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THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

**Transportation
Research Institute**

**Frame Spacing, Alternate Shapes for Longitudinals,
and Wider Plates for Productivity**

U.S. Department of Commerce
Maritime Administration

in cooperation with
Todd Shipyards Corporation

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FOREWORD

This report is the end product of one of the many research projects being performed under the National Shipbuilding Research Program. The Program is a cooperative, cost-shared effort between the Maritime Administration's Office of Advanced Ship Development and the shipbuilding industry. The objective, as conceived by the Ship Production Committee of the Society of Naval Architects and Marine Engineers, emphasizes productivity.

The research effort contained herein is one of the nine General Category projects being managed and cost shared by Todd Shipyards Corporation. It was performed in response to the task statement titled "Ship Structural Design." The work was assigned, by subcontract, to the McDonnell Douglas Astronautics Corporation (MDAC) after evaluation of several proposals.

Mr. J. T. Hofeditz of MDAC'S Structures and Mechanical Department, Research and Development Subdivision, was the Study Manager; he was assisted by Mr. H. Chao.

Mr. L. D. Chirillo, Todd Shipyards Corporation, Seattle Division, was the Program Manager. Mr. C. S. Jonson of the Los Angeles Division, was the Project Manager who provided technical direction.

Special acknowledgment is due also to the following for their constructive criticism of this report in its draft form: Mr. P. Jaquith, Chief Loft Supervisor, Bath Iron Works; Prof. N. Lewis, Director of Research and Research Professor of Naval Architecture, Webb Institute of Naval Architecture; Mr. H. Nehrenheim, Head, Naval Architectural Department, Todd Shipyards Corporation, Los Angeles Division.

EXECUTIVE SUMMARY

Two real modern-ship designs, one for a tanker and the other for a container ship, were investigated with primary emphasis on productivity. Three aspects were considered separately:

- . increased transverse frame spacing;
- . use of bulb flat, flat bar or Yoder angles for Longitudinals; and
- . use of wider plates.

Equations were developed for evaluation of the costs that would apply to alternate configurations of the two ship designs. These equations comply with the requirements of the American Bureau of Shipping and they are incorporated herein. They can be applied using estimated costs for any ship construction program. They could yield, early in the design phase, the anticipated effects of the various configurations on productivity.

For the ship designs investigated, the findings are qualitatively similar. The transverse frame spacing which yielded the largest cost-saving potential is approximately 25% greater. The bulb flat is the alternate shape for longitudinal which would have been most economical. These alternatives would have yielded the following estimated savings per hull:

	<u>Tanker</u>	<u>Container Ship</u>
Frame Spacing	\$152,000 (12' - 4 1/8")	\$52,000 (12' - 10 1/4")
Bulb Flat for Longitudinals	\$83,000	\$26,000

With respect to the use of plates wider than 10-feet the cost savings achieved were offset by the steel industry's practice of assigning extra-width charges. In both ship designs there were several instances where 11.5-foot widths could have been economically substituted. However, the net cost savings were insignificant. The potential cost savings if extra-width charges could be eliminated are:

	<u>Tanker</u>	<u>Container Ship</u>
for 13-foot wide plate	\$74,000	\$33,000
for 16-foot wide plate	\$106,000	\$37,000

An added exploration yielded the following recommendations for future study that might further reduce construction costs:

- . Alternate Longitudinal Stiffner Spacing
- . Reduced Fillet Weld Sizes
- . Reduced Structural Requirements

The plans of action and descriptions of end products for these recommendations are contained herein.

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SYMBOLS

b_j^N	Width of j^{th} row of plates in N-row assembly of plates, in.
c	Construction cost that is dependent on design variables under consideration ($C \equiv C_T - C_0$), \$
C_b	Cost of burning included in C_R , \$
C_{ew}	Cost associated with extra width charge for plates, \$
C_{fs}	cost of fabricated stiffeners ($C_{fs} \equiv C - C_R$), \$
C_{fsc}	cost of fabricated stiffeners cut from channels, \$
C_{fsc_i}	Cost of i^{th} fabricated stiffener cut from channels, \$
C_{fst}	cost of fabricated stiffeners cut from tees, \$
C_{fst_i}	cost of i^{th} fabricated stiffener cut from tees, \$
C_{fsw}	cost of welded-angle stiffeners, \$
C_{fsw_i}	cost of i^{th} welded-angle stiffener, \$

C_m	Cost of material included in C_R , \$
C_{mp}	Cost of material preparation included in C_R , \$
C_o	Construction cost that is independent of design variables under consideration ($C_o \equiv C_T - C$), \$
C_p	Cost of penetration of transverse members by stiffeners, \$
$C_{p_{ij}}$	Cost of i^{th} penetration in j^{th} group of penetrations, \$
C_{p_j}	Cost of j^{th} group of penetrations, \$
C_R	Construction cost that is dependent on design variables under consideration, excluding cost of fabricated stiffeners ($C_R = C - C_{fs}$), \$
C_T	Total construction cost of section of ship under consideration, \$
C_w	Cost of welding included in C_R , \$
D_{ij}	Depth of stiffener for i^{th} penetration of j^{th} group, in.
$\bar{D}_j$	Average depth of stiffeners for j^{th} group of penetrations, in.
E	Extra width charge for plates, \$/100 lbs.
L	Length of assembly of plates, ft.

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L_b	Amount of burning included in C_b , ft.
L_{fsc}	Total length of fabricated stiffeners cut from channels, ft.
L_{fsc_i}	Length of i^{th} fabricated stiffener cut from channels, ft.
L_{fst}	Total length of fabricated stiffeners cut from tees, ft.
L_{fst_i}	Length of i^{th} fabricated stiffener cut from tees, ft.
L_p	Length of plates whose material preparation cost is included in C_{mp} , ft.
L_{s_i}	Length of i^{th} stiffener whose material preparation cost is included in C_{mp} , ft.
$L_{w_{ji}}$	Length of i^{th} size of j^{th} group of welds, ft.
N_{fsc}	Number of fabricated stiffeners cut from channels
N_{fst}	Number of fabricated stiffeners cut from tees
N_{fsw}	Number of welded-angle stiffeners
N_m	Number of different groups of materials whose cost is included in C_m
N_p	Number of penetrations of transverse members by stiffeners

N_{pj}	Number of penetrations in j^{th} group of penetrations
N_s	Number of stiffeners whose material preparation cost is included in C_{mp}
N_w	Number of different groups of welds
N_{wj}	Number of different weld sizes in j^{th} group
w	Weight of plate, lb./ft. ²
w_{fsc_i}	Weight of i^{th} fabricated stiffener cut from channels, tons
w_{fst_i}	Weight of i^{th} fabricated stiffener cut from tees, tons
w_{fsw_i}	Weight of i^{th} welded angle stiffener, tons
w_i	Weight of i^{th} group of material whose cost is included in c_m , tons
α_b	Cost per lineal foot of burning included in C_b , \$/ft.
α_{bc}	Cost per lineal foot of burning included in C_{fsc} , \$/ft.
α_{bt}	Cost per lineal foot of burning included in C_{fst} , \$/ft.
$^{a}fs C_i$	Cost of material per ton for i^{th} fabricated stiffener cut from channels, \$/ton

α_{fst_i}	Cost of material per ton for i^{th} fabricated stiffener cut from tees, \$/ton
α_{fsw_i}	Cost per ton of i^{th} welded-angle stiffener, \$/ton
α_{m_i}	Cost per ton of i^{th} group of material whose cost is included in C_m , \$/ton
α_{mp_p}	Material preparation cost per lineal foot of plate, \$/ft.
$\alpha_{mp_{s_i}}$	Material preparation cost per lineal foot of i^{th} stiffener, \$/ft.
α_{p_j}	Portion of $C_{p_{ij}}$ that is independent of stiffener size, \$
α_s	Cost per lineal foot of seam in plate assembly, \$/ft.
$\alpha_{w_{ji}}$	Cost per lineal foot of i^{th} size of weld in j^{th} group of welds, \$/ft.
β_{p_j}	Coefficient that accounts for dependence of $C_{p_{ij}}$ on stiffener size, \$/in.
γ_{fsc_i}	Cost per lineal foot for straightening of i^{th} fabricated stiffener cut from channels, \$/ft.
γ_{fst_i}	Cost per lineal foot for straightening of i^{th} fabricated stiffener cut from tees, \$/ft.

$\delta(\dots)^{AB}$ Increment in any quantity (...) incurred in passing from a base-line configuration (B) to an alternate configuration (A);
 $\delta(\dots)^{AB} \equiv (\dots)^A - (\dots)^B$

Section 1

INTRODUCTION AND SUMMARY

1.1 Objective

The overall objective of the work reported here was to determine a more economical arrangement of plates and shapes for merchant ship hulls. Specific objectives were to estimate the effects on construction cost of increased frame spacing, the use of alternate structural shapes for stiffeners, and the use of wider plates. By way of background, the present study as well as others sponsored by the United States Maritime Administration (MARAD) is intended to assist the U.S. shipyards in becoming more competitive with foreign shipyards.

1.2 Summary

In order to determine more economical hull configurations, cost equations were developed which permit rapid comparison of configurations with alternate . transverse frame spacing, alternate stiffener shapes, and alternate plate widths. The cost equations are in a form so that an individual shipyard can apply them using its own cost figures. The form of the cost equations also permits their application at various levels of detail, commensurate with an individual shipyard's cost data. For maximum benefit these equations should be applied early in the design and planning phases.

The cost equations were used to evaluate alternate configurations of two typical modern designs -- a tanker and a container ship. These designs, used as baselines, are not "straw-man" designs postulated simply for the purpose .

of this study. They are for real ships that reflect the current state of the art for structural design and construction of U.S.-built ships. Steel drawings were supplied by a U.S. shipyard.

For the tanker, six out of seven alternate structural configurations were found to have cost-saving potential. Two of the six configurations have increased transverse frame spacing, and utilize welded angles for longitudinal stiffeners in contrast to angles cut from channels that are used on the baseline. A third has increased frame spacing, but its stiffeners are similar to the baseline stiffeners. The remaining three have the same transverse frame spacing as the baseline but utilize stiffeners having one of the three shapes: bulb flat, flat bar, or a Yoder angle. In order of cost-saving, the ranking is:

<u>Frame Spacing</u>	<u>Longitudinal Stiffeners</u>
1. 12'-4-1/8"	Welded angles
2. 16'-5-1/2"	Welded angles
3. 9'-10-1/2"	Bulb flat,
4. 9'-10-1/2"	Yoder angle
5. 9'-10-1/2"	Flat bar
6. 12'-4-1/8"	Cut channels

A parallel investigation of seven alternate structural configurations of the container ship yielded four with the following ranking in order of cost-saving potential:

<u>Frame Spacing</u>	<u>Longitudinal Stiffeners</u>
1. 12'-10-1/4"	Welded angles
2. 11'-3"	Welded angles
3. 10'-0"	Bulb flat
4. 10'-0"	Yoder angle

The rankings were obtained by means of the cost equations developed in Sections 2.5 and 3.5. In the application of the cost equations, each shipyard, of necessity must use its own cost figures. The cost figures used herein, to exemplify the use of the cost equations, are based on estimates from different sources, not one particular shipyard. However, it is believed the economic evaluation does provide at least a ranking, at best a semi-quantitative assessment of relative costs of the alternate configurations.

Based on interviews with shipyard personnel and naval architects, it is believed that the above-listed alternate configurations are not beyond the current state of the art of the U.S. shipbuilding industry. The alternate configurations employ no new concepts, but differ only in construction details. Moreover, current American Bureau of Shipping (ABS) rules were followed in determining the alternate configurations.

The use of wider plates, ranging from 10 to 16 feet, was evaluated by means of cost equations developed in Section 4.5. Possible reductions in seams range from approximately 5,000 to 11,000 feet, but the extra width charge essentially cancels the cost saving achieved by the reduction in seams. Thus, to achieve significant cost savings, standard

plate widths (no extra width charge) produced especially for shipbuilding are required.

1.3 Approach

The approach used was to examine various perturbations -- alternate configurations -- of two baseline designs, one for a typical modern tanker, the other for a typical modern container ship, The particulars for the tanker are (see Figure 1-1):

Length, overall	810' -0"
Length, B.P.	786' -0"
Breadth, molded	105' -0"
Depth, molded to upper deck at side	57' -0'
Deadweight, tons	70,000

For the container ship (see Figure 1-2):

Length, overall	720' -5-1/2"
Length, B.P.	677' -0"
Breadth, molded	95' -0"
Depth, molded	54' -0"
Deadweight, tons	65,000

In the examination of alternate configurations, three aspects were considered separately to determine if a more economical structural arrangement could be found: (1) increased transverse frame spacing, (2) use of alternate structural sections for stiffeners, (3) use of wider plates.

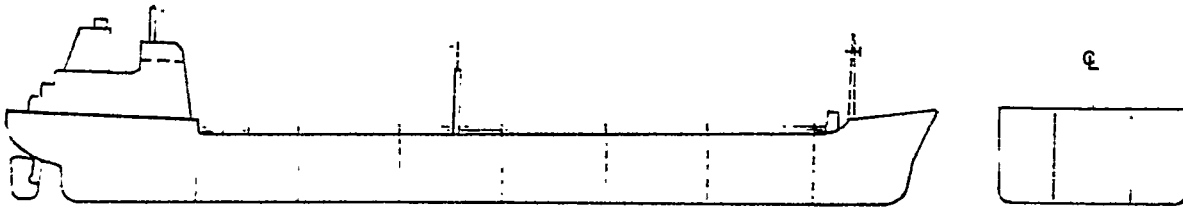


Figure 1-1. Profile of Tanker

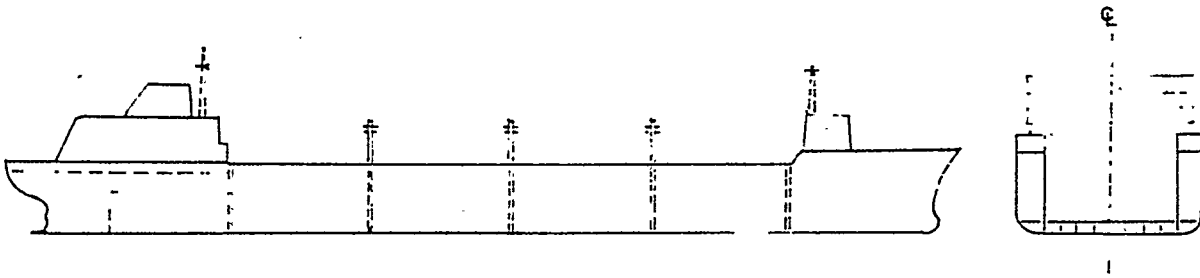


Figure 1-2. Profile of Container Ship

To determine the effects of increased frame spacing, a midship cargo section (approximately 100 feet long for both ships) of each ship was examined. Configurations having increased frame spacing were obtained by the removal of from one up to four transverse frames, resulting in a maximum frame spacing of approximately 16.5 feet, compared to a baseline frame spacing of approximately ten feet. Two different configurations were considered for each frame spacing: one in which longitudinal stiffeners were cut (when necessary) from "channels" or tees as in the baseline, and one in which welded angles, formed by welding two plates together, were used instead. Although welded angles are even more unpopular than cutting and straightening channels at some yards, they are used by other yards who either make them in-house with automated equipment or buy them from a steel fabricator.

To determine the effects of using alternate structural sections for stiffeners, the section of each ship considered was the same as for the investigation of frame spacing. Stiffeners used on the baselines are flat bar, structural tees (for the container ship only), rolled angles, and angles cut from channels. Three alternate configurations were considered for each ship wherein angles and angles cut from channels were replaced by bulb flat in the first case, and replaced by flat bar in the second case. In the third case, angles cut from channels were replaced by Yoder angles. Yoder angles were examined because a steel mill in the United States is considering producing them as an alternate to bulb flat, which, although in high demand by shipyards, is not produced by
Moreover, U.S. shipyards cannot buy foreign steel
for use on MARAD-subsidized ships.

Scantlings and weld sizes for the alternate configurations were determined on the basis of a single guiding principle: consistency with the baseline. ABS rules (Reference 1) were used to size structural members in the alternate configurations such that they had the same load-resisting capacity as the baseline configuration. Fillet welds on the alternate configurations were sized so as to be in consistent proportion to those on the baseline configuration, using Lloyds Register (Reference 2) as a guide.

The economic evaluation of configurations having alternate frame spacing and alternate structural shapes for stiffeners were carried out in a similar manner. Expressions were developed that give the cost increment, in terms of a set of cost-affecting parameters, incurred in passing from a baseline configuration to an alternate configuration. The cost increment was then determined for each of the alternate configurations.

The parameters chosen were such items as weight of steel, lineal feet of burning and welding, and the number and type of stiffener penetrations through transverse members. The choice of parameters is subjective because it necessarily depends on the level of detail as well as the manner in which cost data are organized at a particular shipyard. For this reason a more detailed physical description of the alternate configurations is given than would be necessary were there a unique proper choice of cost-affecting parameters.

The functional relationship between the cost and the parameters chosen is also subjective, for one may choose a relationship that is either too crude or too refined, and in fact may be both, insofar as two different shipyards are concerned. For this reason, the equations for cost are written in a form that

permits varying degrees of refinement. Welding cost, for example, is expressed in the following form:

$$C_w = \sum_{j=1}^{N_w} \sum_{i=1}^{N_{w_j}} \alpha_{w_{ji}} L_{w_{ji}} \quad (1-1)$$

The form of Equation 1-1 is based on the notion of subdividing the total amount of welding into groups according to type and size of weld. If there are N_w different types of welds and N_{w_j} different sizes of welds of the j^{th} type, then the cost is taken as the sum of the products of cost per lineal foot, $\alpha_{w_{ji}}$, and length of weld, $L_{w_{ji}}$, for each type-size combination. A crude estimate of cost is obtained by subdividing the welds into only two groups, say fillet and butt welds, each group having one (average) size. In this case $N_w = 2$ and $N_{w_i} = 1$. Improved estimates can be obtained by use of a finer subdivision, that is, by increasing N_w and N_{w_j} .

