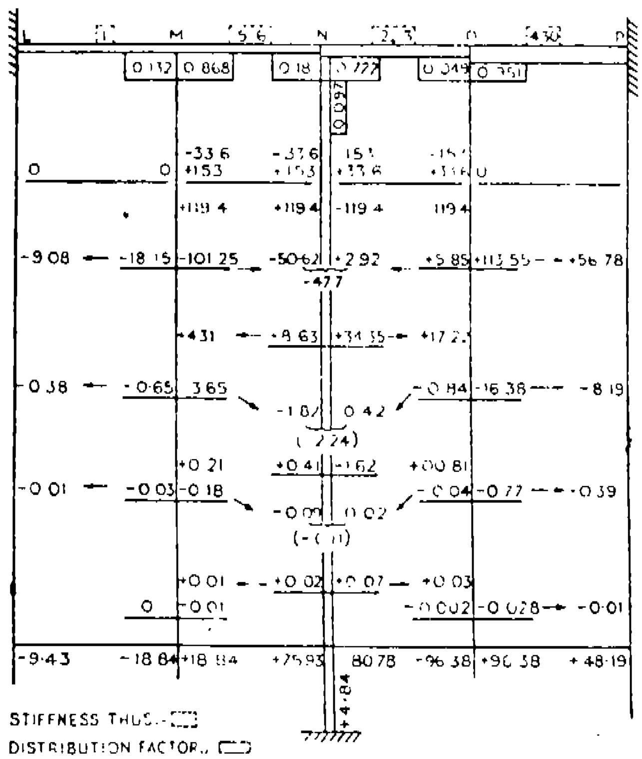
390 FT. 56 FT. × 30 FT. FREIGHTER. PARABOLIC TEMPERATURE GRADIENT

No.	1 A	2 θ	3 y	4 $A_a\theta$	5 $A_s\theta$	6 $yA_a\theta$	7 $yA_s\theta$	8 yA_a	9 yA_s	10 p_θ	11 p_l	12 p_t	13 $+p_tA$	14 $-p_tA$
1	230	80·0	38	18,400		709,000		8,750		3·57	1·38	2·19		503
2	29	70·0	37	2,030		75,100		1,070		- 2·98	1·33	1·65		48
3	29	58·0	35	1,680		62,500		1,018		2·30	- 1·22	1·08		31
4	29	50·5	33	1,462	3	48,400		958		1·87	+ 1·12	0·75		22
5	29	45·0	31	1,310	35,020	40,600		900		1·56	1·01	0·55		16
6	200	42·5	30	24,882	8,500	935,600	255,000	12,696	6,000	0·79	2·86	2·07	414	
7	30	40·3	29	1·9	1,209	0·63	35,000		870	0·59	2·70	2·11	63	
8	30	36·5	27		1,095		29,600		810	0·24	2·38	- 2·14	64	
9	30	33·0	25		990		26,800		750	- 0·07	- 2·06	2·13	64	
10	30	30·5	23		915		21,100		690	0·30	- 1·75	2·05	61	
11	30	28·2	21		846		17,800		630	- 0·51	1·43	1·94	58	
12	30	26·5	19		795		15,100		570	0·66	- 1·12	- 1·78	53	
13	30	25·0	17		750		12,700		510	0·80	- 0·78	- 1·58	47	
14	30	24·0	15		720		10,800		450	0·89	0·47	- 1·36	41	
15	30	22·9	13		687		8,920		390	- 0·99	- 0·14	- 1·13	34	
16	30	22·0	11		660		7,250		330	- 1·07	0·17	- 0·90	27	
17	30	21·2	9		636		5,720		270	- 1·14	0·49	0·65	20	
18	30	20·6	7		618		4,320		210	1·20	- 0·81	0·39	12	
19	30	20·3	5		609		3,045		150	- 1·22	1·13	- 0·09	3	
20	245	20·2	4		4,950		19,800		980	- 1·23	1·29	0·06		16
21	156	20·0	2		3,120		6,240		312	- 1·25	1·62	- 0·37		58
22	396	20·0	0		7,920		0		0	- 1·25	1·92	0·67		265
Σ	Sq. in.	°F	Feet	47,300	105,060	589,400	477,195	4,232	13,922	Ton/sq.in.	Ton/sq.in.	Ton/sq.in.	961 Tons	959 Tons

$$\phi/\alpha_s = \frac{\Sigma\,\text{Col. 4} + \Sigma\,\text{Col. 5}}{A_a + 3\,A_s} = \frac{152{,}360}{4{,}507} = 33\cdot 8 \quad\text{and}\quad \phi/\alpha_a = 17\cdot 8.$$

Hogging bending moment $= [\phi/\alpha_s \,.\, \Sigma\,(\text{Col. 8} + \Sigma\,\text{Col. 9}) - (\Sigma\,\text{Col. 6} + \Sigma\,\text{Col. 7})] \cdot E_s \alpha_s$
$= (33\cdot 8 \times 18{,}154 - 1{,}066{,}595)\, 0\cdot 0904$
$= 41{,}200$ tons feet.

The Hardy Cross distribution of the transverse bending moments arising from the gradient described above is given below.