The use of wider plates was investigated by considering two cases of maximum available plate width: 13 feet and 16 feet, as compared to a maximum of ten feet for both of the baselines. The midbody portion of each ship was examined--about 590 feet for the tanker and 400 feet for the container ship.

The economic evaluation of wider plates was approached somewhat differently than the evaluation of alternate frame spacing and structural shapes. The first thing determined was the maximum reduction both in lineal feet of seams and in the number of plates as a function of maximum plate width available. This was done by examining the plating plans and counting the number of instances in which two or more plates having the same length, thickness and

material specification could be replaced by a fewer number of wider plates. The possible reductions were large enough to warrant a more detailed analysis. An economic model, applicable to most regions of the ship, was developed to provide a criterion--welding and material preparation cost versus the charge for extra width--for determining if the use of wider plates is economically desirable.

Section 2

INVESTIGATION OF ALTERNATE TRANSVERSE FRAME SPACING

2.1 Baseline Configurations

The midship section of the tanker between transverse oil-tight bulkheads at frames 71 and 81 was selected as the baseline configuration (see Figures 2-1 and 2-2). This section of the ship is 98.75 feet long and is one of six similar cargo sections located between frames 49 and 103, a length of 592.5 feet. Two longitudinal oil-tight bulkheads, located 22'-2" (P&S) off the centerline, divide the section into three tanks. A transverse swash bulkhead is located at frame 76, midway between the bulkheads at frames 71 and 81, and in addition, there are eight transverse web frames, four equally spaced at 9'-10-1/2" on either side of the swash bulkhead. Thus, including the swash bulkhead, there are a total of nine transverse frames.

For the container ship the baseline configuration was chosen as the midship portion of the ship between the transverse water-tight bulkheads at frames 108 and 148, a 100-foot section that is representative of four other cargo sections between frames 64 and 260, a length of 489 feet (see Figures 2-3 and 2-4). Cargo is carried in the region above the innerbottom and between two longitudinal water-tight bulkheads, located 36'-1-1/2" (P&S) off the centerline. Transverse frames are formed by nine vertical webs, equally spaced at 10'-0", located between the sides and longitudinal bulkheads and extending from the innerbottom to the upper deck, and nine transverse webs (floors) located between the bottom and innerbottom.

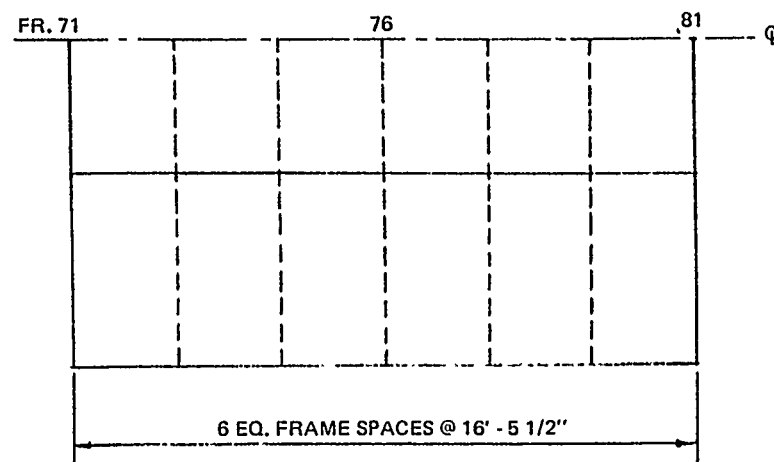
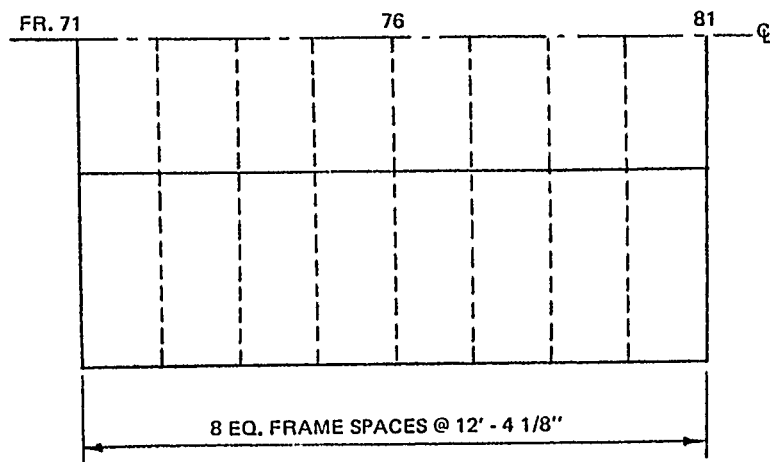
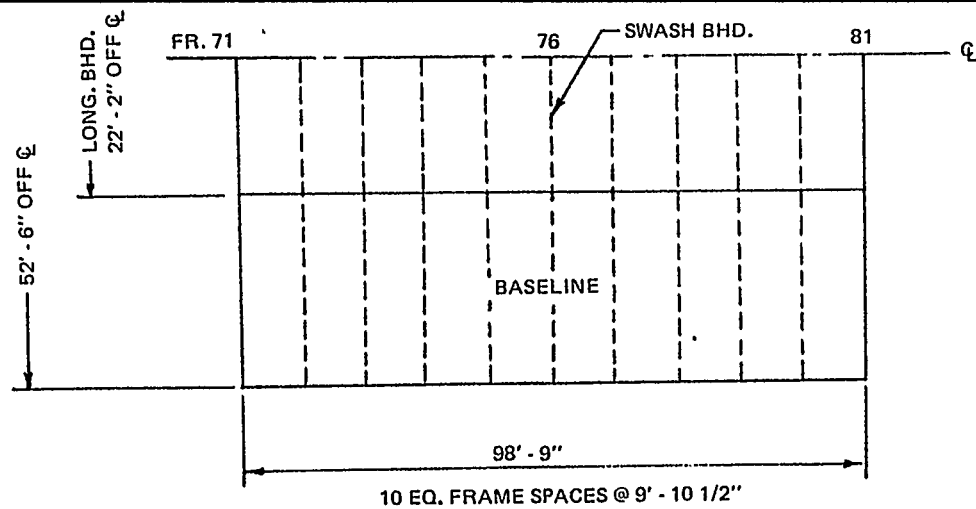


Figure 2-1. Baseline and Two Alternate Transverse Frame Spacings for Tanker

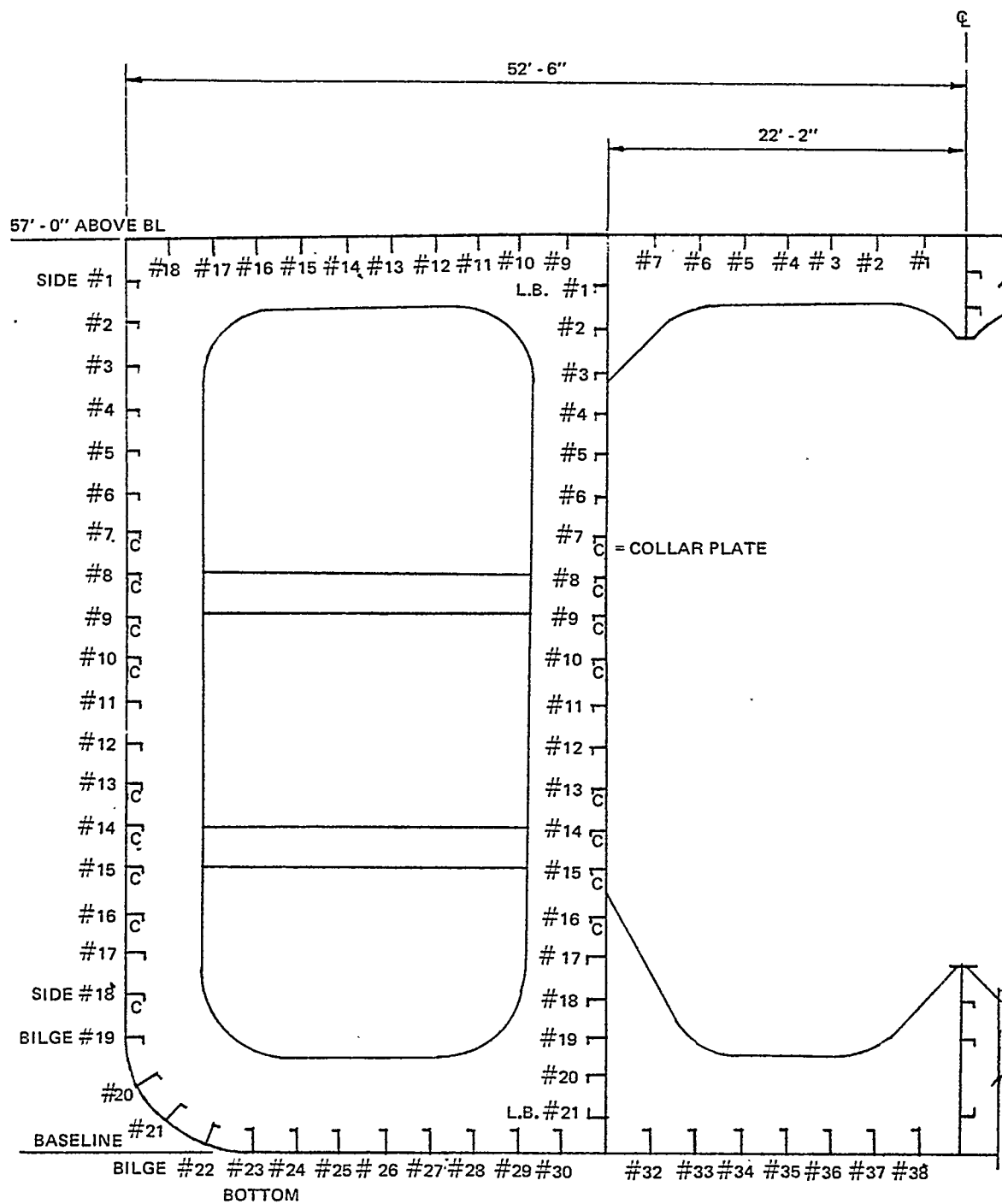


Figure 2-2. Tanker Hull Section

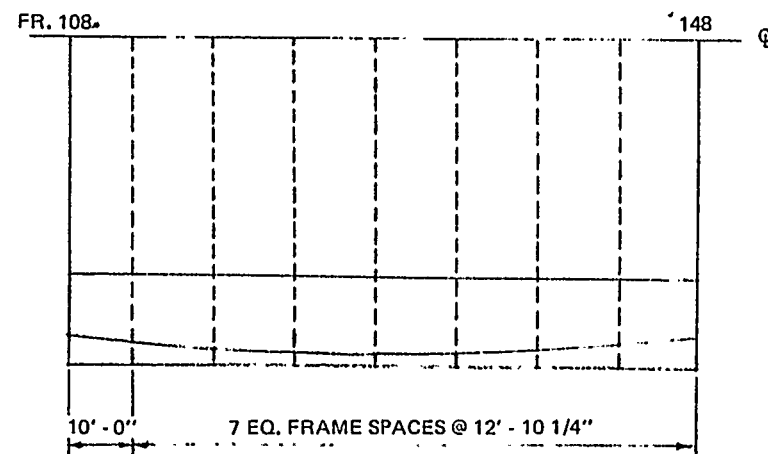
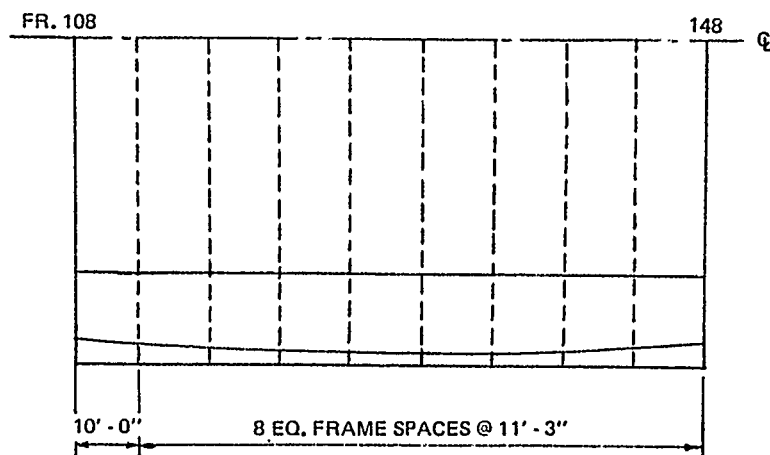
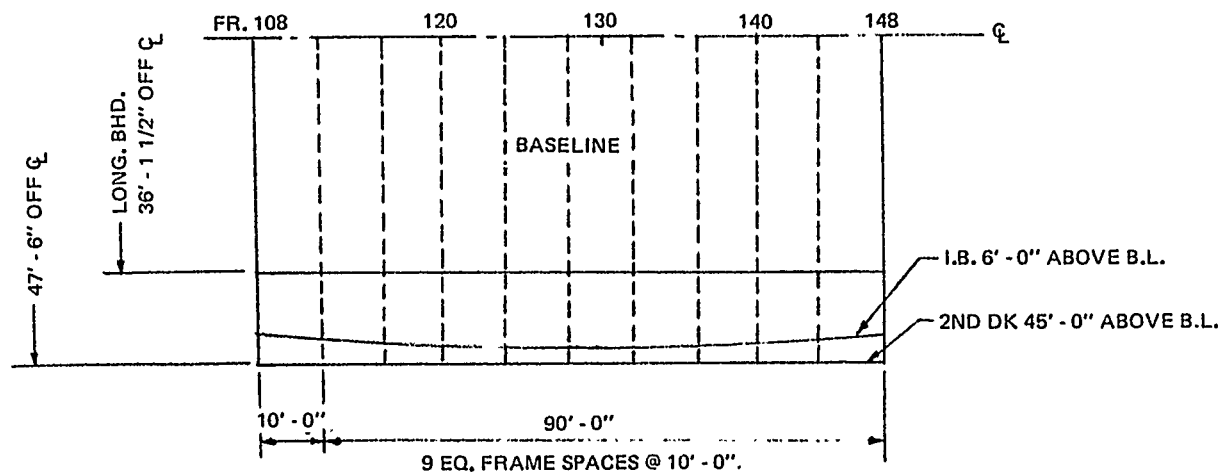


Figure 2-3. Baseline and Two Alternate Transverse Frame Spacings for Container Ship

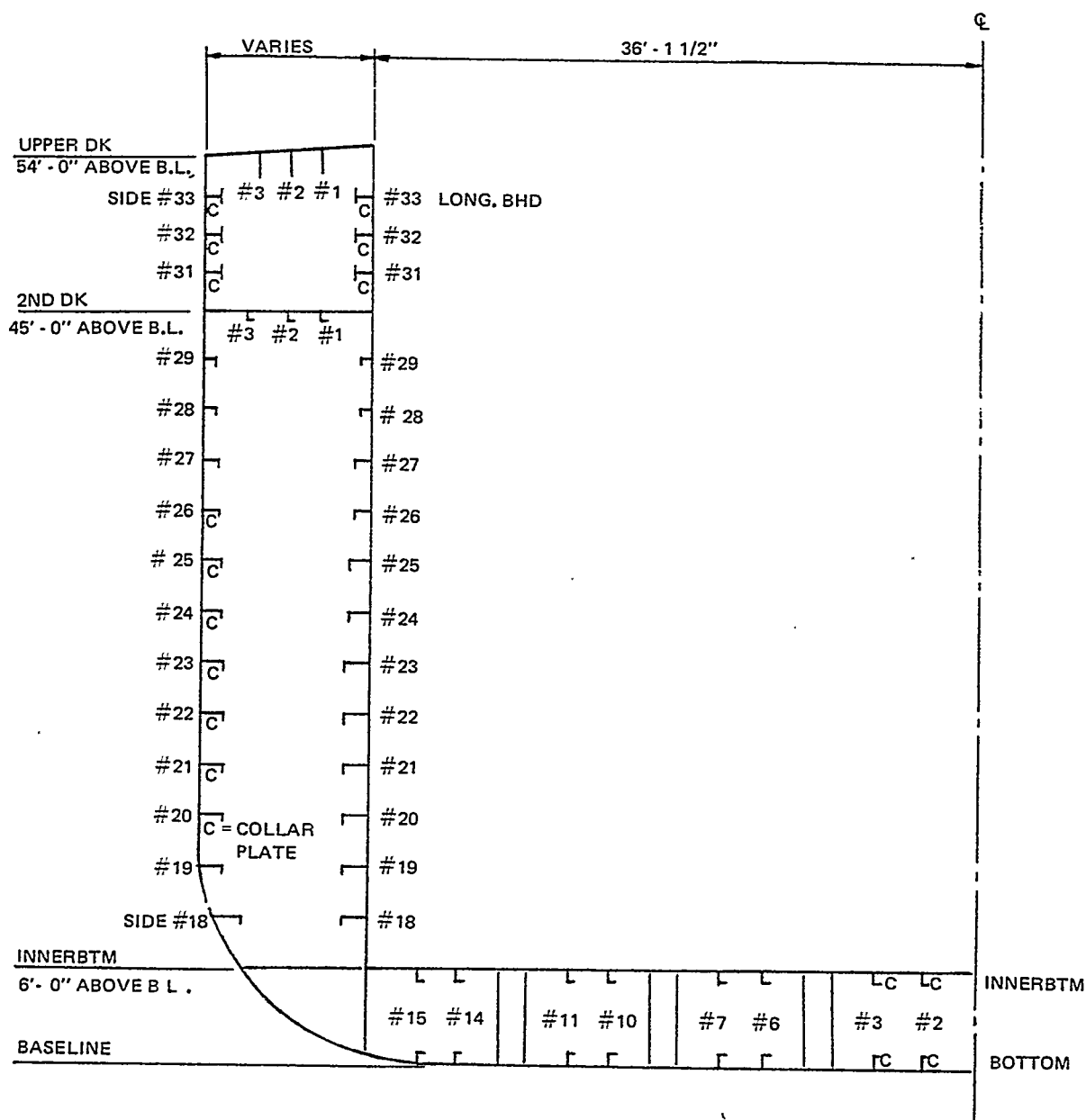


Figure 2-4. Container Ship Hull Section

2.2 Alternate Configurations

Two alternate transverse frame spacings were considered for each ship. For the tanker, the frame spacings were 12'-4-1/8", corresponding to seven transverse frames instead of nine for the baseline, and 16'-5-1/2", corresponding to five transverse frames (see Figures 2-1 and 2-2). In both cases the location of the oil-tight bulkheads at frames 71 and 81 and the swash bulkhead at frame 76 remain the same as for the baseline; for this reason an even number of web frames is used in both of the alternate configurations.

For the container ship, the alternate transverse frame spacings were 11'-3", corresponding to eight web frames instead of nine for the baseline, and 12'-1 0-1/4", corresponding to seven web frames (see Figure 2-3 and 2-4). The location of the aftermost web frame, located at frame 112, was not changed because this web frame also serves as the forward bulkhead of a stabilizer tank whose volume capacity was not altered.

For each alternate frame' spacing, configurations were generated for. two different kinds of longitudinal stiffeners: fabricated angles made by welding two plates together and angles made by cutting standard channels or tees. Because of the accounting procedure used in the economic evaluation, both kinds of stiffeners are referred to as "fabricated" stiffeners. Fabricated stiffeners are of course used only where standard angles of sufficient size are not available.

2.3 Method of Sizing Alternate Configurations

For all alternate configurations, longitudinal stiffeners were resized so that their section modulus in combination with associated plating would not be less than the corresponding baseline section modulus multiplied by a factor equal to the square of the ratio of alternate frame spacing to baseline frame spacing. Thus, for the tanker configuration with seven frames spaced 12'-4-1/8" apart, the factor would be $(12.34/9.875)^2 = 1.563$. In addition, stiffener areas were required to be such that the hull-girder section modulus would not be less than that for the baseline. Consistent with the baseline configurations, the maximum depth-to-thickness ratio used for flat bar stiffeners was eight, sufficient to preclude local buckling. For welded-angle stiffeners the maximum depth-to-thickness ratio was limited to 40 for the web and eight for the flange, also sufficient to preclude local buckling.

The method used to size longitudinal stiffeners is consistent with Reference 1 as well as with theoretical considerations. The theoretical basis is that a stiffener together with its associated plating behaves like a beam whose span is equal to the web-frame spacing. Because the bending moment increases in proportion to the square of the span, so also must the section modulus. The sizing method used also ensures against panel buckling between web frames. To maintain the same resistance to buckling, the moment of inertia of a stiffener together with its associated plating must increase in proportion to the square of the span. This requirement is always exceeded because it turns out that the moment of inertia increases at a greater rate than the section modulus which itself is required to increase in proportion to the square of the span.

To minimize the amount of additional steel required for the alternate tanker configurations, plate thicknesses for the deck and shear strake (1.375 inches thick on the baseline) and for the bilge and bottom (1.5 inches thick on the baseline) were reduced to as low as 1.25 inches, which is still considerably above the ABS minimum requirements (Reference 1) of approximately 0.85 inches for the deck and 1.1 inches for the bottom. Excessive plate material was thus used to provide some of the additional stiffener material required due to increased frame spacing.

For the alternate tanker configurations, web frames were resized such that both their section moduli with associated plating and shear capacity would not be less than the corresponding quantity for the baseline multiplied by the ratio of the number of baseline web frames to the number of alternate web frames. The minimum required axial load capacity of the struts was determined in the same manner.

The theoretical basis for this procedure is the assumption that the intensity of the loads transmitted to a web frame by adjacent structure varies in direct proportion to the number of web frames available to resist load. This assumption is conservative in so far as the web frames are concerned because the latter are assisted in resisting load by the transverse bulkheads located at the ends of the section of the ship under consideration. But, for the transverse bulkheads, which were not resized, the assumption is unconservative. The web frames for the alternate configurations are therefore slightly overdesigned while the transverse bulkheads are slightly underdesigned. Since there are fewer bulkheads than web frames, the net result is a slight economic penalty for the alternate configurations.

For the alternate container ship configurations, the transverse webs between the innerbottom and upper deck were resized by the same method used for the tanker. The transverse webs (floors) between the bottom and innerbottom, however, were not resized because they are secondary structure, the primary structure consisting of longitudinal girders which are insensitive to transverse frame spacing. Likewise, deck longitudinal #1-#3 and longitudinal #31-#33 on the sides and longitudinal bulkheads remain unchanged, for their primary function is to supplement the deck, side and bulkhead plating so as to furnish the required hull-girder section modulus. As a result, their section moduli are more than sufficient to stiffen the plating between transverse frames.

2.4 Effects of Alternate Frame Spacing

The major effects of alternate frame spacing on the physical characteristics of the configurations examined are given in Tables 2-1 through 2-4 for the tanker and Tables 2-5 through 2-8 for the container ship. The first table in each series is a summary of erected weight, the quantity of fabricated stiffeners required, welding and burning requirements, and the number and kind of stiffener penetrations of transverse members. The second table provides a more detailed breakdown of weight for plate, fabricated stiffeners, and non-fabricated stiffeners. The third table gives lineal feet of welds and pounds of weld metal deposited for different sizes of welds used. Finally, the fourth table gives the required stiffener sizes.

In all cases, the total erected weight of steel increases with increased frame spacing. For the tanker, the increase ranges from approximately 9 to 166 tons out of a baseline total of 1542 tons. The minimum increase occurs

TABLE 2-1

SUMMARY OF TANKER CONFIGURATIONS FOR THREE TRANSVERSE FRAME SPACINGS

(98.75-FOOT SECTION, FRS. 71-81)

ITEM	Baseline 9 Web Frames ⁽¹⁾ 9'-10'1/2" O.C.	7 Web Frames ⁽¹⁾ 12'-4-1/8" O.C.		5 Web Frames 16'-5-1/2" O.C.	
	34 Flat Bar 34 Γ 82 Γ/Γ	34 Flat Bar 80 Γ/Γ 36 ST/ Γ	34 Flat Bar 116 Welded Angles	34 Flat Bar 40 Γ/Γ 76 ST/ Γ	34 Flat Bar 116 Welded Angles
● Erected Weight, Tons ⁽²⁾					
Total	1542.4	1577.7	1551.6	1708.5	1644.4
Fabricated Stiffeners ⁽³⁾	146.8	249.4	223.3	369.7	305.6
Total Less Fabricated Stiffeners	1395.6	1328.3	1328.3	1338.8	1338.8
● Fabricated Stiffeners ⁽³⁾					
Lineal Feet	8,100	11,455	11,455	11,455	11,455
Purchased Weight, Tons	176.2	320.9	223.3	507.4	305.6
● Welding ⁽⁴⁾					
Fillet, Lineal Feet	61,070	52,915	52,915	45,355	45,355
Pounds Deposited	9,405	9,308	9,310	11,600	10,520
Butt, Lineal Feet	3,425	3,385	3,385	3,340	3,340
Pounds Deposited	10,950	9,535	9,535	8,895	8,895
● Burning, Lineal Feet ⁽⁵⁾	0	-4,400	-4,400	-8,800	-8,800
● Transverse Penetrations					
O.T.	150	150	150	150	150
N.T. Without Collar	1008	784	784	560	560
N.T. With Collar	342	266	266	190	190

(1) See Table 2-4 for stiffener sizes.

(2) See Table 2-2 for details.

(3) Includes Γ/Γ and ST/ t' and welded angles.

(4) See Table 2-3 for details. Welding of welded angles not included.

(5) Change relative to the baseline, excluding fabricated stiffeners.

TABLE 2-2

ERECTED WEIGHT OF TANKER CONFIGURATIONS FOR THREE TRANSVERSE FRAME SPACINGS

ITEM	Baseline 9 Web Frames 9'-10-1/2" O.C	7 Web Frames 12'-4-1/8" O.C,		5 Web Frames 16'-5-1/2" O.C.	
	34 Flat Bar 34 r 82 [/r	34 Flat Bar 80 [/r 36 ST/r	34 Flat Bar 116 Welded Angles	34 Flat Bar 40 [/r 76 ST/r	34 Flat Bar 116 Welded Angles
●Deck, Bilge, and Bottom Plate	646.5	590.6	590.6	560.7	560.7
Fabricated Stiffeners	92.7	125.0	120.0	191.8	153.2
Nonfabricated Stiffeners	86.3	125.1	125.1	188.4	188.4
●Sides and Longitudinal Bulkheads					
Plate	322.1	318.0	318.0	318.0	318.0
Fabricated Stiffeners	54.1	124.4	103.3	177.9	152.4
Nonfabricated Stiffeners	33.9	0	0	0	0
●Transverse Web Frames	306.8	294.6	294.6	271.7	271.7
TOTAL	1,542.4	1,577.7	1,551.6	1,708.5	1,644.4

TABLE 2-3

WELDS FOR TANKER CONFIGURATIONS FOR THREE TRANSVERSE FRAME SPACINGS

(98.75-FOOT SECTION, FRS. 71-81)

ITEM	Baseline 9 Web Frames 9'-10-1/2" O.C.		7 Web Frames 12'-4-1/8" O.C.				5 Web Frames 16'-5-1/2" O.C.			
	34 F.B. 34 Γ 82 Γ/Γ		34 F.B. 80 Γ 36 ST/ Γ		34 F.B. 116 Welded Angles		34 F.B. 40 Γ/Γ 76 ST/ Γ		34 F.B. 116 Welded Angles	
Weld	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited
Fillet 1/4	22,675	2,430	15,405	1,650	15,405	1,650	15,405	1,650	15,405	1,650
	31,015	5,195	25,265	4,230	25,265	4,230	9,800	1,640	16,515	2,765
	7,380	1,780	6,785	1,635	6,785	1,635	0	0	0	0
	0	0	5,460	1,790	5,460	1,790	12,045	3,960	5,330	1,750
	0	0	0	0	0	0	4,460	1,910	4,460	1,910
	0	0	0	0	0	0	3,645	2,440	3,645	2,440
	0	0	0	0	0	0	0	0	0	0
TOTAL	61,070	9,405	52,915	9,305	52,915	9,305	45,355	11,600	45,355	10,515
Butt* 1/2	165	90	0	0	0	0	0	0	0	0
	0	0	125	85	125	85	0	0	0	0
	0	0	0	0	0	0	80	115	80	115
	0	0	1,690	4,550	1,690	4,550	3,260	8,780	3,260	8,780
	1,690	5,260	1,570	4,900	1,570	4,900	0	0	0	0
	1,570	5,600	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0
TOTAL	3,425	10,950	3,385	9,535	3,385	9,535	3,340	8,895	3,340	8,895
TOTAL Fillet Plus Butt	64,495	20,355	56,300	18,840	56,300	18,840	48,695	20,495	48,695	19,410

* Single Vee joint included angle = 30°; root gap = 1/4" for thickness greater than 5/8, 1/8" for thickness of 5/8" and less.

TABLE 2-4
LONGITUDINAL STIFFENERS FOR TANKER CONFIGURATIONS FOR THREE TRANSVERSE FRAME SPACINGS
(98.75-FOOT SECTION, FRS. 71-81)

Item		Baseline 9 Web Frames 9'-10-1/2" O.C.	7 Web Frames 12'-4-1/8" O.C.		5 Web Frames 16'-5-1/2" O.C.	
		34 F.B. 34 Γ 82 Γ/Γ	34 F.B. 80 Γ/Γ 36 ST/ Γ	34 F.B. 116 Welded Angles	34 F.B. 40 Γ/Γ 76 ST/ Γ	34 F.B. 116 Welded Angles
Deck	#1 - #7 #9 - #18	11x1-3/8 F.B. Do	13x1-11/16 F.B. Do	13x1-11/16 F.B. Do	16x2-1/16 F.B. ⁽¹⁾ Do	16x2-1/16 F.B. ⁽²⁾ Do
Side	#1 - #2	8x4x19.6# Γ	12x4x45.0# Γ/Γ	15x3/8; 5x7/8 ⁽³⁾	18x4x42.7# Γ/Γ	15x3/8; 5x7/8
	#3	Do	12x3-1/2x32.9# Γ/Γ	12x5/16; 5x7/8	Do	Do; 5x5/8
	#4 - #6	Do	12x3-1/2x30.9# Γ/Γ	Do; 4x1/2	Do	Do; Do
	#7 - #8	9x4x21.3# Γ	13x4x31.8# Γ/Γ	Do; 4x5/8	Do	Do; 5x3/4
	#9	9x4x23.8# Γ	15x3-3/8x33.9# Γ/Γ	Do; 4-1/2x3/4	18x4x51.9# Γ/Γ	Do; 5x7/8
	#10	10x4x28.5# Γ/Γ	Do	Do; Do	Do	Do; 6-1/2x3/4
	#11 - #13	12x3-1/2x30.9# Γ/Γ	18x4x42.7# Γ/Γ	Do; 5x7/8	ST 16 WF 65#/ Γ	18x15/32; 6x3/4
	#14 - #15	13x4x31.8# Γ/Γ	Do	15x3/8; 4x7/8	ST 16 WF 76#/ Γ	Do; 5-1/2x1
	#16 - #18	15x3-3/8x33.9# Γ/Γ	18x4x51.9# Γ/Γ	Do; 5x7/8	ST 18 WF 85#/ Γ	Do; 6-1/2x1-1/16
Bilge	#19	15x3-3/8x40.0# Γ/Γ	18x4x58.0# Γ/Γ	21x9/16; 4-1/2x1/2	ST 18 WF 97#/ Γ	21x9/16; 6-1/2x1
	#20 - #22	Same as Bottom #23	Same as Bottom #23	Same as Bottom #23	Same as Bottom #23	Same as Bottom #23
Bottom	#23 - #30 #32 - #38	18x4x58.0# Γ/Γ Do	ST 18 WF 91#/ Γ Do	21x9/16; 7x1-1/16 Do	ST 18 WF 150#/ Γ Do	21x9/16; 10x1-1/4 Do
Long. Bulkhead	#1 - #3	8x4x19.6# Γ	13x4x31.8# Γ/Γ	12x5/16; 4x1/2	18x4x42.7# Γ/Γ	15x3/8; 5x5/8
	#4 - #6	Do	Do	Do; Do	Do	Do; Do
	#7 - #8	9x4x21.3# Γ	Do	Do; 4-1/2x5/8	Do	Do; 5x3/4
	#9 - #10	10x4x28.5# Γ/Γ	15x3-3/8x33.9# Γ/Γ	Do; 4-1/2x3/4	18x4x51.9# Γ/Γ	Do; 6-1/2x3/4
	#11 - #13	12x3-1/2x30.9# Γ/Γ	18x4x42.7# Γ/Γ	Do; 5x7/8	ST 16 WF 65#/ Γ	18x15/32; 6x3/4
	#14	13x4x31.8# Γ/Γ	Do	15x3/8; 4x7/8	ST 16 WF 76#/ Γ	Do; 5-1/2x1
	#15 - #16	Do	Do	Do; Do	Do	Do; Do
	#17 - #18 #19 - #21	15x3-3/8x33.9# Γ/Γ Do	18x4x51.9# Γ/Γ Do	Do; 5x7/8 Do; Do	ST 18 WF 85#/ Γ Do	Do; 6-1/2x1-1/16 Do; Do

(1) Alternate: ST WF 91#/ Γ

(2) Alternate: 21x9/16; 7-1/2x1

(3) Web; Flange

TABLE 2-5
SUMMARY OF CONTAINER SHIP CONFIGURATIONS FOR THREE TRANSVERSE FRAME SPACINGS
(100-FOOT SECTION, FRS. 108-148)

ITEM	Baseline 9 Transverse Webs 10'-0" O.C.	8 Transverse Webs ⁽¹⁾ 11'-3" O.C.		7 Transverse Webs ⁽¹⁾ 12'-10-1/4" O.C.	
	6 Flat Bar 12 ST r 40 [/r	6 Flat Bar 12 ST 18 r 68 [/r	6 Flat Bar 12 ST 18 r 68 Welded Angles	6 Flat Bar 12 ST 6 r 56 [/r 24 ST/r	6 Flat Bar 12 ST 6 r 80 Welded Angles
• Erected Weight, Tons					
Total	925.9	947.4	930.0	962.4	941.5
Fabricated Stiffeners ⁽²⁾	63.8	118.1	100.7	150.7	129.8
Total Less Fabricated Stiffeners	862.1	829.3	829.3	811.7	811.7
• Fabricated Stiffeners ⁽²⁾					
Lineal Feet	4,000	6,800	6,800	8,000	8,000
Purchased Weight, Tons	79.0	143.0	100.7	195.9	129.8
• Welding ⁽³⁾					
Fillet, Lineal Feet	43,215	40,630	40,630	38,040	38,040
Pounds Deposited	4,865	4,850	4,850	4,600	4,600
Butt, Lineal Feet	740	655	655	575	575
Pounds Deposited	520	715	715	745	745
• Burning, Lineal Feet ⁽⁴⁾	0	-720	-720	-1,440	-1,440
• Transverse Penetrations					
O.T.	248	248	248	248	248
N.T. Without Collar	516	446 "	446	376	376
N.T. With Collar	276	242	242	208	208

(1) See Table 2-8 for stiffener sizes.

(2) Includes [/r, ST/r and welded angles.

(3) See Table 2-7 for details. Welding of welded angles not included.

(4) Change relative to the baseline, excluding fabricated stiffeners.