APPENDIX D

EFFECT OF WEATHER CONDITIONS UPON THE TEMPERATURES OF EXPOSED SURFACES

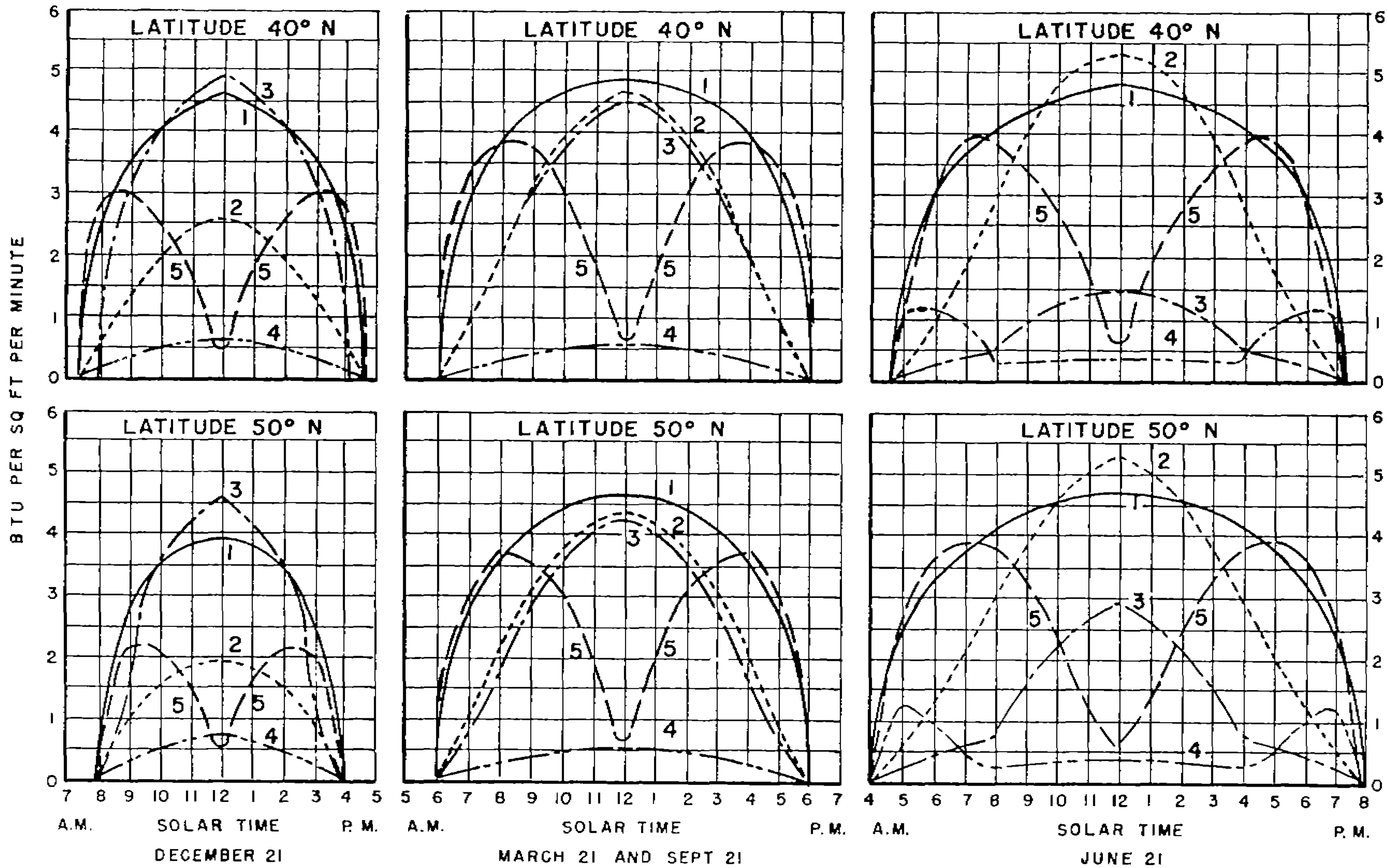
1. Weather Conditions Which Affect the Temperature of Exposed Surfaces. The principal weather conditions which act to change the temperature of an exposed surface are the difference between the temperatures of the ambient air and the surface; insolation; atmospheric conditions such as humidity, smoke, and cloudiness; wind; and precipitation. The heat transfer through the exposed surfaces of a structure depends upon the amount of insolation; the absorptivity of the exposed surfaces; the losses by convection, conduction, and radiation to surrounding media; the heat capacity of the structure; and the thermal resistance of the structure.

2. Weather Conditions and Heat Transfer by Radiation. The temperature of a structure which is not exposed to insolation will tend to approach and subsequently reach the ambient air temperature. However, if the structure is exposed to insolation, an exposed surface will develop a temperature higher than that of the ambient air.

The amount of insolation received on an exposed surface is related to the inclination of the surface with respect to the sun's rays and the time of the year. Tables (26--28) for computing the angle of incidence and the rate of insolation are available. These data were summarized by Hand(29) in the form shown in Fig. D-1. It may be seen that the amount of insolation varies with the time of the day, the season of the year, and the latitude.

Atmospheric conditions which reduce the intensity of radiation are water vapor as measured by humidity, smoke, dust, and clouds. On a humid day in an industrial area, as much as 35 to 50 per cent of the total insolation(28) may be intercepted by water vapor, smoke, and dust. Clouds also shield the earth's surface from insolation. Hand(27) found that a cloud cover of 10/10 (complete cloudiness) at the Blue Hill Observatory in Massachusetts reduced the total insolation by as much as 40 per cent during the winter months. It should be noted that cloudiness is measured in terms of the portion of the sky area obscured by clouds and not in terms of cloud depth.

The intensity of the insolation on a vertical or almost vertical surface may be tremendously increased during the several-hour period following sunrise and preceding sunset by an effect known as "albedo". Quantitatively, "albedo" is used to represent the percentage of insolation reflected from a horizontal surface. If the sun's rays pass over a horizontal plane of considerable extent before striking the exposed surface in question, insolation impinging upon the horizontal plane at a flat angle is reflected against the exposed surface.



1. NORMAL INCIDENCE.
2. HORIZONTAL SURFACE.
3. VERTICAL SURFACE FACING SOUTH.
4. VERTICAL SURFACE FACING NORTH.
5. VERTICAL SURFACE FACING EAST DURING MORNING AND WEST DURING AFTERNOON.

Fig. D-1. Diurnal Variation of Insolation at Sea Level for Average Clear Sky Conditions (Hand).

The albedo for various types of reflecting surfaces as reported by a number of investigators[30--32] is shown in Fig. D-2. The albedo of clean ice and snow[31] is even higher than that of dry sand[32]. It may be seen that albedo at low solar altitudes may increase the total insolation by as much as 100 per cent.

During the period just after sunrise, a vertical surface facing a direction lying between east and south can receive an intensity of insolation in mid-winter approaching or even surpassing that at midday in the summer. This situation can occur when very clear skies, albedo, and the slow rate of change of solar altitude when the sun is low in the sky combine to produce an intense insolation.

The temperatures attained by horizontal surfaces exposed to the summer sun are shown in Fig. D-3[33]. The humidity at the hours of 0800, 1200, and 1700 was reported[34] as 46, 17, and 15 per cent, respectively, these data being observed at a weather station about fifteen miles distant. The sky was clear with an ulimited ceiling. These values therefore should correspond to "average clear sky" conditions.

The effect of color upon the absorption of insolation is clearly shown by Fig. D-3. While the temperatures of the white and the aluminum surfaces were only 10 to 13 F above that of the air at midday, those of the red and black surfaces were 40 and 55 F higher. These values are in substantial agreement

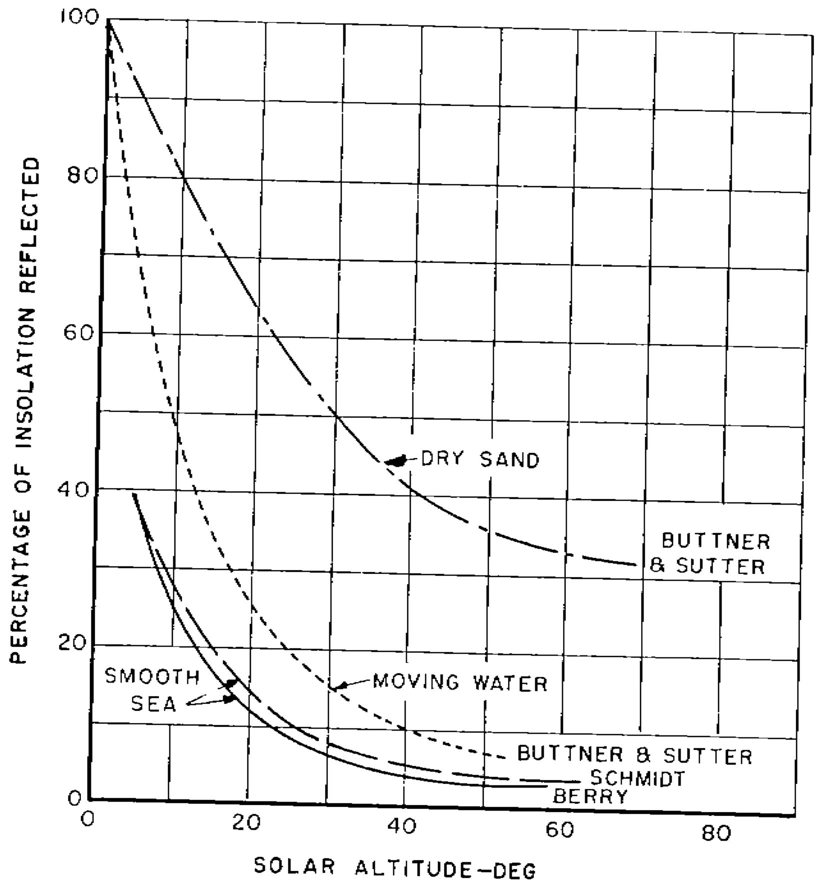


Fig. D-2. Relation of Albedo to Solar Altitude for Total Solar Radiation on Clear Days.