TABLE 2-6

ERECTED WEIGHT OF CONTAINER SHIP CONFIGURATIONS FOR THREE TRANSVERSE FRAME SPACINGS

(100-FOOT SECTION, FRS, 108-148)

ITEM	Baseline Transverse Webs 10'-0" O.C.	8 Transverse Webs 11'-3" O.C.		7 Transverse Webs 12'-10-1/4" O.C.	
	6 Flat Bar 12 ST 46 r 40 [/r	6 Flat Bar 12 ST 18 r 68 [/r	6 Flat Bar 12 ST 18 r 68 Welded Angles	6 Flat Bar 12 ST 6 r 56 [/r 24 ST/r	6 Flat Bar 12 ST 6 r 80 Welded Angles
● Upper and 2nd Deck Plate	123.2	123.2	123.2	123.2	123.2
Fabricated Stiffeners				0	0
Nonfabricated Stiffeners	46.6	47.7	47.7	48.9	48.9
● Sides and Longitudinal Bulkheads					
Plate	249.8	249.8	249.8	249.8	249.8
Fabricated Stiffeners	63.8	94.8	79.7	111.9	93.7
Nonfabricated Stiffeners	44.5"	36.0	36.0	36.0	36.0
● Bottom and Innerbottom					
Plate	184.8	184.8	184.8	184.8	184.8
Fabricated Stiffeners		23.3	21.0	38.8	36.1
Nonfabricated Stiffeners	31.2	12.8	12.8	0	0
● Transverse Webs and Floor	182.0	175.0	175.0	169.0	169.0
TOTAL	925.9	947.4	I 930.0	962.4	I 941.5

ABLE 2-7

WELDS FOR CONTAINER SHIP CONFIGURATIONS FOR THREE TRANSVERSE FRAME SPACINGS

(100-FOOT SECTION, FRS. 108-148)

ITEM	Baseline 9 Transverse Webs 10'-0" O.C.		8 Transverse Webs 11'-3" O.C.				7 Transverse Webs 12'-10-1/4" O.C.			
	6 F.B. 12 ST 46 r 40 [/r		6 F.B. 12 ST 38 r 48 [/r		6 F.B. 12 ST 18 r 68 Welded Angles		6 F.B. 12 ST 6 r 56 [/r 24 ST/r		6 F.B. 12 ST 6 r 80 Welded Angles	
Weld	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited
Fillet 3/16	8,175	490	8,140	490	8,140	490	8,105	490	8,105	490
1/4	26,255	2,815	19,985	2,140	19,985	2,140	18,615	1,995	18,615	1,995
5/16	7,980	1,335	11,550	1,935	11,550	1,935	9,590	1,605	9,590	1,605
3/8	480	115	665	160	665	160	1,320	320	1,320	320
7/16	325	105	0	0	0	0	160	55	160	55
1/2	0	0	290	125	290	125	0	0	0	0
9/16	0	0	0	0	0	0	250	135	250	135
TOTAL	43,215	4,860	40,630	4,850	40,630	4,850	38,040	4,600	38,040	4,600
Butt* 0.54	110	65	95	55	95	55	85	50	85	50
5/8	630	455	0	0	0	0	0	0	0	0
0.70	0	0	560	660	560	660	0	0	0	0
0.80	0	0	0	0	0	0	490	695	490	695
TOTAL	740	520	655	715	655	715	575	745	575	745
TOTAL Fillet Plus Butt	43,955	5,380	41,285	5,565	41,285	5,565	38,615	5,345	38,615	5,345

*Single Vee joint; included angle = 30°; root gap = 1/4" for thickness greater than 5/8, 1/8" for thickness of 5/8" and less.

TABLE 2-8
LONGITUDINAL STIFFENERS FOR CONTAINER SHIP CONFIGURATIONS FOR THREE TRANSVERSE FRAME SPACING
(100-FOOT SECTION, FRS. 108-148)

ITEM	Baseline 9 Transverse Webs 10'-10" O.C.	8 Transverse Webs 11'-3" O.C.		7 Transverse Webs 12'-10-1/4" O.C.	
	6 F.B. 12 ST 46 Γ 40 Γ/Γ	6 F.B. 12 ST 38 Γ 48 Γ/Γ	6 F.B. 12 ST 18 Γ 68 Welded Angles	6 F.B. 12 ST 6 Γ 56 Γ/Γ 24 ST/ Γ	6 F.B. 12 ST 6 Γ 80 Welded Angles
Up. Deck #1 - #3	18x2-5/16 F.B.	18x2-5/16 F.B.	20x2-3/8 F.B.	18x2-5/16 F.B.	18x2-5/16 F.B.
2nd Deck #1 - #3	7x4x13.6# Γ	8x4x17.2# Γ	8x4x17.2# Γ	9x4x21.3# Γ	9x4x21.3# Γ
Side #18	18x4x42.7# Γ/Γ	18x4x58.0# Γ/Γ	16x7/16; 5x15/16 ⁽¹⁾	ST 16 WF 76#/ Γ	16x7/16; 5x1-3/8
#19 - #23	Do	Do	Do; Do	Do	Do; Do
#24 - #25	15x3-3/8x33.9# Γ/Γ	18x4x42.7# Γ/Γ	13x3/8; 5x13/16	18x4x58.0# Γ/Γ	Do; 4-1/2x7/8
#26 - #27	12x3-1/2x30.9# Γ/Γ	15x3-3/8x33.9# Γ/Γ	Do; 4-1/2x5/8	18x4x42.7# Γ/Γ	14x3/8; 5x11/16
#28 - #29	9x4x21.3# Γ	12x3-1/2x30.9# Γ/Γ	Do; 4x3/8	15x3-3/8x33.9# Γ/Γ	Do; 4x1/2
#31 - #33	ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#
Long. Bulkhead #18 - #19	18x4x42.7# Γ/Γ	18x4x58.0# Γ/Γ	16x7/16; 5-1/2x7/8	ST 16 WF 76#/ Γ	16x7/16; 5x1-3/8
#20 - #22	Do	Do	Do; Do	Do	Do; Do
#23	Do	Do	Do; Do	Do	Do; Do
#24	15x3-3/8x40# Γ/Γ	18x4x42.7# Γ/Γ	13x3/8; 5x1	18x4x58.0# Γ/Γ	Do; 5x1
#25	Do	Do	Do; Do	Do	Do; Do
#26 - #27	12x3-1/2x30.9# Γ/Γ	15x3-3/8x33.9# Γ/Γ	Do; 4-1/2x5/8	18x4x42.7# Γ/Γ	14x3/8; 5x11/16
#28 - #29	9x4x21.3 Γ	12x3-1/2x30.9# Γ/Γ	Do; 4x3/8	15x3-3/8x33.9# Γ/Γ	Do; 4x1/2
#31 - #33	ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#
Inner-Bottom #2 - #3	8x4x17.2 Γ	9x4x21.3 Γ	9x4x21.3# Γ	13x4x31.8# Γ/Γ	14x3/8; 2-1/2x3/8
#6 - #7	Do	Do	Do	Do	Do; Do
#10 - #11	Do	Do	Do	Do	Do; Do
#14 - #15	8x4x19.6# Γ	12x3x25.0# Γ/Γ	13x3/8; 2-1/2x3/8	Do	Do; 3-1/2x3/8
Bottom #2 - #3	9x4x21.3# Γ	13x4x31.8# Γ/Γ	Do; 3x1/2	Do	Do; 4x7/16
#6 - #7	Do	Do	Do; Do	Do	Do; Do
#10 - #11	Do	Do	Do; Do	Do	Do; Do
#14 - #15	Do	Do	Do; Do	Do	Do; Do

(1) Web; flange

for the first alternate frame spacing (12'-4-1/8") with welded-angle stiffeners. The maximum increase occurs for the second alternate frame spacing (16'-5-1/2") with stiffeners cut from channels and tees. The change in purchased weight of steel (sum of purchased weight of fabricated stiffeners plus total erected weight excluding fabricated stiffeners) ranges from a decrease of approximately 20 tons to an increase of 275 tons, relative to a baseline total of 1572 tons. The decrease occurs for the first alternate frame spacing with welded angle stiffeners. The maximum increase occurs for the second alternate frame spacing with stiffeners cut from channels and tees. The weight increases are due primarily to the increase in stiffener sizes. It is of course possible to reduce the weight increases by using angle-shaped stiffeners for the deck instead of flat bar. For the two alternate stiffeners noted in Table 2-4 for the second alternate frame spacing, the reduction in purchased weight is 35 tons using an angle cut from a tee and 65 tons using a welded angle. These options introduce the problem of tank cleaning, a problem outside the scope of the present investigation, and for this reason are merely mentioned in passing and not pursued further.

The weight trend for the container ship is similar to that for the tanker. The increase in erected weight ranges from approximately 4 to 37 tons out of a baseline total of 926 tons. The minimum increase occurs for the first alternate frame spacing (11'-3") with welded-angle stiffeners. The maximum increase occurs for the second alternate frame spacing (12'-10-1/4") with stiffeners cut from channels and tees. The change in purchased weight of steel ranges from a decrease of approximately 11 tons to an increase of 67

tons out of a baseline total of 941 tons. The decrease occurs for the first alternate frame spacing with welded angle stiffeners. The maximum increase occurs for the second alternate frame spacing with stiffeners cut from channels and tees.

The number and weight of fabricated stiffeners increases with frame spacing in all cases. For the tanker, 116 fabricated stiffeners are required for each alternate frame spacing, compared to 82 for the baseline. The purchased weight ranges from 223 to 507 tons compared to 176 tons for the baseline. For the container ship, 68 fabricated stiffeners are required for the first alternate frame spacing and 80 for the second, compared to 40 for the baseline. The purchased weight ranges from approximately 101 to 196 tons, compared to 79 tons for the baseline.

The lineal feet of welding and burning, excluding that required for fabricated stiffeners, decreases with increased frame spacing in all cases. (The reason for the exclusion is that in the economic evaluation of the alternate configurations, such welding and burning is included in the cost of fabricated stiffeners.) For the tanker, lineal feet of welding (fillet plus butt) decreases approximately 8200 feet for the first alternate frame spacing and 15,800 feet for the second, out of a baseline total of 64,500 feet. Lineal feet of burning decreases 4,400 feet for the first alternate frame spacing and 8,800 feet for the second. The change in amount of weld metal deposited ranges from a decrease of approximately 1,500 lbs. to an increase of 140 lbs., compared to a baseline total of 20,400 lbs. The maximum decrease occurs in both configurations for the first frame spacing. The maximum increase occurs

for the second frame spacing with stiffeners cut from channels and tees. The decrease in deposited weld material is not due to increased frame spacing, however; it is due to the reduced thickness of the deck and bottom plating used in the alternate configurations.

For the container ship, lineal feet of welding (fillet plus butt) decreases approximately 2,700 feet for the first alternate frame spacing and 5,400 feet for the second, out of a baseline total of 44,000 feet. Lineal feet of burning decreases 720 feet for the first alternate frame spacing and 1,440 feet for the second. The amount of weld metal deposited increases by 180 lbs. for the first alternate frame spacing and 45 lbs. for the second, compared to a baseline total of 5,400 lbs.

The number of penetrations of transverse members by stiffeners decreases with increasing frame spacing because there are fewer web frames. For the tanker, the number of penetrations decreases by 300 for the first alternate frame spacing and decreases by 600 for the second, out of a total of 1,500 for the baseline. For the container ship, the number of penetrations decreases by 104 for the first alternate frame spacing and 208 for the second, out of a total of 1040 for the baseline.

2.5 Economic Evaluation of Alternate Frame Spacing

In order to evaluate the economic effect of alternate frame spacing it is necessary to derive equations with which to calculate the cost increment incurred in passing from either of the baseline configurations to an alternate configuration. The total cost, C_T , for the section of the ship considered can be regarded as the sum of two parts: one part, C , that varies with frame spacing, and another part, C_0 , that is independent of frame spacing. Thus,

$$C_T = C + C_0. \quad (2-1)$$

The frame-spacing-dependent part of the cost can also be written as the sum of two parts: the cost of fabricated stiffeners, C_{fs} , plus C_R , the remaining portion of C ,

$$C = C_{fs} + C_R. \quad (2-2)$$

Because three different kinds of fabricated stiffeners are considered, the term C_{fs} is equal to the sum of the cost of stiffeners cut from channels, C_{fsc} ; stiffeners cut from tees, C_{fst} ; and stiffeners made from welded angles, C_{fsw} :

$$C_{fs} = C_{fsc} + C_{fst} + C_{fsw}. \quad (2-3)$$

For convenience, fabricated stiffeners are treated as a "subcontracted" item. Upon delivery to the shipyard, the fabricated stiffeners are (for the purpose of economic analysis) treated in the same way as standard angles. Thus, C_{fs}

includes only the cost of material, the cost of burnings and straightening, and the cost of welding required to fabricate stiffeners. The cost C_R excludes the above costs, but includes the cost of other material, C_m ; the cost of material preparation (blasting and coating), C_{mp} ; the cost of all other burning, C_b ; the cost of all other welding, C_w ; and the cost, C_p , associated with penetrations of transverse members by stiffeners. Thus, from Equations 2-2 and 2-3,

$$C = C_m + C_{mp} + C_b + C_w + C_p + C_{fsc} + C_{fst} + C_{fsw}. \quad (2-4)$$

Now each cost term in Equation 2-4 must be determined in terms of the physical parameters defining the configuration.

The cost of material, C_m , is obtained by subdividing the material into groups according to the cost per ton. If there are N_m different groups and the i^{th} group contains W_i tons costing α_{m_i} dollars per ton, then

$$C_m = \sum_{i=1}^{N_m} \alpha_{m_i} W_i. \quad (2-5)$$

Scrap is neglected, because it is assumed to be nearly independent of frame spacing, and is for this reason included in the term C_o in Equation 2-1.

The cost of material preparation, C_{mp} , is based on the use of semi-automatic blasting and coating facilities, in which case the cost will depend primarily on the lineal feet of material that passes through the facilities. Thus, C_{mp} can be expressed in the form,

$$C_{mp} = \alpha_{mp_p} L_p + \sum_{i=1}^{N_s} \alpha_{mp_{s_i}} L_{s_i}, \quad (2-6)$$

where L_p is the lineal feet of plate; L_{s_i} is the lineal feet of the i^{th} type of stiffener (flat bar, angle, etc.); α_{mp_p} and $\alpha_{mp_{s_i}}$ are the respective material preparation costs per lineal foot. In the case of manual blasting, which is not considered here, C_{mp} would depend primarily on the surface area of the material.

The cost of burning, C_b , depends mainly on lineal feet and to a lesser extent on thickness of the member. Because the average thickness of the alternate configurations do not differ greatly from that of the baseline, C_b is assumed to be directly proportional to the lineal feet of burning:

$$C_b = \alpha_b L_b, \quad (2-7)$$

where α_b is the average cost per lineal foot.

The cost of welding, C_w , is obtained by subdividing the total amount of welding into groups according to the type of weld. For a given size and type of weld, it is assumed that the cost is directly proportional to the lineal feet of weld. Thus, for the j^{th} group, if $L_{w_{ji}}$ is the amount of lineal feet of the i^{th} size, and the cost per lineal feet for this size is $\alpha_{w_{ji}}$, then the cost of welds of the j^{th} group is

$$C_{w_j} = \sum_{i=1}^{N_{w_j}} \alpha_{w_{ji}} L_{w_{ji}}, \quad (2-8)$$

where N_{wj} is the number of different sizes in the j^{th} group. The total cost of welding is then given by

$$C_w = \sum_{j=1}^{N_w} \sum_{i=1}^{N_{wj}} \alpha_{wji} L_{wji}, \quad (2-9)$$

where N_w is the number of different types of welds.

The cost associated with stiffener penetrations of transverse members is obtained by subdividing the stiffeners into groups according to the combination of stiffener shape and kind of penetration, such as oil- or water-tight, non-tight with or without a collar-plate reinforcement. The cost of a penetration within a given group is primarily a function of the cross-section dimensions of the stiffener. In addition, there is some minimum cost no matter how small the stiffener is. To account for the size-dependence, we use as a measure of size, the depth of the stiffener. Then, as a first approximation, the cost of the i^{th} penetration in the j^{th} group of penetrations is taken as a linear function of the depth of the stiffener:

$$C_{p_{ij}} = \alpha_{p_j} + \beta_{p_j} D_{ij} \quad (2-10)$$

where D_{ij} is the depth of the stiffener for the i^{th} penetration in the j^{th} group, and α_{p_j} and β_{p_j} are constants which depend on the kind of penetration. If N_{pj} is the number of penetrations in the j^{th} group, then the cost for the j^{th} group of penetrations is

$$C_{pj} = \sum_{i=1}^{N_{pj}} (\alpha_{pj} + \beta_{pj} D_{ij}),$$

$$C_{pj} = \alpha_{pj} N_{pj} + \beta_{pj} \sum_{i=1}^{N_{pj}} D_{ij}, \quad (2-11)$$

$$C_{pj} = N_{pj} (\alpha_{pj} + \beta_{pj} \bar{D}_j),$$

where $\bar{D}_j$ is the average depth of stiffener for penetrations in the j^{th} group. Finally, if there are N_p different groups of penetrations, the total cost is

$$C_p = \sum_{j=1}^{N_p} N_{pj} (\alpha_{pj} + \beta_{pj} \bar{D}_j). \quad (2-12)$$

The cost of fabricated stiffeners that are cut from channels is the sum of material cost, burning cost, and straightening cost. For a typical stiffener, say the i^{th} , the material cost is proportional to the purchased weight, W_{fsc_i} ; and as before, it is assumed that the burning cost is proportional to the length, L_{fsc_i} . The cost of straightening is assumed to be equal to the length, multiplied by a factor, γ_{fsc_i} , which is a function of the dimensions of the stiffener cross-section. The cost of the i^{th} stiffener is therefore given by

$$C_{fsc_i} = \alpha_{fsc_i} W_{fsc_i} + \alpha_{bc} L_{fsc_i} + \gamma_{fsc_i} L_{fsc_i} \quad (2-13)$$

where α_{bc} is the burning cost per lineal foot for channels. If there is a total of N_{fsc} stiffeners, the total cost will be

$$C_{fsc} = \sum_{i=1}^{N_{fsc}} (\alpha_{fsc_i} W_{fsc_i} + \gamma_{fsc_i} L_{fsc_i}) + \alpha_{bc} L_{fsc}, \quad (2-14)$$

where L_{fsc} is the total lineal feet of stiffeners. The dependence of the quantity γ_{fsc_i} on cross-section dimensions is not clear. For a given distortion the cost of straightening increases with increasing cross-sectional dimensions. However, the amount of distortion generally decreases with increasing dimensions. Therefore, until better cost data are available, γ_{fsc_i} is taken as a constant as a first-order approximation.