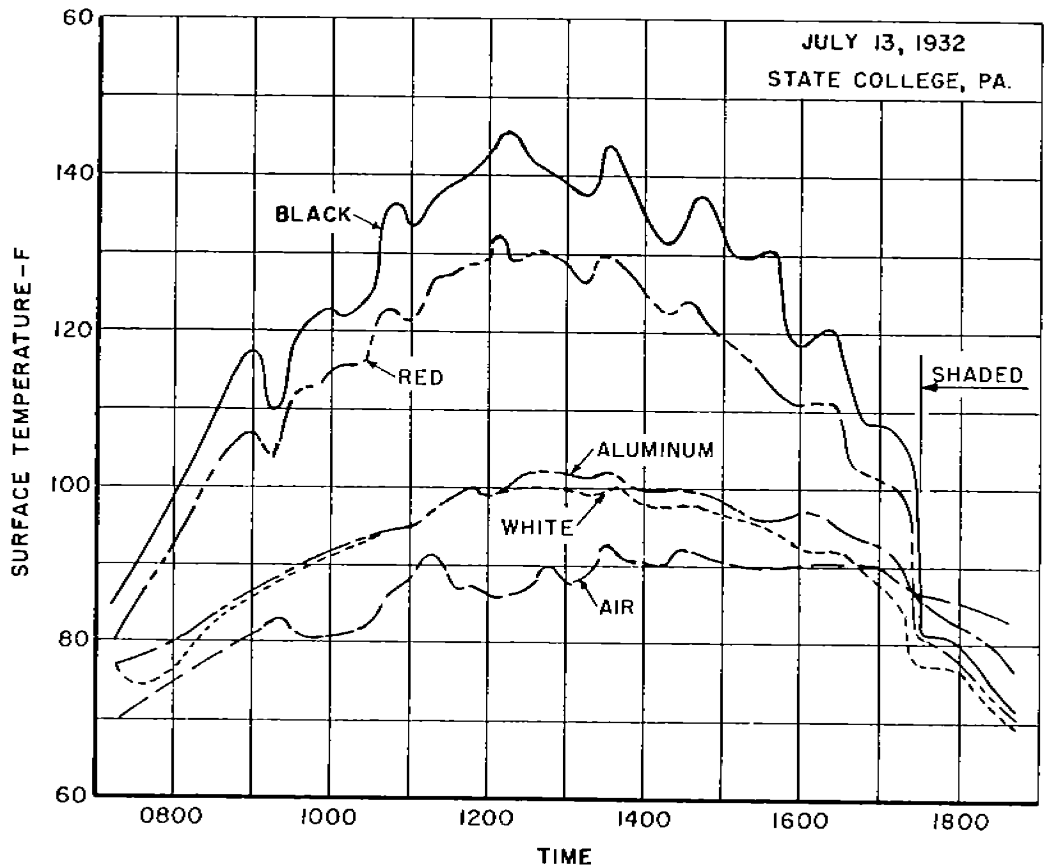


Fig. D-3. Effect of Color upon Temperature of Horizontal Surfaces Subjected to Isolation (Hechler and Queer).

with the differentials of 52 to 62 F recommended by heating and ventilating engineers[28] for light and medium construction roofs and less than the differential of 80 to 90 F reported for black surfaces by Schropp[25].

In these tests a tree shaded the test panels after the hour of 1730. The twenty-degree drop in temperature in a few minutes as a result of this shade can be seen in Fig. D-3. In other tests[35] the measured insolation was reduced to 8 per cent when a roof was placed over the pyrheliometer and to about 18 per cent when the instrument was shaded by the observer's hand.

A very extensive bibliography on insolation is listed by Crabb[36], and on heat transmission by McAdams[37].

Another type of radiation occurs at night when a horizontal surface radiates heat to the relatively colder outer space beyond the atmosphere of the earth and thereby cools itself. This phenomenon is known as "nocturnal radiation" and results in the temperature of the exposed surface becoming appreciably lower than that of the ambient air. Table D-I gives data observed by Schropp[25] under unspecified weather conditions. The differential of 5 F in these tests appears small when it is remembered that this phenomenon is employed in northern India to freeze water in shallow pans on very clear summer nights.

Nocturnal radiation increases as the cloud height increases[31] and also as the amount of water vapor, dust, and

TABLE D-I

EFFECT OF NOCTURNAL RADIATION ON TEMPERATURES OF HORIZONTAL SURFACES

Time of Day	Temp. of Air--F	Temperature of Horizontal Surface--F		
		Bright Aluminum Foil	Black Paper	White Paper
2100	19.4	19.6	12.4	13.5
2400	15.8	15.8	10.8	9.5
0030	15.6	--	10.2	9.5
2135	24.8	--	17.0	17.6
2235	24.8	22.4	18.0	18.8

Observations made by Schropp(25) on horizontal surfaces protected from wind at Munich, Germany, Latitude 48°N, on February 11--12, 1930. Sky conditions, humidity, and nature of area surrounding location of test not given.

smoke in the atmosphere decreases. However, even a gentle wind reduces the effect of this radiation by mixing the great mass of air over the exposed surface. Therefore, nocturnal radiation most effectively reduces the temperature of a horizontal surface on a still night.

3. <u>Convection of Heat by Wind</u>. The effectiveness of wind in removing heat from a dry smooth surface is shown in Fig. D-4[38], where the temperature of the moving air was maintained at a constant differential above that of the surface. A wind velocity of 25 mph removed about six to eight times as much heat as a velocity of zero. Moreover, the angle at which the wind impinged on the exposed surface made no substantial change in the rate of heat loss through convection.

Moving air will absorb heat from a wet surface as long as the wet-bulb temperature of the air is lower than that of the water on the surface[28]. The rate of heat absorption increases with an increase in the wind velocity and with the difference between the wet-bulb temperature of the air and the initial temperature of the water film. If the above conditions are present, a wet surface will be cooled more rapidly than a dry surface at the same temperature.