By analogy, the cost of stiffeners cut from tees is obtained by replacing the subscript c in Equation 2-14 by t:

$$C_{fst} = \sum_{i=1}^{N_{fst}} (\alpha_{fst_i} W_{fst_i} + \gamma_{fst_i} L_{fst_i}) + \alpha_{bt} L_{fst}. \quad (2-15)$$

The cost of fabricated stiffeners that are welded angles is proportional to the weight of angles purchased. Thus, the cost of a typical stiffener, say the i^{th} one, is

$$C_{fsw_i} = \alpha_{fsw_i} W_{fsw_i}, \quad (2-16)$$

where α_{fsw_i} is the cost per ton and W_{fsw_i} is the weight in tons. If there is a total of N_{fsw} stiffeners, then the total cost will be

$$C_{fsw} = \sum_{i=1}^{N_{fsw}} \alpha_{fsw_i} W_{fsw_i}. \quad (2-17)$$

We are now in a position to obtain expressions needed to calculate the cost increment incurred in passing from a baseline configuration to an alternate configuration. Let the increment in any quantity (...) be defined by

$$\delta(\dots)^{AB} \equiv (\dots)^A - (\dots)^B, \quad (2-18)$$

where the superscripts A and B refer to the alternate and baseline configurations, respectively. Then from Equation 2-4 there follows

$$\delta C^{AB} = \delta C_m^{AB} + \delta C_{mp}^{AB} + \delta C_b^{AB} + \delta C_w^{AB} + \delta C_p^{AB} + \delta C_{fsc}^{AB} + \delta C_{fst}^{AB} + \delta C_{fsw}^{AB}. \quad (2-19)$$

It is important to note that a negative value of δC^{AB} indicates that the alternate configuration costs less than the baseline configuration. A negative cost increment is therefore good; a positive one is bad.

From the standpoint of convenience it is well to observe that the cost increment is independent of the cost C_0 introduced in Equation 2-1 (because, by definition, C_0 is independent of frame spacing). The physical portion of the ship to which C_0 corresponds is therefore arbitrary, except that the cost of whatever portion is selected must indeed be independent of frame spacing.

Thus, any convenient selection can be made in evaluating each of the individual cost increments on the right-hand side of Equation 2-19. Advantage of this observation should be taken in order to simplify the calculations as much as possible.

The preceding equations will now be used to obtain an economic assessment of the alternate configurations with increased frame spacing. The assessment is at best semi-quantitative because of the assumptions made regarding the various costs appearing in the equations. A more accurate assessment would have to be based on cost data for an individual shipyard so as to account for regional differences in labor rates and the facilities and capabilities of the individual yard.

To demonstrate the use of the cost equations, consider, as an example, the calculation of the cost increment incurred in passing from the tanker baseline to the alternate configuration in which the frame spacing is 12'-4-1/8" and the fabricated stiffeners are welded angles.

Equation 2-5 is used to calculate the increment in material cost (excluding the material for fabricated stiffeners). The material is divided into two groups corresponding to two different grades of steel:

W_1 = weight of bilge, bottom and deck plating

W_2 = remainder of erected weight (excluding fabricated stiffeners)

From Table 2-1

$$\{W_i^B\} = \{646.5; 749.1\} \text{ tons}; \{W_i^A\} = \{590.6; 737.7\} \text{ tons}$$

The costs per ton are taken as

$$\{\alpha_{m_i}\} = \{275; 210\} \text{ \$/ton}$$

for both the baseline and the alternate configuration.

From Equation 2-5,

$$C_m^B = \$335,100, \quad C_m^A = \$317,330, \quad \delta C_m^{AB} = - \$17,770$$

Equation 2-6 is used to calculate the increment in material preparation cost.

The material is divided into three groups:

L_p = lineal feet of plates

L_{s_1} = lineal feet of flat bar stiffeners

L_{s_2} = lineal feet of angle-shaped stiffeners

Since the only change in L_p is due to the use of fewer web frames, all other plates can be ignored. The lineal feet of plates in two web frames is 800 feet. Hence, take

$$L_p^B = 0 \text{ ft.}, \quad L_p^A = - 800 \text{ ft.}$$

From Table 2-4,

$$\{L_{s_i}^B\} = \{3,360; 11,450\} \text{ ft}; \quad L_{s_i}^A = \{3,360; 11,450\} \text{ ft.}$$

The costs per lineal foot are taken as

$$\alpha_{mp_p} = \$0.10/\text{ft.}; \quad \{\alpha_{mp_{s_i}}\} = \{0.10; 0.20\} \text{ \$/ft.}$$

From Equation 2-6,

$$C_{mp}^B = \$2,630, \quad C_{mp}^A = \$2,550, \quad \delta C_{mp}^{AB} = - \$80.$$

Equation 2-7 is used to calculate the increment in burning cost (excluding fabricated stiffeners). From Table 2-1:

$$L_b^B = 0 \text{ ft.}, \quad L_b^A = - 4,400 \text{ ft.}$$

The cost Per lineal foot is taken as

$$\alpha_b = \$0.50/\text{ft.}$$

From Equation 2-7,

$$C_b^B = \$0, \quad C_b^A = - \$2,200, \quad \delta C_b^{AB} = - \$2,200$$

Equation 2-9 is used to calculate the increment in welding cost (excluding fabricated stiffeners). The welds are divided into two groups: $j=1$ for fillet; $j=2$ for butt. The L_{wi} are defined as follows:

$$\{L_{w1i}\} = \text{lineal feet of } \{1/4; 5/16; 3/8; 7/16\} \text{-inch fillet weld;}$$

$$\{L_{w2i}\} = \text{lineal feet of } \{1/2; 0.6; 1-1/4; 1-3/8; 1-1/2\} \text{-inch butt weld.}$$

From Table 2-3,

$$\{L_{w1i}^B\} = \{22,675; 31,015; 7,380; 0\} \text{ ft.},$$

$$\{L_{w2i}^B\} = \{165; 0; 0; 1,690; 1,570\} \text{ ft.},$$

$$\{L_{w1i}^A\} = \{15,405; 25,265; 6,785; 5,460\} \text{ ft.},$$

$$\{L_{w2i}^A\} = \{0; 125; 1,690; 1,570; 0\} \text{ ft.},$$

The costs per lineal foot are taken as

$$\{\alpha_{w1i}\} = \{2.00; 2.40; 2.85; 3.30\} \text{ \$/ft.},$$

$$\{\alpha_{w2i}\} = \{4.50; 5.30; 11.90; 13.40; 15.00\} \text{ \$/ft.}$$

From Equation 2-9,

$$C_W^B = \$188,000, \quad C_W^A = \$171,000, \quad \delta C_W^{AB} = - \$17,000.$$

Equation 2-12 is used to calculate the cost associated with stiffener penetrations of transverse members. The different groups of penetrations are defined as follows:

- j=1 flat bar; oil- or water-tight penetration.
- j=2 angle; oil- or water-tight penetration.
- j=3 flat bar; non-tight; no collar plate.
- j=4 angle; non-tight; collar plate.
- j=5 angle; non-tight; no collar plate.

From Table 2-4 and Figure 2-2,

$$\{N_{p_j}^B\} = \{34; 116; 306; 343; 702\},$$

$$\{D_j^B\} = \{11.0; 13.2; 11.0; 13.2; 13.2\} \text{ in.}$$

$$\{N_{p_j}^A\} = \{34; 116; 238; 266; 546\},$$

$$\{D_j^A\} = \{13.0; 15.7; 13.0; 15.7; 15.7\} \text{ in.}$$

The cost coefficients are taken as

$$\{\alpha_{p_j}\} = \{8; 18; 5; 10; 5\} \$,$$

$$\{\beta_{p_j}\} = \{0.25; 0.60; 0.15; 0.30; 0.15\} \$/\text{in.}$$

From Equation 2-12,

$$C_p^B = \$15,080, \quad C_p^A = \$13,150, \quad \delta C_p^{AB} = - \$1,930$$

Equation 2-14 is used to calculate the cost of fabricated stiffeners cut from channels. The cost coefficients are taken as

$$\alpha_{bc} = \$0.50/\text{ft.}, \quad \alpha_{fsc_i} = \$210/\text{ton}, \quad \gamma_{fsc_i} = \$0.50/\text{ft.}$$

From Table 2-1:

$$N_{fsc}^B = 82, \quad N_{fsc}^A = 0, \quad N_{fsc}^A = 0,$$

$$L_{fsc_i}^B = 98.75 \text{ ft.}, \quad L_{fsc_i}^A = 0,$$

$$L_{fsc}^B = 8,100 \text{ ft.}, \quad L_{fsc}^A = 0.$$

Since α_{fsc_i} is the same for each stiffener, only the total purchased weights of stiffeners, given in Table 2-1, are needed:

$$\sum_{i=1}^{N_{fsc}^B} W_{fsc_i}^B = 176.2 \text{ tons}, \quad \sum_{i=1}^{N_{fsc}^A} W_{fsc_i}^A = 0.$$

From Equation 2-14,

$$C_{fsc}^B = \$45,100, \quad C_{fsc}^A = 0, \quad \delta C_{fsc}^{AB} = - \$45,100$$

Equation 2-17 is used to calculate the cost of welded-angle stiffeners. The cost coefficient is taken as $\alpha_{fsw_i} = \$230/\text{ton}$. Since α_{fsw_i} is the same for each stiffener, only the total purchased weights of stiffeners, given in Table 2-1, are needed:

$$\sum_{i=1}^{N_{fsw}^B} W_{fsw_i}^B = 0, \quad \sum_{i=1}^{N_{fsw}^A} W_{fsw_i}^A = 223.3 \text{ tons.}$$

$\delta C^{AB} = - \$10,960$ for 11'-3" frame spacing with welded angles;

$\delta C^{AB} = \$4,930$ for 11'-3" frame spacing with angles cut from channels;

$\delta C^{AB} = \$26,990$ for 12'-10-1/4" frame spacing with angles cut from channels and tees.

The above cost increments are based on the cost coefficients used in the numerical example plus the following additional cost coefficients:

$\{\alpha_{w1i}\} = \{1.65; 3.80; 4.40\}$ \$/ft. for
{3/16; 1/2; 9/16} -inch fillet welds;

$\{\alpha_{w2i}\} = \{3.25; 4.05; 4.75; 5.00; 5.50; 5.75; 5.95; 6.05; 6.30;$
6.45; 6.60; 6.90; 7.20; 7.80; 7.95; 8.40; 9.05; 9.40;
10.05; 10.45; 11.15; 11.90; 18.35; 20.15; 22.00} \$/ft. for

{5/16; 7/16; 17/32; 9/16; 5/8; 21/32; 0/68; 11/16; 23/32;
47/64; 3/4; 25/32; 13/16; 7/8; 0.89; 15/16; 1; 1-1/32;
1.09; 1-1/8; 1-3/16; 1-5/16; 1-3/4; 1-7/8; 2} -inch butt
welds;

$\alpha_{fst_i} = \$210/\text{ton}; \alpha_{bt} = \$0.75/\text{ft.}, \gamma_{fst} = \$0.50/\text{ft.}$

In addition, for the container ship, the calculation of C_m (see Equation 2-5 is based on one group of material for which $\alpha_{m_1} = \$210/\text{ton}$.

Section 3

INVESTIGATION OF ALTERNATE STRUCTURAL SHAPES

3.1 Baseline Configurations

The baseline configurations are the same as those used for the investigation of alternate frame spacing (see Figures 2-1 and 2-2). In the tanker baseline configuration, the deck plating is longitudinally stiffened by 34 11x1-3/8 inch flat bars, spaced approximately 33 inches apart. The bottom plating is longitudinally stiffened by 30 angles cut from 18x4x58.0# channels, spaced approximately 33 inches apart. The plating for the sheer strake, sides, longitudinal bulkheads, and the bilge is longitudinally stiffened by 34 angles ranging in size from 8x4x19.6# to 9x4x23.8#, and by 52 angles cut from channels ranging in size from 10x4x28.5# to 18x4x58.0#; spacing of these stiffeners varies from 29 to 33 inches.

In the container ship baseline configuration (see Figures 2-3 and 2-4), the second deck plating is longitudinally stiffened by three 7x4x13.6# angles spaced at 34.5 inches. Between the second deck and the innerbottom the plating for the sides and longitudinal bulkheads are longitudinally stiffened by eight 9x4x21.3# angles and by 40 angles cut from channels ranging in size from 12x3-1/2x30.9# to 18x4x42.7#; spacing of these stiffeners is 36 inches. Plating for the bottom and innerbottom is longitudinally stiffened by 32 angles ranging in size from 8x4x17.2# to 9x4x21.3#.

3.2 Alternate Configurations

Three alternate structural shapes for longitudinal stiffeners were considered for each ship: bulb flat, flat bar, and Yoder angles (see Figure 3-1). The baseline stiffener spacing is maintained in all cases. Depending on the

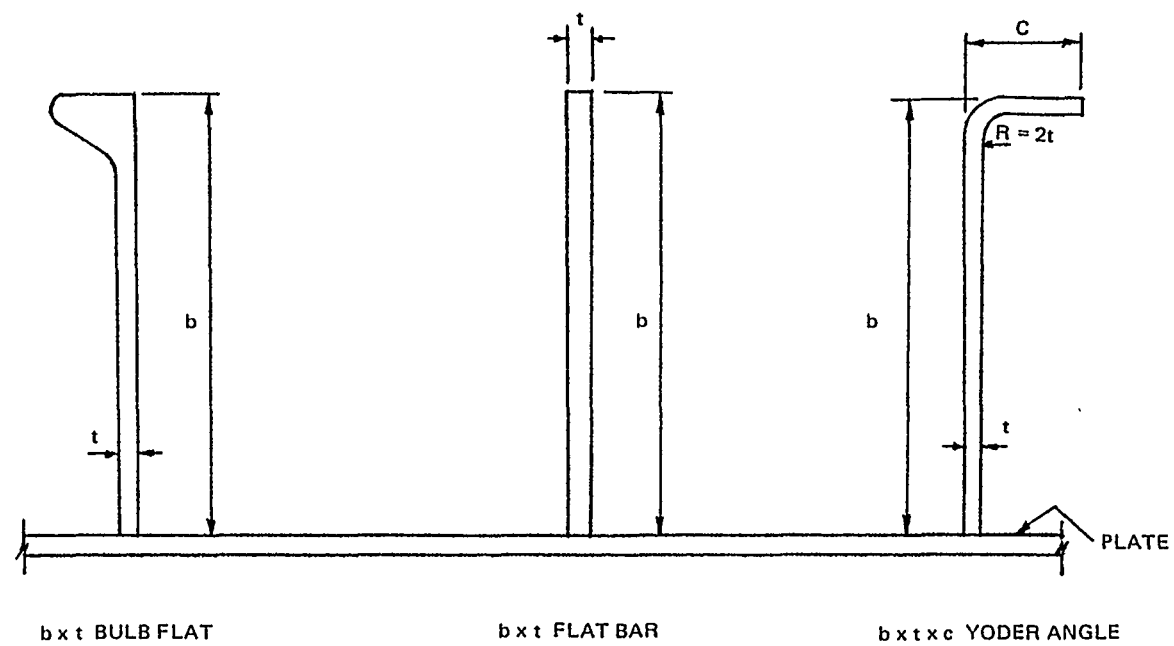


Figure 3-1. Alternate Stiffener Shapes

alternate shape considered, certain baseline stiffeners are maintained because there is not even a potential advantage in changing them. Flat bar stiffeners in the baseline always remain as flat bar stiffeners in an alternate configuration. Standard angles in the baseline are replaced by bulb flat in an alternate configuration but are not replaced by Yoder angles. Angles cut from channels are replaced by whatever alternate section is being considered.

3.3 Method of Sizing Alternate Configurations

The alternate configurations are sized to provide at least the same hull strength as for the baseline. The section modulus of the alternate stiffener in combination with the associated plating must be at least as great as that for the corresponding baseline stiffener. Moreover, the cross-sectional area of the alternate stiffener must be such that the hull-girder section modulus " is at least equal to that for the baseline. In the case of the tanker, plate thickness were reduced whenever beneficial, subject to the restrictions described in Section 2.3.

3.4 Effects of Alternate Structural Sections

The major effects of alternate structural sections on the physical characteristics of the configurations examined are given in Tables 3-1 through 3-5 for the tanker and Tables 3-6 through 3-10 for the container ship. The first three tables in each series gives, for each of the three shapes, a summary of erected weight, welding requirements, and the number and kind of stiffener penetrations of transverse members. The fourth table gives lineal feet of welds and pounds of weld metal deposited for different sizes of welds used. Finally, the fifth table gives the required stiffener sizes.

TABLE 3-1

SUMMARY OF ALTERNATE TANKER CONFIGURATIONS WITH BULB FLAT STIFFENERS
(98.75-FOOT SECTION, FRS. 71-81)

ITEM	SIDES AND LONGITUDINAL BULKHEADS ⁽¹⁾		DECK, BOTTOM, AND BILGE ⁽¹⁾	
	Baseline 34 Γ 44 $[\Gamma$ ⁽²⁾	78 Bulb Flat	Baseline 34 Flat Bar 38 $[\Gamma$ ⁽³⁾	34 Flat Bar 38 Bulb Flat
● Erected Weight, Tons				
Total	410.1	418.1	825.5	826.0
Stiffeners ($\Gamma+[\Gamma$ or Bulb Flat)	88.0	96.0	92.7	108.0
Total Less Stiffeners	322.1	322.1	732.8	718.0
● Welding				
Fillet, Lineal Feet	15,405	15,405	14,220	14,220
Pounds Deposited	1,650 ⁽⁴⁾	1,650 ⁽⁴⁾	2,380	2,380
Butt, Lineal Feet	0	0	3,260	3,260
Pounds Deposited	0	0	10,860	10,490
● Transverse Penetrations				
O.T.	78	78	72	72
N.T. Without Collar	360	702	648	648
N.T. With Collar	342.	0	0	0

(1) See Table 3-5 for stiffener sizes.

(2) Requires 4345 feet of burning to remove 15.1 tons of flange from 69.0 tons of channels.

(3) Requires 3750 feet of burning to remove 14.3 tons of flange from 107.0 tons of channels.

(4) No change in butt welds.

SUMMARY OF ALTERNATE TANKER CONFIGURATIONS WITH FLAT BAR STIFFENERS
(98.75-FOOT SECTION, FRS. 71-81)

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(2) Requires 4345 feet of burning to remove 15.1 tons of flange from 69.0 tons of channels.