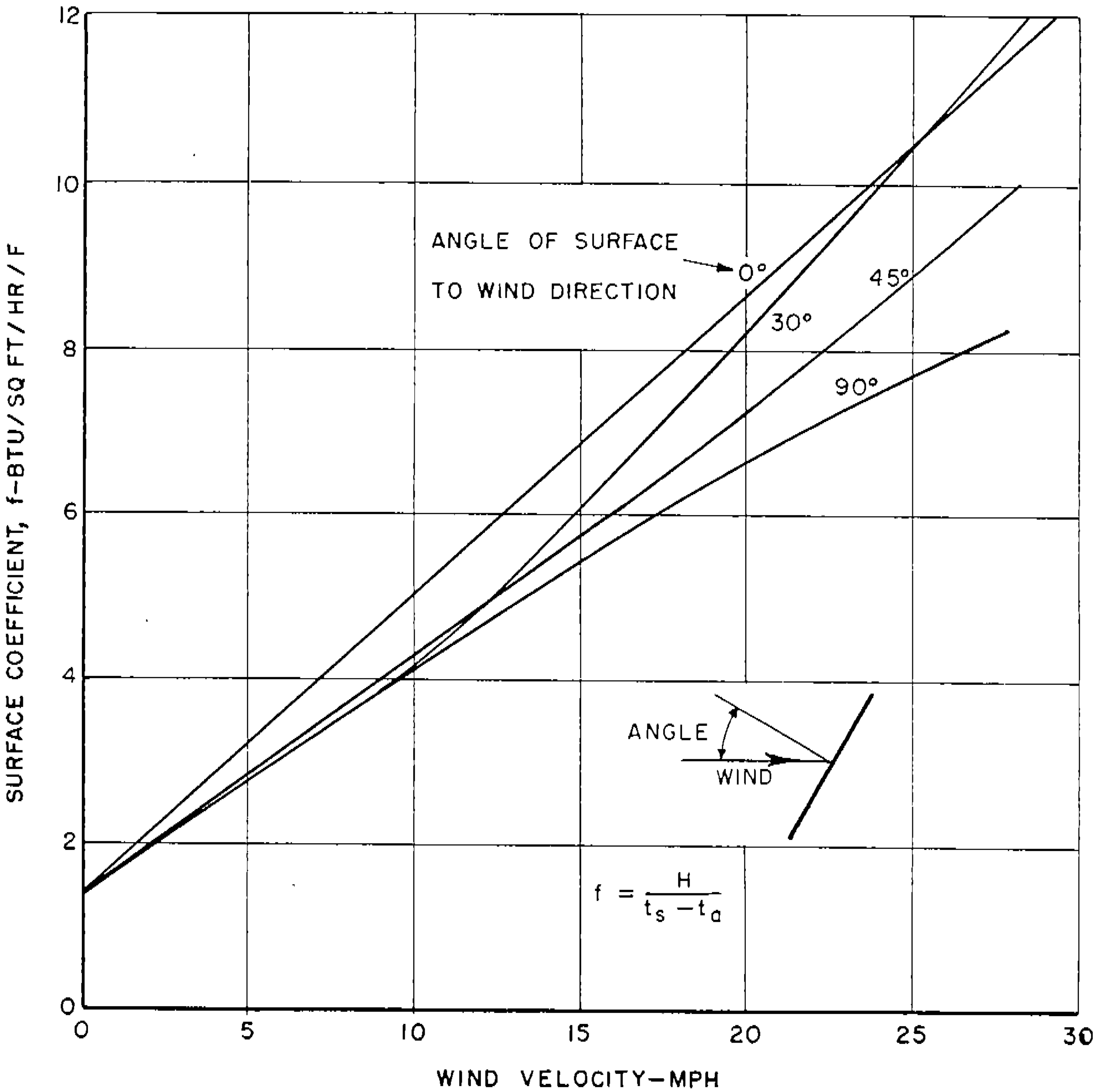


Fig. D-4. Surface Coefficients for Dry Smooth Pine Surface for Different Wind Velocities (Rowley and Eckley).

APPENDIX E

TYPICAL SHIP CASUALTIES

This section gives brief descriptions of ship casualties. Cases of Group I casualties are given for the following types of vessels:

Tankers:	T2	19 ships
	Miscellaneous	3 "
Liberty ships		11 "
Miscellaneous dry-cargo		4 "
Refrigerated ships		2 "

In addition to these thirty-nine cases, two other lesser casualties were of interest and are included. The casualties follow in numerical order according to the number assigned by the American Bureau of Shipping.

The wind velocity is often described according to the Beaufort wind scale. The following table gives the force numbers used in this scale:

Velocity mph	Force No.	Weather Bureau Designation
0	0	Light
1--3	1	
4--7	2	
8--12	3	Gentle
13--18	4	Moderate
19--24	5	Fresh

Velocity mph	Force No.	Weather Bureau Designation
25--31 32--38	6 7	Strong
39--46 47--54	8 9	Gale
55--63 64--75	10 11	Whole Gale
Above 75	12	Hurricane

Vessel: Casualty No. 8 Type: EC2-S-C1 Liberty

Class of Casualty: Group I Date of Casualty: 12/25/42, 2320

Ship's Location: 54°-40' N, 143°-07' W. Gulf of Alaska, 450 miles W. of Ketchikan

Course: S. E. Drafts: Fwd. 6'-6" Aft 15'-8"

Weather: --- Sea Condition: Heavy

Wind: Force 5 T_A 40 F T_W 40--46 F

Circumstances Surrounding Failure: En route Kodiak to Seattle. Increasing water temperature. Vessel converted to troopship.

Location of Fracture: Sheer and stringer plates, Fr. 90-91, port side, in way of refrigerated space.

Vessel: Casualty No. 13 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 1/16/43, 2300

Ship's Location: Outfitting Dock, Portland, Oregon.

Course: Moored, approx. S. E. Drafts: Fwd. 6'-4" Aft 17'-0"

Weather: Clear turning misty Sea Condition: Calm

Wind: 14-5 mph. T_A 23 F T_W 40 F

Circumstances Surrounding Failure:

Hourly air temperatures:

Hour:	1200	1400	1600	1800	2000	2200	2400
Temp. F:	38	39	33	31	28	24	23

Sunshine 3/10 during afternoon, sunset 1652.

Vessel completed trials in Columbus River and returned to dock on Willamette River about 1530. Wind on port side, fracture origin on starboard side. Stress in deck 10,700 psi tension.

Location of Fracture: Ship broke in two through No. 5 Tanks. Origin of fracture at aft end fashion plate on starboard side (just aft of bridge structure.)

Vessel: Casualty No. 16 Type, EC 2-S-Cl Liberty

Class of Casualty: Group I Date of Casualty: 2/15/43, 0735

Ship's Location: At anchor, Upper New York Bay, New York

Course: At anchor headed NNW Drafts: Fwd. 22'-10" Aft 26'-5"

Weather: Clear Sea Condition: Normal

Wind: Force 4 T_A -8 F T_W 33 F

Circumstances Surrounding Failure: Sun rose at 0650 and struck stbd. side of vessel. Fracture at 0735. Rel. humidity 47% at 0730 and 26% at noon. Very clear day with 100% sunshine. Average wind velocity for day 32 mph. Max. temperature day before, 24 F; two days before 37 F. Sundden drop in temperature.

Location of Fracture: Fr. 83-84. Crack in stringer plate and two strakes inboard, sheer and strake below, port side. Sun struck starboard side, fracture on port side.

Casualty No. 17 occurred a few miles away on the same morning under similar circumstances.

Vessel: Casualty No. 17 | Type: EC 2-S-C1 Liberty

Class of Casualty: Group I | Date of Casualty: 2/16/43, 1040

Ship's Location: S. side Pier 7, New York, New York

Course: Moored, approx. E | Drafts: Fwd. 24'-0" Aft 27'-6"

Weather: Clear | Sea Condition: Calm

Wind: Av. for day 32 mph. | T_A 10 F T_W 31 F

Circumstances Surrounding Failure: Sun rose at 0650 and struck stbd. side of vessel. Fracture at 1040. Rel. humidity 47% at 0730 and 26% at noon. Very clear day with 100% sunshine. Av. wind velocity for day 32 mph from NW. Max. temperature day before, 24 F; two days before, 37 F. Sudden drop in temperature. Min. preceding night, -7 F. Air temperatures:

Hour:	0900	1040	1200	High
Temp. F:	7	10 (Fracture)	17	22

Location of Fracture: Fr. 62--64. Main deck centerline to gunwale and down port side into strake below sheer. Sun struck starboard side, fracture on port side.

Casualty No. 16 occurred a few miles away on same morning under similar circumstances.

Vessel: Casualty No. 22 — Type: EC 2-S-C1 Liberty

Class of Casualty: Group I — Date of Casualty: 3/14/43, 0745

Ship's Location: 230 miles E. of St. Johns, Newfoundland

Course: E'ly — Drafts: Fwd. 23'-3" Aft 28'-6"

Weather: Foggy and overcast — Sea Condition: Calm

Wind: Gentle — T_A 32 F T_W 30 F

Circumstances Surrounding Failure: Ship leaving coastal waters and entering region where cold Labrador current and warm Gulf Stream meet. Note low water temperature.

Location of Fracture: Fr. 73-74. Crack corner No. 3 Hatch across deck port side and down side to 2 ft above second deck.

Vessel: Casualty No. 25 — Type: T2-SE-A1 Tanker

Class of Casualty: Group I — Date of Casualty: 3/29/43, 1205

Ship's Location: Ambrose Channel, New York Harbor, New York

Course: Outbound — Drafts: Fwd. 12'-1" Aft 18'-7"

Weather: Clear with bright sun — Sea Condition: Slight ground swell

Wind: Force 2 — T_A 30-42 F (Rising) T_W ---

Circumstances Surrounding Failure:

Failure while taking on water ballast.

Mean average water temperature at Battery, New York, 38 F.

Computed stillwater tension bending stress in deck, 12,500 psi.

Location of Fracture: Broke in two at Fr. 55-56.

Vessel: Casualty No. 58 — Type: EC 2-S-C1 Liberty

Class of Casualty: Group I — Date of Casualty: 1/2/44, 0300

Ship's Location: At anchor, Murmansk, Russia.

Course: At anchor — Drafts: Fwd. 24'-0" Aft 25'-2"

Weather: Normal — Sea Condition: Calm

Wind: Force 1 — T_A 13 F T_W 38 F

Circumstances Surrounding Failure: Note failure at middle of night under clear skies.

Location of Fracture: Fr. 104-105, port side. Crack inboard 6 ft in deck and 9 ft down side. Also into second deck.

Vessel: Casualty No. 77 — Type: Z-ET1-S-C3 Tanker

Class of Casualty: Group I — Date of Casualty: 1/28/44, 2036

Ship's Location: 54°-17'N, 166°-25'W, 20 miles north of Dutch Harbor, Alaska in Bering Sea.

Course: 25° True (Outbound) — Drafts: Fwd. 25'-0" Aft 28'-4"

Weather: Snowing — Sea Condition: Heavy

Wind: Force 8 — T_A 24 F T_W 34 F

Circumstances Surrounding Failure:

Oil in tanks being heated for pumping out and had reached average temperature of 90 F.

Location of Fracture: Fr. 113, starboard side. Deck 14 ft inboard, 15 ft down side, 4 ft into Second Deck.

Vessel: Casualty No. 90 | Type: T2-SE-A1 Tanker

Class of Casualty: Group I | Date of Casualty: 3/2/44, 0515

Ship's Location: At anchorage at New York, New York

Course: Anchored | Drafts: Fwd. 4'-7" Aft 15'-11"

Weather: --- | Sea Condition: Normal

Wind: Force 4 | T_A 16 F T_W 35 F

Circumstances Surrounding Failure:

Air Temperatures at Battery Weather Station, New York, New York

Hour:	1600	1800	2000	2200	2400	0200	0400	0500	0600
Temp. F:	32	26	22	19	17	17	16	16	15
Rel. Humidity			43%						29%

Cloudiness 5/10, sunshine 99% of possible, average wind velocity 22 mph. Butterworthing tanks with 210 F water. No. 7 Tanks just completed and No. 8 Tanks begun when fracture occurred.

Location of Fracture: No. 7 Starboard Wing Tank, Fr. 53-54.

Crack 17'-6" long in side shell and 9'-7" into deck.

Vessel: Casualty No. 95 | Type: EC2-S-C1 Liberty

Class of Casualty: Group I | Date of Casualty: 3/5/44, 1310

Ship's Location: Loading at dock, Hoboken, N. J.

Course: Moored | Drafts: Fwd. 19'-4" Aft 24'-6"

Weather: Fine Clear | Sea Condition: Calm

Wind: Light N'ly | T_A 34 F T_W 35 F

Circumstances Surrounding Failure:

Air temperatures at Battery Weather Station, New York, New York

Hour:	0400	0600	0800	1000	1200	1300	1400	1600
Temp. F:	16	16	17	18	26	29	30	33
Rel. Humidity:			42%		30%			

Note rapid rise in temperature prior to fracture at 1310, low relative humidity, cloudiness 5/10, sunshine 84 per cent of possible, and average wind velocity of 17 mph.

Location of Fracture: Fr. 137 1/2, port side. Sheer strake and two strakes below. Stringer plate into adjacent plate. Fracture in vicinity of prior damage from collision.

Vessel: Casualty No. 96 | Type: EC2-S-C1 Liberty

Class of Casualty: Group I | Date of Casualty: 3/15/44, 0300

Ship's Location: 36°-54'N, 72°-37'W, outbound from Lynnhaven Roads, Va.

Course: E'ly | Drafts: Fwd. 28'-7" Aft 28'-7"

Weather: Very clear | Sea Condition: Rough

Wind: Force 4 | T_A 50 F T_W 70 F

Circumstances Surrounding Failure: In port on 3/14/55, ship experienced very clear day with low humidity and 10/10 sunshine with max. temperature of 50 F. Mean temperature of water in Norfolk area averages 42 F in March. Ship sailed quickly into water at 70 F (entering Gulf Stream).

Location of Fracture: Deck starboard side from No. 3 Hatch to gunwale and down side shell 6 ft.

Vessel: Casualty No. 100 Type: EC 2-S-C1 Liberty

Class of Casualty: Group I Date of Casualty: 12/16/44, 0505

Ship's Location: 98 miles S. E. Ambrose Channel, New York

Course: S. E. (outbound) Drafts: Fwd. 27'-1" Aft 30'-5"

Weather: Fine and clear . Sea Condition: ---

Wind: Force 5 T_A 47 F T_W 52 F

Circumstances Surrounding Failure: Left New York previous evening. Air temperature increased 8 F and water 4 F in few hours before fracture when leaving Continental Shelf and entering deeper warmer water of Gulf Stream.

Location of Fracture: ---

Vessel: Casualty No. 101 Type: C1-M-AV1 Dry Cargo

Class of Casualty: Group I Date of Casualty: 1/9/45, 1130

Ship's Location: At dock, Superior, Wisc.

Course: Moored Drafts: Fwd. 1'-11" Aft 14'-0"

Weather: Extreme Cloudiness Sea Condition: Calm

Wind: 5--17 mph. T_A --- T_W 32 F

Circumstances Surrounding Failure:

Temperatures at Duluth, Minnesota (across bay)

Hour:	0400	0600	0800	1000	1100	1200
Temp. F:	-20	-21	-15	-10	-7	-6

Temperatures at Superior: Min. during night of Jan. 8-9, -16 F.
Max. during day of Jan. 9, 6 F.