(3) Requires 3750 feet of burning to remove 14.3 tons of flange. from 107.0 tons of channels.

(4) No change in butt welds.

TABLE 3-3

SUMMARY OF ALTERNATE TANKER CONFIGURATIONS WITH YODER ANGLE STIFFENERS

(98.75-FOOT SECTION, FRS. 71-81)

ITEM	SIDES AND LONGITUDINAL BULKHEADS ⁽¹⁾		DECK, BOTTOM, AND BILGE ⁽¹⁾	
	Baseline 34 I 44 I/I ⁽²⁾	34 I 44 Yoder Angles	Baseline 34 I/I ⁽³⁾ 34 Flat Bar	0 I 38 Yoder Angles 34 Flat Bar
- Erected Weight, Tons - Total Stiffeners (I/I or Yoder) - Total Less Stiffeners - Welding - Fillet, Lineal Feet Pounds Deposited - Transverse Penetrations - O.T. - N.T. Without Collar - N.T. With Collar	410.1 54.1 356.0 15,405 1,650 78 360 342	411.4 55.4 356.0 15,405 1,650 78 360 342	825.5 92.7 732.8 14,215 2,380 72 648 0	826.4 93.6 732.8 14,215 2,380 72 648 0

(1) See Table 3-5 for stiffener sizes.

(2) Requires 4345 feet of burning to remove 15.1 tons of flange from 69.0 tons of channels.

(3) Requires 3750 feet of burning to remove 14.3 tons of flange from 107.0 tons of channels.

TABLE 3-4

WELDS FOR TANKER CONFIGURATIONS WITH ALTERNATE STRUCTURAL SHAPES

(98.75-FOOT SECTION, FRS. 71-81)

ITEM	Baseline 34 F.B. 34 Γ 82 [/Γ		Bulb Flat Replaces Γ and [/Γ 34 F.B. 116 B.F.		Flat Bar Replaces Γ and [/Γ 150 F.B.		Yoder Angle Replaces [/Γ 34 F.B. 34 Γ 82 [/Γ		
Weld	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	
Fillet 1/4	22,675	2,430	Same As Baseline		7,665	820	Same As Baseline		
	5/16	31,015			5,195	46,024			7,710
	3/8	7,380			1,780	7,380			1,780
	TOTAL	61,070	9,405	61,070	9,405	61,070	10,310	61,070	9,405
Butt* 1/2	165	90	165	90	165	90	Same As Baseline		
	1-1/4	0	0	0	1,570	4,225			
	1-3/8	1,690	5,260	1,690	5,260	1,690			5,260
	1-7/16	0	0	1,570	5,230	0			0
	1-1/2	1,570	5,600	0	0	0			0
	TOTAL	3,425	10,950	3,425	10,580	3,425	9,575	3,425	10,950
TOTAL Fillet Plus Butt	64,495	20,355	64,495	19,985	64,495	19,885	64,495	20,355	

*Single Vee joint; included angle = 30°; root gap = 1/4" for thickness greater than 5/8, 1/8" for thickness of 5/8" and less.

TABLE 3-5

BULB FLAT, FLAT BAR, AND YODER ANGLE LONGITUDINAL STIFFENERS FOR TANKER

(98.75-FOOT SECTION, FRS. 71-81)

ITEM		Baseline 34 F.B. 34 Γ 82 $[/math>\Gamma$	Bulb Flat Replaces Γ and $[/math>\Gamma34 F.B.116 B.F.$	Flat Bar Replaces Γ and $[/math>\Gamma150 F.B.$	Yoder Angle Replaces $[/math>\Gamma34 F.B.34 \Gamma82 Y.A.$
Deck	#1 - #7 #9 - #18	11 x 1-3/8 F.B. Do	11 x 1-3/8 F.B. Do	11 x 1-3/8 F.B. Do	11 x 1-3/8 F.B. Do
Side	#1 - #2 #3 #4 - #6 #7 - #8 #9 #10 #11 - #13 #14 - #15 #16 - #18	8 x 4 x 19.6# Γ Do Do 9 x 4 x 21.3# Γ 9 x 4 x 23.8# Γ 10 x 4 x 28.5# $[/math>\Gamma12 x 3-1/2 x 30.9# [/math>\Gamma13 x 4 c 31.8# [/math>\Gamma15 x 3-3/8 x 33.9# [/math>\Gamma$	240 x 12mm x 19.6# Do Do 260 x 12mm x 21.7# 280 x 12mm x 23.9# 280 x 11mm x 22.5# 300 x 11mm x 24.6# 320 x 12mm x 28.5# 320 x 15mm x 33.6#	8-1/2 x 1-1/16 Do Do 9 x 1-1/8 9-1/2 x 1-3/16 Do 10-1/2 x 1-5/16 11 x 1-3/8 11-1/2 x 1-7/16	8 x 4 x 19.6# Γ Do Do 9 x 4 x 21.3# Γ 9 x 4 x 23.8# Γ 12 x 3/8 x 5-1/2 x 21.3# 15 x 3/8 x 5 x 24.5# Do 15 x 7/16 x 5 x 28.4#
Bilge	#19 #20 - #22	15 x 3-3/8 x 40.0# $[/math>\GammaSame as Bottom #23$	370 x 15mm x 40.6# Same as Bottom #23	12 x 1-9/16 Same as Bottom #23	16 x 9/16 x 6 x 39.9# Same as Bottom #23
Bottom	#23 - #30 #32 - #38	18 x 4 x 58.0# $[/math>\GammaDo$	430 x 19mm x 58.5# Do	14-1/2 x 1-13/16 Do	18 x 11/16 x 5 x 50.4# Do
Long. Bulkhead	#1 - #3 #4 - #6 #7 - #8 #9 - #10 #11 - #13 #14 #15 - #16 #17 - #18 #19 - #21	8 x 4 x 19.6# Γ Do 9 x 4 x 21.3# Γ 10 x 4 x 28.5# $[/math>\Gamma12 x 3-1/2 x 30.9# [/math>\Gamma13 x 4 x 31.8# [/math>\GammaDo15 x 3-3/8 x 33.9# [/math>\GammaDo$	240 x 12mm x 19.6# Do 260 x 12mm x 21.7# 280 x 11mm x 22.5# 300 x 11mm x 24.6# 320 x 12mm x 28.5# Do 320 x 15mm x 33.6# Do	8-1/2 x 1-1/16 8-1/2 x 1-1/16 9 x 1-1/8 9-1/2 x 1-3/16 10-1/2 x 1-5/16 11 x 1-3/8 Do 11-1/2 x 1-7/16 Do	8 x 4 x 19.6# Γ Do 9 x 4 x 21.3# Γ 12 x 3/8 x 5-1/2 x 21.3# 15 x 3/8 x 5 x 24.5# Do Do 15 x 7/16 x 5 x 28.4# Do

TABLE 3-6

SUMMARY OF ALTERNATE CONTAINER SHIP CONFIGURATIONS WITH BULB FLAT STIFFENERS

(100-FOOT SECTION, FRS. 108-148)

ITEM	SIDES AND LONGITUDINAL BULKHEADS ⁽¹⁾		BOTTOM AND INNERBOTTOM ⁽¹⁾	
	Baseline 8 I 40 I/r ⁽²⁾ 12 ST	48 Bulb Flat 12 ST	Baseline 32 r	32 Bulb Flat
● Erected Weight, Tons				
Total	358.1	369.0	216.0	217.1
Stiffeners (I+I/r or Bulb Flat)	72.3	83.2	31.2	32.3
Total Less Stiffeners	285.8	285.8	184.8	184.8
● Welding				
Fillet, Lineal Feet	12,340	12,340	6,400	6,400
Pounds Deposited	1,170	1,170	685	685
● Transverse Penetrations				
O.T.	192	192	32	32
N.T. Without Collar	204	336	216	288
N.T. With Collar	204	72	72	0

(1) See Table 3-10 for stiffener sizes.

(2) Requires 4000 feet of burning to remove 14.6 tons of flange from 78.4 tons of channels.

TABLE 3-7

SUMMARY OF ALTERNATE CONTAINER SHIP CONFIGURATIONS WITH FLAT BAR STIFFENERS

(100.FOOT SECTION, FRS. 108-148)

ITEM	SIDES AND LONGITUDINAL BULKHEADS ⁽¹⁾		BOTTOM AND INNERBOTTOM ⁽¹⁾	
	Baseline 8 I 40 L/I ⁽²⁾ 12 ST	48 Flat Bar 12 ST	Baseline 32 I	32 Flat Bar
- Erected Weight, tons - Total 358.1 - Stiffeners (I+L/I or Flat Bar) 72.3 - Total Less Stiffeners 285.8 - Welding - Fillet, Lineal Feet 12340 - Pounds Deposited 1171.8 - Transverse Penetrations - O.T. 192 - N.T. Without Collar 204 - N.T. With Collar 204				
		429.7	216.0	235.8
		143.9	31.2	51.0
		285.8	184.8	184.8
		12340	6400	6400
		1171.8	686.1	686.1
		192	32	32
		336	216	288
		72	72	0

(1) See Table 3-10 for stiffener sizes.

(2) Requires 4000 feet of burning to remove 14.6 tons of flange from 78.4 tons of channels.

TABLE 3-8

SUMMARY OF ALTERNATE CONTAINER SHIP CONFIGURATIONS WITH YODER ANGLE STIFFENERS

(100-FOOT SECTION, FRS. 108-148)

ITEM	SIDES AND LONGITUDINAL BULKHEADS ⁽¹⁾	
	Baseline 8 I 40 L/I 12 ST	8 I 40 Yoder Angles 12 ST
- Erected Weight, Tons - Total 358.1 - Stiffeners (L/I or Yoder) 63.8 - Total Less Stiffeners 294.3 - Welding - Fillet, Lineal Feet 12,340 - Pounds Deposited 1,170 - Transverse Penetrations - O.T. 192 - N.T. Without Collar 240 - N.T. With Collar 204		

(1) See Table 3-10 for stiffener sizes.

(2) Requires 4000 feet of burning to remove 14.6 tons of flange from 78.4 tons of channels.

TABLE 3-9

WELDS FOR CONTAINER SHIP CONFIGURATIONS WITH ALTERNATE STRUCTURAL SHAPES

(100-FOOT SECTION, FRS. 108-148)

ITEM		Baseline 6 F.B. 12 ST 46 r 40 [/		Bulb Flat Replaces " and [/ 6 F.B. 12 ST 86 BF		Flat Bar Replaces and [/ 92 F.B. 12 ST		Yoder Angle Replaces [/ 6 F.B. 12 ST 46 40 Y.A.	
Weld		Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited	Lineal Feet	Pounds Deposited
Fillet	3/16	8,175	490	Same As Baseline		315	20	Same as	Baseline
	1/4	26,255	2,815			24,815	2,660		
	5/16	7,980	1,340			7,980	1,340		
	3/8	480	115			9,780	2,360		
	7/16	325	105			325	105		
	TOTAL	43,215	4,865			43,215	6,485		

TABLE 3-10

BULB FLAT, FLAT BAR, AND YODER ANGLE LONGITUDINAL STIFFENERS FOR CONTAINER SHIP

(100-FOOT SECTION; FRs. 108-148)

ITEM		Baseline 6 F.B. 12 ST 46 r 40 [/r	Bulb Flat Replaces r and [/r 6 F.B. 12 ST 86 B.F.	Flat Bar Replaces r and [/r 92 F.B. 12 ST	Yoder Angle Replaces
SC	Up. Deck #1 - #3	18x 2-5/16	18 X 2-5/16	18x 2-5/16	18 X 2-5/16
	2nd Deck #1 - #3	7x4x 13.6#r	220 x 10mmx15.3#	7x15/16	7x4x 13.6# r
	Side #18	18x 4 x 42.7# [/r	370 x 16mmx42.5#	13x 1-5/8	18x 1/2x 5x37.3#
		#19- #23 Do	Do	Do	Do
		#24 - #25 15 X 3-3/8 X 33.9# [/r	320 x 15mm 33.6#	11-1/2x 1-7/16	15 x 7/16 x 5 x 28.4#
		#26 - #27 12 X 3-1/2 X 30.9# [/r	300 x 11mm 24.6#	10-1/2 X 1-5/16	12 x 7/16 x 5-1/2 x 2
		#28 - #29 9 x 4 x 21.3# r	260 x 12mmx 21.7#	9x 1-1/8	9 x 4 x 21.3# r
		#31 - #33 ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#
	Long. Bulkhead #18 - #19	18 x 4 x 42.7# [/r	370x16mmx42.5#	13x 1-11/16	18 x 1/2 x 5 x 37.3#
		#20- #22 Do	Do	Do	Do
		#23 Do	Do	Do	Do
		#24 15 X 3-3/8 X 40.0# [/r	370X 12mm 34.7#	12X 1-1/2	16 x 1/2 x 5 x 33.9#
		#25 Do	Do	12x 1-9/16	Do
		#26 - #27 12 X 3-1/2 X 30.8# [/1	300x 11mm 24.6#	10-1/2x 1-5/16	12 x 7/16 x 5-1/2 x 2
	Innerbottom #28 - #29	9x4x 21.3#r	260x12mmx21.7#	9x 1-1/8	9 x 4 x 21.3# r
		#31 - #33 ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#	ST 12 WF 60#
	Bottom #2 - #3	8x4x 17.2\$lr	240x11mmx18.4#	8x 1-1/16	8x4x 17.2#r
		#6 - #7 Do	Do	Do	Do
		#10 - #11 Do	Do	Do	Do
		#14 - #15 8x4x 19.6#r	240x12mmx19.6#	8-1/2x 1-1/16	8x4x19.6 * :
	Bottom #2 - #3	9x4x21.3#r	260x12mmx21.7#	9 x 1-1/R	9X4X21.3 * :
		#6 - #7 Do	Do	Do	Do
		#10- #11 Do	Do	Do	Do
		#14 - #15 Do	Do	Do	Do

In all cases, the erected weight of steel increases for the alternate configurations. For the tanker, the increases are approximately nine tons with bulb flat, 74 tons with flat bar, and two tons with Yoder angles. As noted in Table 3-1, there is 29.4 tons of scrap channel flange for the baseline. The purchased weight of steel therefore decreases approximately 21 tons with bulb flat, increases 45 tons with flat bar, and decreases 27 tons with Yoder angles.

For the container ship, the increase in erected weight is approximately 12 tons with bulb flat, 91 tons with flat bar, and three tons with Yoder angles. As noted in Table 3-6, there is 14.6 tons of scrap channel flange for the baseline. The purchased weight of steel therefore decreases approximately three tons with bulb flat, increases 77 tons with flat bar, and decreases 11 tons with Yoder angles.

Fabricated stiffeners are eliminated by using any of the three alternate structural sections. For the tanker, 82 fabricated stiffeners (angles cut from channels) with a purchased weight of 176 tons are eliminated. For the container ship, 40 fabricated stiffeners (also angles cut from channels) with a purchased weight of 78 tons are eliminated.

The lineal feet of welding and burning, excluding burning required for fabricated stiffeners, remains the same in each case. The change in weld metal deposited for the tanker is a decrease of 370 lbs. with bulb flat, a decrease of 475 lbs. with flat bar, and zero with Yoder angles. The change in weld metal deposited for the container ship is zero with bulb flat, an increase of 1,620 lbs. for flat bar, and zero with Yoder angles.

Although the total number of stiffener penetrations of transverse members remains the same in each case, the use of either bulb flat or flat bar eliminates non-tight penetrations requiring a collar-plate reinforcement: 342 eliminated on the tanker and 204 eliminated on the container ship.

3.5 Economic Evaluation of Alternate Structural Shapes

In order to evaluate the economic effect of alternate structural shapes it is necessary to obtain equations with which to calculate the cost increment incurred in passing from either of the baseline configurations to an alternate configuration. The development of the required equations is nearly identical to that used for the investigation of frame spacing. The total cost, C_T , for the section of the ship considered is regarded as the sum of two parts: one part, C , that is affected by the use of alternate structural shapes, and another part, C_0 , that is unaffected. Thus,

$$C_T = C + C_0, \quad (3-1)$$

which is identical in form to Equation 2-1. The only difference is that a different meaning is assigned to C_0 . Therefore, Equations 2-2 through 2-19, although derived for the investigation of frame spacing, are also applicable to the investigation of alternate structural shapes.

These equations will now be used to obtain an economic assessment of the configurations with alternate structural shapes. To demonstrate the use of the cost equations, the calculation of the cost increment incurred in passing from the baseline to the alternate container ship configuration in which longitudinal stiffeners that are angles or angles cut from channels are replaced by bulb-flat stiffeners.

Equation 2-5 is used to calculate the increment in material cost (excluding the material for fabricated stiffeners). In this case all of the steel is

put into one group; thus

$$W_{m_1} = \text{erected weight (excluding fabricated stiffeners)}.$$

From Table 3-6,

$$\{W_{m_1}^B\} = \{510.3\} \text{ tons}; \{W_{m_1}^A\} = \{586.1\} \text{ tons}.$$

The cost per ton is taken as

$$\alpha_{m_1} = 210 \text{ \$/ton}$$

for both the baseline and alternate configuration.

From Equation 2-5,

$$C_m^B = \$107,160, \quad C_m^A = \$123,080, \quad \delta C_m^{AB} = \$15,920.$$

Equation 2-6 is used to calculate the increment in material preparation cost.