Bay frozen over. 100 per cent sunshine for previous day and max. temperature of -6 F.

Location of Fracture: Fr. 81-82, starboard side. Crack from hatch coaming to gunwale bar.

Vessel: Casualty No. 103 Type: C2-S-E1 Dry Cargo

Class of Casualty: Group I Date of Casualty: 1/27/45, 0110, 0440

Ship's Location: 40°-10'N, 69°-24' W, 225 miles E. of New York, N. Y.

Course: 086° True (Outbound) Drafts: Fwd. 26'-2" Aft 27'-1"

Weather: Clear Sea Condition: Normal

Wind: Force 4 T_A 32 F T_W 47 F

Circumstances Surrounding Failure: Vessel just entering warmer Gulf Stream. Completely clear sky preceding day and during night. 10/10 sunshine previous day. Ship was returning to New York when at 0440 second fracture occurred.

Location of Fracture: At 0110 No. 3 Hatch across main deck, down port side to third deck, down starboard side below third deck, across second deck starboard side and into second deck port side.

At 0440, No. 4 Hatch, main deck from hatch girder to bulwark and down side short distance.

Vessel: Casualty No. 112 Type: Tanker not M. C.

Class of Casualty: Group I Date of Casualty: 5/11/45, 1830, 2150

Ship's Location: 41°-25'N, 63°-25'W, 180 miles from Halifax and leaving Gulf Stream.

Course: 035-055° True | Drafts: Fwd. 30'-11" Aft 31'-3"

Weather: Overcast | Sea Condition: Heavy

Wind: Force 5-6 | T_A 43 F T_W 42 F

Circumstances Surrounding Failure:

Cargo oil being heated for discharge. Had reached 108 F. Computed stillwater bending stresses: Deck 7700 psi (compression), bottom, 7500 psi (tension).

Location of Fracture: Two fractures. Bottom shell and up port side almost to deck, Fr. 28-31. Bottom shell and up stbd. side, Fr. 29-32.

Vessel: Casualty No. 123 | Type: T2-SE-A1 Tanker

Class of Casualty: Group I | Date of Casualty: 1/8/46, 0830

Ship's Location: At dock in harbor at LeHavre, France.

Course: Moored | Drafts: Fwd. 25' Aft 27'

Weather: --- | Sea Condition: ---

Wind: --- | T_A 25 F T_W 45 F

Circumstances Surrounding Failure:

Air Temperatures:

Hour:	1200	2000	2400	0400	0800	1200
Temp. F:	36	29	25	24	25	29

Fracture at 0830

Ship arrived 1/6/46, 1320. Cargo discharge begun 1/7/46, 2000, from all tanks. Gasoline in No. 7 tanks (no heating of cargo in these tanks).

Location of Fracture: No. 7 starboard Wing Tank around turn of bilge.

Vessel: Casualty No. 124 | Type: T2-SE-A1 Tanker

Class of Casualty: Group I | Date of Casualty: 1/14/46, 0200

Ship's Location: At dock, Boston, Mass.

Course: Moored | Drafts: Fwd. 22'-4" Aft 25'-6"

Weather: Cold and clear | Sea Condition: Calm

Wind: Force 3-4 | T_A 8 F T_W 36 F

Circumstances Surrounding Failure:

Ship arrived at dock on 1/13/46, 1400, and began to discharge Bunker-C fuel oil at 120 F. Fracture found when 28 per cent of cargo discharged.

Location of Fracture: Fr. 60-61, No. 5 starboard Wing Tank, Crack 9 ft long around turn of bilge.

Vessel: Casualty No. 126 | Type: EC2-S-C1 Liberty

Class of Casualty: Group I | Date of Casualty: 1/19/46, 1955

Ship's Location: 43°-06N, 64°-25'W, 120 miles S. Halifax, N. S.

Course: 027° True | Drafts: Fwd. 22'-7" Aft 24'-6"

Weather: Good | Sea Condition: Smooth

Wind: Froce 2 | T_A 30 F T_W 43 F

Circumstances Surrounding Failure: Ship approaching Halifax and entering colder coastal waters.

Location of Fracture: Fr. 141-142. Main deck starboard side No.5 Hatch to gunwale.

Vessel: Casualty No. 128 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 1/22/46, 0600

Ship's Location: Entering Boston Harbor, Mass.

Course: Various Drafts: Fwd. 28'-8" Aft 30'-8"

Weather: Overcast Sea Condition: Smooth

Wind: Force 3-4 T_A 36 F T_W 36 F

Circumstances Surrounding Failure: Fracture just after passing harbor entrance. Loaded with Bunker-C fuel oil and probably therefore heating oil.

Location of Fracture: No. 5 Port Wing Tank. 21-ft crack around turn of bilge.

2-ft crack in same tank after repair while filling it with water for test.

Vessel: Casualty No. 137 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 3/19/46, 0438

Ship's Location: 38°-17'N, 74°-11'W, leaving Gulf Stream and skirting shore waters near Delaware.

Course: 010° True Drafts: Fwd. Loaded Aft Loaded

Weather: Rain squalls Sea Condition: Rough

Wind: Force 7 T_A 46 F T_W 48 F

Circumstances Surrounding Failure:

Storm started at 0200 and air temperature dropped 30 F in 2 1/2 hours.

Location of Fracture: No. 5 and No. 6 center and starboard Wing Tanks. 35-ft crack, bottom, around bilge, and up side.

Vessel: Casualty No. 155 | Type: T2-SE-A2 Tanker

Class of Casualty: Group I | Date of Casualty: 12/9/47, 0815

Ship's Location: At dock, Boston, Mass.

Course: Moored, approx. W. | Drafts: Fwd. 14'-0" Aft 18'-0"

Weather: Clear | Sea Condition: Smooth

Wind: 25-45 mph. | T_A 34 F T_W 41 F

Circumstances Surrounding Failure: Sun rose at 0702 and struck port side of vessel. Sheltered stretch of water between ship and sun. Fracture at 0815. Shed lying to south of ship on adjacent pier did not afford shade except at very low solar altitudes. Rel. humidity 0730, 52%; 1330, 49%. Clear day. Bright sun, 10/10 of possible for day. Strong wind on starboard side. Tanks in vicinity of fracture empty. High tide at 0833, height 10 ft.

Air Temperatures:

Hour:	2400	0200	0400	0600	0800	0815	0900
Temp. F:	43	38	35	35	34	Fracture	34

Location of Fracture: Broke in two between No. 6 and 7 Tanks. Sun on port side. Fracture origin on starboard side at base of chock on stringer plate.

Vessel: Casualty No. 158 | Type: C2-SU Reefer

Class of Casualty: Group I | Date of Casualty: Found 12/19/47

Ship's Location: 43°-57'N, 47°-11'W, 230 miles E. of St. Johns, Newfoundland

Course: W'ly | Drafts: Fwd. 16'-11" Aft 23'-2"

Weather: --- Sea Condition: Rough swell

Wind: Force 3 T_A 38 F T_W 36 F

Circumstances Surrounding Failure: Ship leaving warmer Gulf Stream and entering Labrador Current (note 36 F temperature). Between 1942 and 1952, this ship sustained ten other separate incidences of cracks sufficient in magnitude to be termed "casualties". Most cracks in main and second deck. Last crack 9'-6" long in second deck while cooling No. 5 hold.

Location of Fracture: No. 4 Hatch. Crack from corner of hatch across starboard side of main deck to gunwale.

Vessel: Casualty No. 163 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 3/19/46, 0430

Ship's Location: 39°-00'N, 73°-00'W, off Cape May, N. J.

Course: 336° True Drafts: Fwd. 28'-11" Aft 30'-11"

Weather: Clear Sea Condition: Moderate to rough

Wind: Force 5-6 T_A 48 F T_W 50 F

Circumstances Surrounding Failure: Coming out of Gulf Stream.

Water Temperatures (Falling):

Hour:	1600	2000	2400	0400	0430	0800	1200
Temp. F:	74	62	52	50	Fract.	45	44

Rel. Humidity: 80-90%.

Cargo oil kept heated to 100 F for three days prior to failure.

Location of Fracture: No. 6 and 7 starboard Wing Tanks. Crack around turn of bilge.

Vessel: Casualty No. 171 Type: EC2-S-C1 Liberty

Class of Casualty: Group I Date of Casualty: 2/10/48, 0600

Ship's Location: 46°N, 45°W, 400 miles E. St. Johns, Newfoundland

Course: 235° True Drafts: Fwd. 8' Aft 16'

Weather: Overcast, snow Sea Conditions: Rough

Wind: Force 8-9 T_A 27-28 F T_W 42 F

Circumstances Surrounding Failure: Vessel leaving warmer Gulf Stream for colder coastal waters. Ship pounded heavily once at 0600 and cracks found at 0640. Still-water bending stress in deck, 4000 psi tension.

Location of Fracture: Main deck, second deck port and starboard of No. 3 Hatch, six strakes down on port side shell, four strakes down on starboard side shell. Main deck, starboard side, from No. 2 Hatch to gunwale.

Vessel: Casualty No. 183 Type: EC2-S-C1 Liberty

Class of Casualty: Group I Date of Casualty: 11/26/48, 1630

Ship's Location: At dock, Whittier, Alaska, Lat. 61° N.

Course: Moored at 270° True Drafts: Fwd. 15'-11" Aft 22'-5"

Weather: Slightly foggy Sea Condition: Calm

Wind: 42 mph. T_A 0°F T_W 37-40 F

Circumstances Surrounding Failure: Ship arrived at 1600 from Adak. Very clear weather on day of fracture and preceding day. Sunrise, 0803. Sunset, 1525. 42 mph wind on blowing on port side of ship. 4 in. of ice on deck.

Location of Fracture: Fr. 127-128. Starboard side shell down 64 in. in sheer strake and 54 in. into stringer plate.

Vessel: Casualty No. 187 — Type: T1-M-BT1 Tanker

Class of Casualty: Group I — Date of Casualty: 12/25/48, 2315

Ship's Location: Off North Carolina Coast near Cape Hatteras

Course: 020° True — Drafts: Fwd. 4' Aft 12'

Weather: Cloudy — Sea Condition: Long Swells

Wind: Force 10 — T_A 35 F T_W 78 F

Circumstances Surrounding Failure:

Temperatures

Hour:	1200	1600	2000	2315	2400
Air F:	69	63	46	35	34
Water F:	79	78	79	--	78

Ship being towed. Hogging moment under still-water conditions and tension stresses in deck.

Location of Fracture: Ship broke in two at Fr. 34-35 just fwd. of midships. Deck broke first.

Vessel: Casualty No. 189 — Type: T2-SE-A1 Tanker

Class of Casualty: Group I — Date of Casualty: 2/6/49, 0730

Ship's Location: 46°-23'N, 124°-50'W, 25 miles due west of mouth of Columbia River.

Course: 357° True — Drafts: Fwd. 28'-9" Aft 31'-0"

Weather: --- — Sea Condition: Rough

Wind: Force 6-8 T_A 46 F T_W 43 F

Circumstances Surrounding Failure:

Cargo oil heated to 103 F.

Drafts indicated sag of 3 1/2 in. Tension in bottom plating.

Location of Fracture: Fr. 53 1/2, No. 7 Port Wing Tank. 3-ft crack in bottom and 11-ft crack around turn of bilge.

Vessel: Casualty No. 212 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 1/12/51, 0040

Ship's Location: Crossing Columbia River Bar, Oregon

Course: 045° True (inbound) Drafts: Fwd. 29'-5" Aft 31'-1"

Weather: Light drizzle Sea Condition: Slight swell

Wind: Force 1 T_A 48 F T_W Sea 52 F, River 42 F

Circumstances Surrounding Failure: Vessel entering river mouth three hours after low tide from ocean at 52 F into river at 42 F. No. 7, 8 and 9 Tanks across heated to 125 F, no others. All tanks full except No. 1 P & S, No. 5 P & S, and No. 9 center, which were partly full. Still-water bending stress in bottom at point of failure, 5500 psi tension. Paint scraped off bottom near bow. Ship thought to have grounded slightly.

Location of Fracture: ---

Vessel: Casualty No. 225 | Type: T2-SE-A1 Tanker

Class of Casualty: Group I | Date of Casualty: 12/31/51, 2349

Ship's Location: 46°-10'N, 123°-05'W, Heading up Columbia River, Ore. Off Fisher Island.

Course: 308° True | Drafts: Fwd. 30'-6" Aft 30'-6"

Weather: Partly Cloudy | Sea Condition: Smooth

Wind: Force 1-3 | T_A 52 F T_W 42 F

Circumstances Surrounding Failure: No. 5 Center Tank loaded to half capacity or 8 ft below waterline. Temperature of cargo oil, 120 F.

Location of Fracture: No. 5 Center Wing Tank. 23-ft crack across bottom.

Vessel: Casualty No. 226 | Type: T2-SE-A1 Tanker

Class of Casualty: Group I | Date of Casualty: 1/4/52, 2355

Ship's Location: 100 miles south Block Is. (south Providence, R. I.), leaving Gulf Stream for coastal waters.

Course: Inbound | Drafts: Fwd. 29'-3" Aft 29'-8"

Weather: Rain | Sea Condition: Moderate

Wind: Force 4 | T_A 40 F T_W 59 F (Falling)

Circumstances Surrounding Failure:

Cargo oil being heated, temperature 120 F.

Location of Fracture: No. 7 starboard Wing Tank. Crack around turn of bilge into bottom plating.

Vessel: Casualty No. 227 — Type: T2-SE-A1 Tanker

Class of Casualty: Group I — Date of Casualty: 1/9/52, 0930

Ship's Location: Off Columbia River Light Vessel, Oregon.

Course: 080° True — Drafts: Fwd. 30'-4" Aft 31'-0"

Weather: Rain — Sea Condition: Heavy

Wind: Force 8 — T_A 43 F T_W 41 F

Circumstances Surrounding Failure:

Ship inbound. Heating cargo oil at 120 F except 125-137 F in No. 5 center and Port Wing Tanks.

Location of Fracture: No. 4 Port Wing Tank. Crack around turn of bilge, same vessel suffered Casualty No. 239.