Since there is no change in total length of plate, L_p , take $L_p = 0$. The stiffeners are divided into four groups:

$$L_{s_1} = \text{lineal feet of flat bar stiffeners}$$

$$L_{s_2} = \text{lineal feet of T-shaped stiffeners}$$

$$L_{s_3} = \text{lineal feet of angle-shaped stiffeners}$$

$$L_{s_4} = \text{lineal feet of bulb-flat stiffeners}$$

From Table 3-10,

$$\{L_{s_i}^B\} = \{600; 1,200; 8,600; 0\} \text{ ft.}$$

$$\{L_{s_i}^A\} = \{600; 1,200; 0; 8,600\} \text{ ft.}$$

The cost per lineal foot is taken as

$$\{\alpha_{mp s_i}\} = \{0.10; 0.20; 0.20; 0.10\} \text{ \$/ft.}$$

From Equation 2-6,

$$C_{mp}^B = \$2,020; \quad C_{mp}^A = \$1,160; \quad \delta C_{mp}^{AB} = - \$860.$$

Equation 2-7 is used to calculate the increment in burning cost (excluding fabricated stiffeners). In this case the amount of burning for the baseline and alternate configurations is the same, so

$$\delta C_b^{AB} = 0.$$

Equation 2-9 is used to calculate the increment in welding cost (excluding fabricated stiffeners). But from Table 3-9, there is no change in welds, so

$$\delta C_w^{AB} = 0.$$

Equation 2-12 is used to calculate the cost associated with stiffener penetrations of transverse members. The different groups of penetrations are defined as follows:

j=1 flat bar; oil- or water-tight penetration
 j=2 angle; oil- or water-tight penetration
 j=3 flat bar; non-tight; no collar plate
 j=4 T-shape; non-tight; no collar plate
 j=5 angle; non-tight; collar plate
 j=6 angle; non-tight; no collar plate
 j=7 bulb flat; oil- or water-tight penetration
 j=8 bulb flat; non-tight; no collar plate

From Table 3-10 and Figure 2-4:

$$\{N_{p_j}^B\} = \{24; 224; 96; 120; 156; 420; 0; 0\}$$

$$\{D_j^B\} = \{18.0; 12.0; 18.0; 12.0; 12.0; 12.0; 0; 0\} \text{ in.}$$

$$\{N_{p_j}^A\} = \{24; 0; 96; 120; 0; 0; 224; 576\}$$

$$\{D_j^A\} = \{18.0; 0; 18.0; 12.0; 0; 0; 11.7; 11.7\} \text{ in.}$$

The cost coefficients are taken as

$$\{\alpha_{p_j}\} = \{8; 18; 5; 10; 10; 5; 15; 5\} \$$$

$$\{\beta_{p_j}\} = \{0.25; 0.60; 0.15; 0.30; 0.30; 0.15; 0.50; 0.15\} \$/\text{in.}$$

From Equation 2-12

$$C_p^B = \$13,290; \quad C_p^A = \$11,230; \quad \delta C_p^{AB} = - \$2,060.$$

Equation 2-14 is used to calculate the cost of fabricated stiffeners cut from channels. The cost coefficients are taken as

$$\alpha_{bc} = \$0.50/\text{ft.}, \quad \alpha_{fsc_i} = \$210/\text{ton}, \quad \gamma_{fsc_i} = \$0.50/\text{ft.}$$

From Table 3-6:

$$\begin{aligned} N_{fsc}^B &= 40, & N_{fsc}^A &= 0, \\ L_{fsc_i}^B &= 100 \text{ ft.}, & L_{fsc_i}^A &= 0, \\ L_{fsc}^B &= 4,000 \text{ ft.}, & L_{fsc}^A &= 0. \end{aligned}$$

Since α_{fsc_i} is the same for each stiffener, only the total purchased weights of stiffeners, given in Table 3-6, are needed:

$$\sum_{i=1}^{N_{fsc}^B} W_{fsc_i}^B = 78.4 \text{ tons}, \quad \sum_{i=1}^{N_{fsc}^A} W_{fsc_i}^A = 0.$$

From Equation 2-14

$$C_{fsc}^B = \$20,460, \quad C_{fsc}^A = 0, \quad \delta C_{fsc}^{AB} = - \$20,460.$$

Finally, the total cost increment is

$$\delta C^{AB} = - \$7,460.$$

Thus, for the 100-foot section of the container ship, the cost increment incurred in passing from the baseline to the alternate configuration is - \$7,460, the negative sign indicating a cost reduction. Carrying out similar calculations for the other two alternate configurations of the container ship gives the following results:

$$\delta C^{AB} = - \$7,460 \text{ for bulb-flat configuration;}$$

$$\delta C^{AB} = - \$4,900 \text{ for Yoder-angle configuration;}$$

$$\delta C^{AB} = \$17,810 \text{ for flat-bar configuration.}$$

The cost increments for the 98.75-foot section of the tanker are:

$$\delta C^{AB} = - \$17,880 \text{ for bulb-flat configuration;}$$

$$\delta C^{AB} = - \$11,540 \text{ for Yoder-angle configuration}$$

$$\delta C^{AB} = - \$9,300 \text{ for flat-bar configuration.}$$

The above cost increments are based on the cost coefficients used in the numerical examples plus the following cost coefficients associated with Yoder angles:

$$\alpha_{m_1} = \$210/\text{ton}, \quad \alpha_{mp_{s_4}} = \$0.20/\text{ft.},$$

$$\alpha_{p_7} = \$21, \quad \beta_{p_7} = \$0.70/\text{in. for oil- or water-tight penetration};$$

$$\alpha_{p_8} = \$6, \quad \beta_{p_8} = \$0.20/\text{in. for non-tight penetration without collar plate};$$

$$\alpha_{p_9} = \$12, \quad \beta_{p_9} = \$0.40/\text{in. for non-tight penetration with collar plate}.$$

Section 4

INVESTIGATION OF WIDE PLATES

4.1 Baseline Configurations

The baseline configuration for the tanker is the midship portion between frames 49 and 103, a length of 592.5 feet. A total of 1,052 plates and 46,400 lineal feet of seams are used on the upper deck, sheer strake, sides, bilge, bottom, and bulkheads. Plate widths vary from five to a maximum of 10 feet, lengths from 13 to 50 feet, and thicknesses vary from 1/2 to 1-1/2 inches.

The baseline configuration for the container ship is the midship portion between frames 63 to 223, a length of 400 feet. A total of 940 plates and 30,850 lineal feet of seams are used on the decks, sheer strake, sides, bilge, bottom, innerbottom, and bulkheads. Plate widths vary from seven feet to a maximum of 10 feet, lengths from 17.5 to 40 feet, and thicknesses vary from 5/16 to 2 inches.

4.2 Alternate Configurations

Two alternate configurations were considered for each ship. In the first alternate configuration, the maximum plate width available was assumed to be 13 feet; in the second alternate, the maximum width available was assumed to be 16 feet.

4.3 Ground Rules

Plate lengths for the alternate configurations are the same as for the baseline configuration. Plate thickness for the alternate configurations at

any given point is not less than the thickness for the baseline. The first ground rule was used because only the effect of plate width was being investigated. The second ground rule was imposed to ensure that the hull strength of the alternate configurations was at least equal to that of the baseline.

4.4 Effects of Wide Plates

The number of plates and lineal feet of seams for the tanker baseline and alternate configurations are given in Table 4-1. Increasing the maximum available plate width from 10 feet to 13 feet reduces the number of plates from 1,052 to 810, and reduces the lineal feet of seams from 46,400 to 38,180. Increasing the maximum available plate width from 10 feet to 16 feet reduces the number of plates from 1,052 to 725, and reduces the lineal feet of seams from 46,400 to 35,045. Associated with these reductions are weight penalties of 12.9 tons for the 13-foot case and 6.4 tons for the 16-foot case. The weight penalty occurs because adjacent plates on the baseline bulkheads are of different thickness. Therefore, in certain regions of the alternate configurations, the plate thickness is greater than in the baseline configuration.

The trend is similar for the container ship as seen from Table 4-2.

Increasing the maximum available plate width from 10 to 13 feet reduces the number of plates from 940 to 747, and reduces the lineal feet of seams from 30,850 to 25,820. Increasing the maximum available plate width from 10 to 16 feet reduces the number of plates from 940 to 713, and reduces the lineal feet of seams from 30,850 to 25,130. Associated with these reductions are

TABLE 4-1

REDUCTION IN PLATES AND SEAMS FOR TANKER WITH WIDE PLATES
(592. 5-FOOT SECTION, FRS. 49-103)

ITEM	STANDARD PLATES (≤ 10 ft)		WIDE PLATES (≤ 13 ft)		WIDE PLATES (≤ 16 ft)	
	NUMBER OF PLATES	LINEAL FEET OF SEAMS	NUMBER OF PLATES	LINEAL FEET OF SEAMS	NUMBER OF PLATES	LINEAL FEET OF SEAMS
UPPER DECK (40.8#-56.1# PL.)	224	10,160	162	7,780	142	7,025
SHEER STRAKE (33.15#-56.1# PL.)	96	4,710	82	4,060	68	3,410
SIDES (28.05#-53.55# PL.)	200	5,740	162	4,960	138	4,480
BILGE AND BOTTOM (39.525#-61.2# PL.)	190	7,450	134	6,210	120	5,610
LONG. O.T. BHDS. (20.4#-30.6# PL.)	212	10,320	178 ⁽¹⁾	9,170	178 ⁽³⁾	9,170
TRANS. O.T. BHDS. (28.05# PL.)	95	5,380	70 ⁽²⁾	4,120	57 ⁽⁴⁾	3,470
SWASH BHDS. (20.4# PL.)	35	2,640	22	1,880	22	1,880
TOTAL	1,052	46,400	810	38,180	725	35,045

(1) Plate weight increases by 12.2 tons.

(2) Plate weight increases by 0.7 tons.

(3) Plate weight increases by 5.4 tons.

(4) Plate weight increases by 1.0 tons.

TABLE 4-2
REDUCTION IN PLATES AND SEAMS FOR CONTAINER SHIP WITH WIDE PLATES
(400-FOOT SECTION, FRS. 63-223)

ITEM	STANDARD WIDTH $\leq$ 10 FT.		WIDTH $\leq$ 13 FT.		WIDTH 16 FT.	
	NUMBER OF PLATES	LINEAL FEET OF SEAMS	NUMBER OF PLATES	LINEAL FEET OF SEAMS	NUMBER OF PLATES	LINEAL FEET OF SEAMS
UPPER DECK (71.4 - 81.6# PL.)	30	1,220	26	1,110	26	1,110
SECOND DECK (35.7 - 51.0# PL.)	54	1,660	32	980	32	980
INNER BOTTOM (24.48 - 35.7# PL.)	146	5,700	107	4,550	97	4,340
SHEER STRAKE (51.0 - 61.2# PL.)	32	1,170	28	1,080	28	1,080
SIDES (33.15 - 44.47# PL.)	184	5,450	150	4,670	150	4,670
BILGE & BOTTOM (33.15 - 45.9# PL.)	188	6,170	154	5,270	152	5,230
LONG. W.T. BKHDS. (20.4 - 61.2# PL.)	172	5,590	140 ⁽¹⁾	4,870	124 ⁽³⁾	4,470
TRANS. W .T. BHDS . (12.75 - 45.9# PL.)	134	3,890	110 ⁽²⁾	3,290	104 ⁽⁴⁾	3,250
TOTAL	940	30,850	747	25,820	713	25,130

(1) Plate weight increases 6.4 tons.

(2) Plate weight increases 5.4 tons.

(3) Plate weight increases 10.6 tons.

(4) Plate weight increases 5.1 tons.

weight increases of 11.8 tons for the 13-foot case and 15.7 tons for the 16-foot case.

4.5 Economic Evaluation of Wide Plates

Plates in the width range considered here can not be transported economically by railroad or truck. For this reason, if a shipyard is to use plates in this width range, its steel supplier must necessarily be located on a river or harbor so that the plates can be transported by barge or ship. In addition, a shipyard's equipment for blasting and coating, conveyors, etc., must have the required width capacity. If it does not, then the shipyard's management must decide whether or not to allocate capital for the required equipment, and in order to decide, the potential reduction in the cost of building ships with wider plates must be established.

In order to establish the potential cost reduction achieved by using wider plates, consider an assembly of N rows of plates whose total width is b inches and whose total length is L feet as shown in Figure 4-1. This N -row assembly is typical for most regions of the baseline and alternate configurations summarized in Section 4.4. Let W be the weight in pounds per square foot, the same for each plate, and let b_j^N be the width in inches of the j^{th} row of plates. In addition, assume each row contains the same number of plates. Let us regard this N -row assembly as the baseline configuration (more precisely a region of the baseline configuration). Now consider an alternate configuration in which wider plates are used. The only difference is that the alternate configuration has $N-i$ rows of plates instead of N rows, and the width of the j^{th} row is denoted by b_j^{N-i} instead of b_j^N .

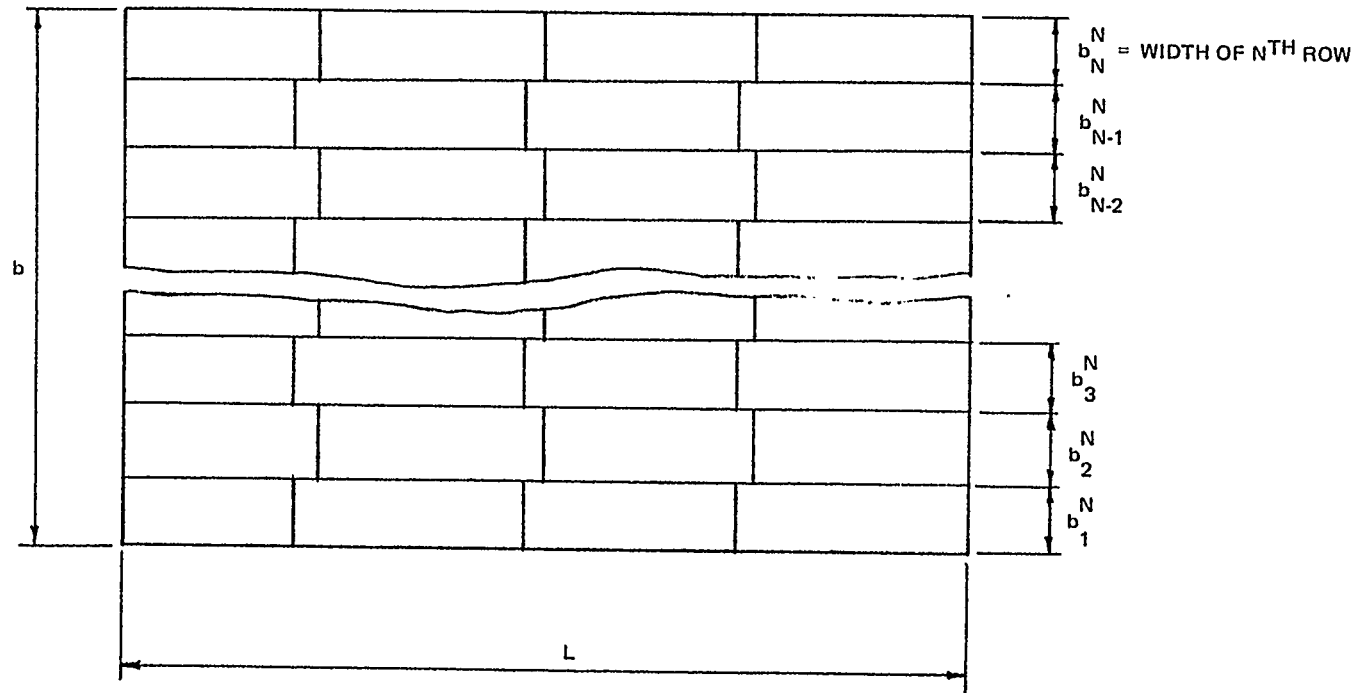


Figure 4-1. Model for Economic Evaluation of Wide Plates

The cost increment incurred in passing from the baseline to the alternate configuration is composed of three parts: the extra width charge, the cost of material preparation, and the cost of welding. The extra width charge is a function of width and thickness as given by Table 4-3. Since the plate thickness is the same in both configurations, the increment in extra width charge is

$$\delta C_{ew}^{AB} = \frac{WL}{(12)(100)} \left[\sum_{j=1}^{N-i} b_j^{N-i} E(b_j^{N-i}) - \sum_{j=1}^N b_j^N E(b_j^N) \right], \quad (4-1)$$

where the superscripts A and B refer to the alternate and baseline configurations, respectively; and where the value of the function E is obtained from Table 4-3. The factor of 12 is introduced to convert widths from inches to feet, and the factor of 100 is introduced because the extra width charges in Table 4-3 are given in dollars per 100 lbs.

The cost increment in material preparation is obtained by specializing Equation 2-6. In the present case the increment in lineal feet of plate is $-iL$, so the corresponding cost increment is

$$\delta C_{mp}^{AB} = -\alpha_{mp} iL. \quad (4-2)$$

The cost increment in welding is obtained by specializing Equation 2-9. In this case all welds are of the same type and size so both N_w and N_w^j are equal to one; moreover, the increment in lineal feet of welding is $-iL$, so the corresponding cost increment is

$$\delta C_w^{AB} = -\alpha_{w1} iL. \quad (4-3)$$

TABLE 4-3
WIDTH AND THICKNESS EXTRAS⁽¹⁾

WIDTH-INCHES	THICKNESS - INCHES				
	5/16 to 3/8 Excl.	3/8 to 1/2 Excl.	1/2 to 1 Excl.	1 to 1-1/2 Incl.	Over 1-1/2 to 3 Incl.
Over 8 to 12 excl.	\$1.50	\$1.30	\$1.25	\$1.30	
12 to 24 excl.	1.45	1.25	1.20	1.25	
24 to 30 excl.	1.35	1.10	1.05	1.10	\$1.90
30 to 36 excl.	1.20	0.95	0.90	1.00	1.70
36 to 48 excl.	1.10	0.85	0.80	0.90	1.50
48 to 60 excl.	0.95	0.70	0.65	0.75	1.30
60 to 80 excl.	0.85	0.60	0.45	0.65	1.10
80 to 90 incl.	0.80	0.55	0.35	0.55	0.95
Over 90 to 100 incl.	0.95	0.75	0.55	0.70	1.10
Over 100 to 110 incl.	1.20'	0.95	0.75	0.80	1.15
Over 110 to 120 incl.	1.40	1.15	0.95	0.95	1.30
Over 120 to 130 incl.	1.60	1.35	1.15	1.15	1.50
Over 130 to 140 incl.	1.90	1.65	1.45	1.50	1.80
Over 140 to 152-1/2 incl. ⁽²⁾		1.95	1.70	1.70	
Over 152-1/2 to 163 Incl. ⁽³⁾			2.00	2.00	
Over 163 to 177 incl. ⁽³⁾			2.40	2.40	
Over 177 to 192 incl. ⁽³⁾			2.80	2.80	

(1) From Reference 3 except as noted.

(2) Reference 4.

(3) Estimated.