Vessel: Casualty No. 229 — Type: VC2 Dry Cargo

Class of Casualty: Group I — Date of Casualty: 2/1/52, 0515

Ship's Location: Channel to Baltimore Harbor

Course: Outbound — Drafts: Fwd. 19'-7" Aft 20'-11"

Weather: Calm — Sea Condition: Smooth

Wind: Light — T_A 34 F T_W 39 F

Circumstances Surrounding Failure: Ship at dock in shallow water, temperature 41-44 F, just before casualty. Fracture occurred upon leaving harbor. Heating fuel oil in double bottom to 185 F, temperature 115-120 F at time of casualty.

Location of Fracture: 66-ft fracture in bottom from Fr. 45, port side, across centerline ship to Fr. 64, starboard side.

Vessel: Casualty No. 232 Type: 500-ft Tanker

Class of Casualty: Group I Date of Casualty: 1/23/52, 0200

Ship's Location: Between Block Island and Brenton Reef Light Vessel off Rhode Island.

Course: Inbound Drafts: Fwd. 29'-4" Aft 29'-4"

Weather: Drizzle Sea Condition: Rough

Wind: Force 4 T_A 50 F T_W 42 F

Circumstances Surrounding Failure:

Temperatures of air and water while leaving Gulf Stream.

Date:	1/21/52	1/22/52	1/22/52	1/23/52
Hour:	2000	1600	2400	0200
Air F:	58	57	52	50
Water F:	68	69	47	42

Cargo oil temperature upon discharge at New Haven, Conn., 1/23/52, 114-129 F. Sixth time ship suffered shell fractures, most in this same location.

Location of Fracture: No. 5 starboard Wing and Center Tanks. Bottom plating.

Vessel: Casualty No. 233 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 2/11/52, 2130

Ship's Location: 39°-00N, 72°-59'W, 100 miles E. Cape May, N. J.

Course: 347° True (Inbound) Drafts: Fwd. 29'-10" Aft 29'-10"

Weather: Cloudy Sea Condition: Rough

Wind: Force 7-8 T_A 38 F T_W 49 F

Circumstances Surrounding Failure: Just coming out of Gulf Stream into colder coastal waters. Struck by heavy wave at time of fracture. Temperature of cargo oil at loading, 126 F; at discharge, 100-118 F. Fracture in No. 4 and 5 Center Tanks. No. 4 Port and Starboard Wing Tanks empty.

Location of Fracture: No. 4 and 5 Center Tanks. 41-ft crack in bottom. Fourteen other small cracks in longitudinals from No. 3 to No. 8 Tanks.

Vessel: Casualty No. 236 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 2/18/51, 0808

Ship's Location: 41°-38'N, 69°-20'W, 10 miles E. Cape Cod, Mass.

Course: 340° True (Inbound) Drafts: Fwd. 30'-0" Aft. 30'-0"

Weather: Foggy, snow Sea Condition: Heavy

Wind: Force 8-9 T_A 35 F T_W 41 F

Circumstances Surrounding Failure: After leaving Gulf Stream. Vessel fully loaded. Not known whether cargo was being heated.

Location of Fracture: Broke in two between No. 5 and 6 Tanks.

Casualty No. 237 occurred on same morning a few miles away.

Vessel: Casualty No. 237 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 2/18/51, 0550

Ship's Location: 41°-36'N, 69°-51'W, few miles off Cape Cod, Mass.

Course: Inbound Draft: Mean 29'-3"

Weather: Foggy, snow Sea Condition: Heavy

Wind: Force 10 T_A 35 F T_W 41 F

Circumstances Surrounding Failure: After leaving Gulf Stream.

Cargo oil not heated.

Location of Fracture: Broke in two between No. 7 and 8 Tanks.

Origin of crack in bottom.

Casualty No. 236 occurred on same morning only a few miles away.

Vessel: Casualty No. 238 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 2/17/52, 2220

Ship's Location: 38°-33'N, 74°-50'W, 20 miles off New Jersey shore at mouth of Delaware Bay.

Course: 346° True (Inbound) Drafts: Fwd. 29'-3" Aft 31'-1"

Weather: Overcast, rain Sea Condition: Heavy

Wind: Force 7 T_A 44 F T_W 55 F

Circumstances Surrounding Failure: After leaving Gulf Stream.

Heating cargo oil.

Shipping heavy seas. Fracture when struck by heavy sea.

Location of Fracture: Fr. 61-62, No. 5 Port Wing Tank. Crack

29-ft long bottom around bilge into side shell.

Vessel: Casualty No. 239 Type: T2-SE-A1 Tanker

Class of Casualty: Group I Date of Casualty: 2/29-3/1/52

Ship's Location: 22 miles N. W. Point Arena, Cal.

Course: 323° True (Outbound) Drafts: Fwd. 30'-4" Aft 31'-4"

Weather: Clear | Sea Condition: Rough

Wind: Force 6-8 | T_A 47 F | T_W 52 F

Circumstances Surrounding Failure:

Temperature of cargo oil 135-142 F when loaded between 2230, 2/28/52, and 1215, 2/29/52. Steam kept on coils during voyage. Oil discharged at 128 F.

Location of Fracture: No. 7 Starboard Wing Tank around turn of bilge. Same vessel suffered casualty No. 227.

Vessel: Casualty No. 244 | Type: R2-S-BV1 Reefer

Class of Casualty: Group I | Date of Casualty: Found 4/13/52

Ship's Location: 50°-04'N, 175°-52'W, 130 miles south of Adak, Alaska

Course: 090° True | Drafts: Fwd. 11'-4" Aft 20'-2"

Weather: Cloudy and snow prior 2 days. | Sea Condition: Rough

Wind: Force 6-7 | T_A 35 F | T_W 39 F

Circumstances Surrounding Failure:

Hold temperature 70 F. Fuel oil in double bottom in way of fracture being heated.

During previous 48 hous, range of air temperature, 29-38 F; of water, 34-40 F.

Location of Fracture: Fr. 78-79, Starboard Side. 11-ft crack around turn of bilge.

Vessel: A | Type: T2-SE-A1 Tanker

Class of Casualty: --- | Date of Casualty: 5/31/44, 0600

Ship's Location: Moored at San Pedro, Cal.

Course: Moored Drafts: Fwd. 31'-0" Aft 26'-5"

Weather: Overcast Sea Condition: Smooth

Circumstances Surrounding Failure: Loading cargo oil at 88 F. All but 11,000 bbls. loaded when fracture occurred. 37 ft aft of midships. Ship in slight sagging condition. No. 6 tank where fracture occurred among first filled.

Location of Fracture: No. 6 Starboard Wing Tank. 45-in. crack on curve of bilge.

Vessel: B Type: VC2 Dry Cargo

Class of Casualty: --- Date of Casualty: 9/11/53, 1020

Ship's Location: Mouth of Stromfjord, Greenland

Course: Outbound Drafts: Fwd. 18'-6" Aft 22'-3

Weather: Calm Sea Condition: Smooth

Wind: Force 2 T_A 43 F T_W 41 F

Circumstances Surrounding Failure: Stromfjord is a narrow fjord 40 miles long surrounded by glaciers. Ship left Sondre Stromfjord at head of fjord and sailed full length of it to mouth where fracture occurred. Heating fuel oil in double bottom. Temperature of oil, 140 F.

Location of Fracture: Fr. 111 1/2. From upper side of bilge curve up port side into second strake below sheer strake. 1 ft into tank top. Crack 10 ft long.