The total cost increment incurred in passing from the baseline configuration with N rows of plates to an alternate configuration with N-i rows of plates is given by the sum of Equations 4-1, 4-2, and 4-3:

$$\delta C^{AB} = + \frac{WL}{1200} \left[\sum_{j=1}^{N-i} b_j^{N-i} E(b_j^{N-i}) - \sum_{j=1}^N b_j^N E(b_j^N) \right] - \alpha_s iL, \quad (4-4)$$

where

$$\alpha_s \equiv \alpha_{mp} + \alpha_{w11}. \quad (4-5)$$

From Equation 4-4 it is clear that the alternate configuration costs less than the baseline (i.e., δC^{AB} is negative) if, and only if,

$$\alpha_s > \frac{W}{1200} \left[\sum_{j=1}^{N-i} b_j^{N-i} E(b_j^{N-i}) - \sum_{j=1}^N b_j^N E(b_j^N) \right]. \quad (4-6)$$

The term α_s on left-hand side of Inequality 4-6 is the cost of material preparation and welding of one foot of seam; the term on the right-hand side is the extra width charge associated with the elimination of one foot of seam. Alternatively, α_s can be regarded simply as the value associated with the elimination of one foot of seam. Whenever the inequality is satisfied, it means that the extra width charge for wider plates is economically justified. If two or more alternate configurations satisfy the inequality, the one yielding the largest (negative) value of δC^{AB} given by Equation 4-4 is the most economical.

The preceding will now be applied to several regions of the tanker and container ship. For each region there are a number of possible alternate configurations. For each alternate, the minimum value of α_s , below which no cost reduction is obtained, is calculated by means of Inequality 4-6. In addition, a range of α_s , for which each alternate is the most economical, is calculated by means of Equation 4-4. Then, using values of α_s based on the cost data of Section 2.5, cost reductions are calculated for the most economical configurations.

On the sides of the tanker are five rows of 0.875-inch thick plates, each 97 inches wide and 328 feet long. One longitudinal seam can be eliminated by using four rows of plates whose total width is 485 inches, for example, two rows of 118-inch wide plates and two rows of 124.5-inch wide plates. In this case:

$$N = 5, i = 1, W = 35.7 \text{ lb/ft}^2;$$

$$b_j^5 = 97 \text{ in.}, E(b_j^5) = \$0.55/100 \text{ lb. for } j = 1 \text{ to } 5;$$

$$b_j^4 = 118 \text{ in.}, E(b_j^4) = \$0.95/100 \text{ lb. for } j = 1, 2;$$

$$b_j^4 = 124.5 \text{ in.}, E(b_j^4) = \$1.15/100 \text{ lb.; for } j = 3, 4;$$

where the values of the function E are from Table 4-3.

Substitution of the above values into Inequality 4-6 gives

$$as > \$7.25/\text{ft.}$$

as the necessary condition for the elimination of one longitudinal seam being worth the extra width charge.

If the maximum available plate width is 13 feet, then only one seam can be eliminated. If the maximum available width is 16 feet, two longitudinal seams can be eliminated by using, for example, three rows of 161.7-inch wide plates. In this case

$$N = 5, i = 2, W = 35.7 \text{ lb/ft}^2,$$

$$b_j^5 = 97 \text{ in.}, E(b_j^5) = \$0.55/100 \text{ lb. for } j = 1 \text{ to } 5;$$

$$b_j^3 = 161.7 \text{ in.}, E(b_j^3) = \$2.00/100 \text{ lb. for } j = 1, 2, 3;$$

Substitution of the above values into Inequality 4-6 gives

$$as > \$10.45/\text{ft.}$$

as the necessary condition for the elimination of two longitudinal seams being worth the extra width charge. The value of α_s determines which of the three configurations is the most economical. From Equation 4-4 it is readily calculated that:

The five-row baseline configuration is most economical if

$$\alpha_s \leq \$7.25/\text{ft.}$$

The four-row configuration is most economical if

$$\$7.25/\text{ft.} < \alpha_s \leq \$13.65/\text{ft.}$$

The three-row configuration is most economical if

$$\alpha_s > \$13.65/\text{ft.}$$

On the tanker deck there are 11 rows of plates each 1.375 inches thick and 400 feet long. There are four rows of 85-inch wide plates, two rows of 86-inch wide plates and five rows of 108-inch wide plates. From Inequality 4-6 and Table 4-3, it is economical to eliminate:

(a) one seam with two 98-inch and eight 108-inch wide plates if

$$\alpha_s > \$5.07/\text{ft.}$$

(b) two seams with one 108-inch and eight 118-inch wide plates if

$$\alpha_s > \$6.30/\text{ft.}$$

(c) three seams with five 128-inch and three 137.3-inch wide plates if

$$\alpha_s > \$9.98/\text{ft.}$$

(d) four seams with seven 150.3-inch wide plates if

$$\alpha_s > \$12.56/\text{ft.}$$

(e) five seams with six 175.3-inch wide plates if

$$\alpha_s > \$16.93/\text{ft.}$$

From Equation 4-4 it is found that:

The eleven-row baseline configuration is most economical if

$$\alpha_s \leq \$5.07/\text{ft.}$$

The ten-row configuration (a) is most economical if

$$\$5.07/\text{ft.} < \alpha_s \leq \$7.53/\text{ft.}$$

The nine-row configuration (b) is most economical if

$$\$7.53/\text{ft.} < \alpha_s \leq \$17.34/\text{ft.}$$

The eight-row configuration (c) is most economical if

$$\$17.34/\text{ft.} < \alpha_s \leq \$20.30/\text{ft.}$$

The seven-row configuration (d) is most economical if

$$\$20.30/\text{ft.} < \alpha_s \leq \$34.41/\text{ft.}$$

The six-row configuration (e) is most economical if

$$\alpha_s > \$34.41/\text{ft.}$$

On the tanker bottom there are nine rows of plates, each 1.5 inches thick and 350 feet long. There are four rows of 118-inch wide plates and five rows of 108-inch wide plates. From Inequality 4-6 and Table 4-3, it is economical to eliminate:

(a) one seam with seven 128-inch and one 116-inch wide plates if

$$\alpha_s > \$13.27/\text{ft.}$$

(b) two seams with two 128.5-inch and five 151-inch wide plates if

$$\alpha_s > \$17.82/\text{ft.}$$

(c) three seams with two 161-inch and four 171.5-inch wide plates if

$$\alpha_s > \$24.13/\text{ft.}$$

From Equation 4-4 it is found that:

The nine-row baseline configuration is most economical if

$$\alpha_s \leq \$13.27/\text{ft.}$$

The eight-row configuration (a) is most economical if

$$\$13.27/\text{ft.} < \alpha_s \leq \$22.37/\text{ft.}$$

The seven-row configuration (b) is most economical if

$$\$22.37/\text{ft.} < \alpha_s \leq \$36.75/\text{ft.}$$

The six-row configuration (c) is most economical if

$$\alpha_s > \$36.75/\text{ft.}$$

Referring to Section 2.5, the cost of 7/8-inch, 1-3/8-inch and 1-1/2-inch butt welds are given, respectively, as \$7.80/ft., \$13.40/ft. and \$15.00/ft.; and α_{mp} is \$0.10/ft. Thus, from Equation 4-5, α_s is \$7.90/ft. for the sides, \$13.50/ft. for the deck and \$15.10/ft. for the bottom. For these values of

as the four-row configuration of plates is most economical for the sides, the nine-row configuration is most economical for the deck, and the eight-row configuration is most economical for the bottom. From Equation 4-4, the corresponding cost reductions are \$426 for (both) the sides, \$5,760 for the deck, \$605 for the bottom.

On the innerbottom of the container ship there are four rows of 0.6-inch thick plates, each 98 inches wide and 350 feet long. Only one longitudinal seam can be eliminated since the maximum plate width considered is 16 feet. From Inequality 4-6 and Table 4-3, it is economical to eliminate one seam with two rows of 128-inch wide plates and one row of 138-inch wide plates if $\alpha_e > \$5.63$. If $\alpha_e \leq \$5.63$, the four-row baseline configuration is more economical.

On the sides of the container ship there are four rows of 0.875-inch thick plates, each 102 inches wide and 300 feet long. From Inequality 4-6 and Table 4-3, it is economical to eliminate one seam with three rows of 136-inch wide plates if $\alpha_e > \$8.48/\text{ft.}$ If $\alpha_e \leq \$8.48/\text{ft.}$, the four-row baseline configuration is more economical.

On the bottom of the container ship there are three rows of 0.89-inch thick plates, each 160 feet long. Two rows are 105 inches wide and the third is 99 inches wide. From Inequality 4-6 and Table 4-3, it is economical to eliminate one seam with one row of 150-inch wide plates and one row of 159-inch wide plates if $\alpha_s > \$10.92/\text{ft.}$ If $\alpha_s \leq \$10.92/\text{ft.}$, the three-row baseline configuration is more economical.

From the cost data in Section 2.5, α_s is \$5.40/ft. for the innerbottom, \$7.90/ft. for the sides and \$8.05/ft. for the bottom. For these values of α_s as the baseline configurations are more economical than the alternates.

The preceding examples show that the extra width charge precludes any significant cost savings. If, however, wide plates were available to the shipbuilding industry with no extra width charge, the wide-plate configurations summarized in Tables 4-1 and 4-2 would offer significant cost savings. Based on the material preparation and welding costs in Section 2.5 (and excluding the extra width charge), a maximum available plate width of 13 feet provides cost savings of \$74,000 for the tanker and \$33,000 for the container ship. A maximum available plate width of 16 feet provides cost savings of \$106,000 for the tanker and \$37,000 for the container ship.

Section 5

FINDINGS AND RECOMMENDATIONS

5.1 Findings

Investigation of Alternate Frame Spacing

Based on the economic evaluation of the four alternate tanker configurations, the ranking in order of cost-saving potential, relative to the baseline, is:

<u>Frame Spacing,</u>	<u>Longitudinal Stiffeners</u>
1. 12'-4-1/8"	Welded angle
2. 16'-5-1/2"	Welded angle
3. 12'-4-1/8"	Cut channels and tees
4. 9'-10-1/2" (baseline)	Cut channels
5. 16'-5-1/2"	Cut channels and tees

For the container ship configurations, the ranking is:

<u>Frame Spacing</u>	<u>Longitudinal Stiffeners</u>
1. 12'-10-1/4"	Welded angles
2. 11' -3"	Welded angles
3. 10'-0'" (baseline)	Cut channels
4. 11'-3"	Cut channels
5. 12'-10-1/4"	Cut channels and tees

The economic evaluations were performed by means of the cost equations developed in Section 2.5, using cost figures obtained from different sources, not from one particular shipyard. In order to obtain cost savings in terms of absolute dollar values, each shipyard, of necessity, must use its own cost figures in place of those used in the text. It should also be noted that

there is at least one factor of conservatism in the approach used in that it contains an inherent bias in favor of the baseline configuration, for the baseline is always assumed to be a perfect design. A competing alternate therefore suffers when a standard plate or shape is almost, but not quite sufficient, thus requiring the use of the next larger size. Thus, the cost equations should be applied early in the design and planning phases to ensure that all competing configurations are evaluated in a non-preferential way.

It is believed, however, that the economic evaluations do provide at least a ranking, at best a semi-quantative assessment of relative costs of the alternate configurations. It is therefore of interest to project the potential cost saving for the entire ship provided by the best alternate. In the case of the tanker the 98.75-foot section is virtually identical to a 328-foot midportion of the 592.5-foot cargo section composed of six sections similar to the baseline section. Now from Section 2.5, the largest cost saving is \$32,740 for the 98.75-foot section considered. Assume that this cost saving per lineal foot holds for the 328-foot midportion and that forward and aft of the midportion the cost saving per lineal foot diminishes by 50 percent as a result of reduced scantlings. Then,

$$\text{cost saving for tanker} = \frac{\$32,740}{98.75} [328 + (0.5)(264.5)],$$

$$\text{cost saving for tanker} = \$152,000.$$

A similar calculation can be made for the container ship. The 100-foot baseline section is similar to the 310-foot aft portion of the cargo section whose total length is 489 feet. From Section 2.5, the largest cost saving

is \$14,700. Because the breadth of the forward portion of the cargo section is considerably less than at mid-ship, assume that only one quarter of the cost saving is achieved in the forward portion.

Then,

$$\text{cost saving for container ship} = \frac{\$14,700}{100} [310 + (0.25)(179)],$$

$$\text{cost saving for container ship} = \$52,000.$$

Investigation of Alternate Structural Sections

Based on the economic evaluation of three alternate structural sections for longitudinal stiffeners on the tanker (see Section 3.5), the ranking in order of cost-saving potential, relative to the baseline, is:

1. Bulb flat
2. Yoder angle
3. Flat bar
4. Cut channels (baseline)

For the container ship configurations, the ranking is:

1. Bulb flat
2. Yoder angle
3. Cut channels (baseline)
- 4, Flat bar

The remarks above regarding the cost figures used in the application of the cost equations and the bias in favor of the baseline apply equally here. Nevertheless, it is of interest to project the potential cost saving for the

entire ship. From Section 3.5, the largest cost savings are \$17,880 for the 98.75-foot section of the tanker considered and \$7,460 for the 100-foot section of the container ship considered.

Hence, the projections are:

cost saving for tanker = \$83,000;

cost saving for container ship = \$26,000.

Investigation of Wide Plates

Based on the economic evaluation of the use of wider plates (see Section 4.5) it was found that the cost saving achieved by the reduction in seams is essentially cancelled by the extra width charge. Several instances were found where use of wider plates could be economically justified, but the widest plate that could be justified was 11.5 feet (compared to a maximum width of 10 feet used on the baselines) and the net cost savings were insignificant. Thus, to achieve significant cost savings, standard plate widths (no extra width charge) produced especially for shipbuilding are required.

A maximum available plate width of 13 feet permits the lineal feet of seams to be reduced by approximately 8,200 feet compared to a baseline total of 46,400 feet for the tanker. For the container ship the reduction in lineal feet of seams is approximately 5,000 feet compared to a baseline total of 30,850 feet. The corresponding estimated cost savings, excluding the extra width charge, are \$74,000 for the tanker and \$33,000 for the container ship.

A maximum available plate width of 16 feet permits the lineal feet of seams to be reduced by approximately 11,350 feet for the tanker and 5,700 feet for the container ship. The corresponding estimated cost savings, excluding the extra width charge, are \$106,000 for the tanker and \$37,000 for the container ship. These figures indicate the potential cost savings if the extra width charge could be eliminated.

5.2 RECOMMENDATIONS FOR FUTURE STUDY

Based on the present investigation, three areas for future study are recommended.

A. Alternate Longitudinal Stiffener Spacing

Objective

Determine potential reduction in hull construction cost due to optimum spacing of longitudinal stiffeners.

Plan of Action

1. Devise a method for determining optimum longitudinal stiffener spacing for both uniform and nonuniform spacing.
2. Generate alternate configurations (of the baseline designs used in the present investigation) having optimum uniform and nonuniform spacing of longitudinal stiffeners.
3. Determine reduction in hull construction cost, relative to the baseline design, by means of cost equations similar to those developed in the present investigation.

End Product

A technical report containing the necessary cost equations and illustrating their application in determining the optimum spacing of longitudinal stiffeners and the associated reduction in hull construction cost.

Schedule

- 0 - 4 months - Devise optimization method
- 4 - 8 months - Generate alternate configurations and perform economic evaluations
- 8 - 12 months - Compile results and write report

B. Reduced Fillet Weld Sizes

Objective

Determine potential reduction in hull construction cost resulting from reduced fillet weld sizes.

Plan of Action

1. Conduct a survey to determine current fillet weld criteria and practices both within and outside of the merchant shipbuilding industry.
2. Formulate an "interim" criterion for fillet weld sizes by combining the least conservative portions of existing standards and codes.
3. Determine reduction in construction cost, relative to the baseline designs used in the present investigation, provided by the interim criterion.

4. Formulate improved criteria for fillet weld sizes. The formulation is to be in parametric form in order to facilitate economic evaluation, with special consideration given to: (a) analysis of loads and stress, (b) distinction between primary and secondary structure, (c) joint efficiency requirements, (d) alternate electrode-flux combinations, (e) tighter fit-up tolerances, (f) inspection and maintenance requirements.
5. Conduct a parametric economic evaluation of the improved criteria to determine the optimum criterion for fillet weld sizes.
6. Conduct tests needed for verification and acceptance of the optimum criterion. (Contingent upon the optimum criterion determined in Item 5 showing a significantly greater cost reduction than the interim criterion formulated in Item 3).

End Product

A technical report containing criteria for reduced fillet weld sizes and the associated reduction in hull construction cost.

Schedule

- 0 - 3 months - Conduct survey
- 3 - 5 months - Formulate interim criterion and determine reduction in construction cost
- 3 - 8 months - Formulate optimum criterion and determine reduction in construction cost
- 8 - 15 months - Conduct verification and acceptance tests for optimum criterion
- 14 - 18 months - Compile results and write report

c. Reduced Structural Requirements

Objective

Determine potential reduction in hull construction cost as a function of the degree of reduction of structural requirements.

Plan of Action

1. Generalize the ABS equations for structural requirements by introducing parameters whose values can be adjusted to reflect reduced structural requirements permitted by either improved analyses or improved definition of loading environment, or both.
2. Perform a parametric economic evaluation to determine reductions in hull construction cost, relative to the baseline designs used in the present investigation, as a function of the parameters defining structural requirements.
3. Identify current structural requirements whose reduction offers significant reductions in hull construction cost.

End Product

A technical report that identifies those structural requirements that are cost drivers. The results would serve as a guide in allocating resources for the development of improved techniques for structural analysis and for the definition of loading environment.

Schedule

- 0 - 2 months - Write ABS equations in generalized parametric form
- 2 - .8 months - Perform parametric economic evaluation
- 7 - 8 months - Identify cost-driving structural requirements
- 9 - 12 months - Compile results and write report

REFERENCES

1. American Bureau of Shipping, "Rules for Building and Classing Steel", 1972 Edition.
2. Kaiser Steel Corporation, "Hot Rolled Carbon and Kaiser Steel Plate-Extra," Section D-4 (Denotes Revision), dated September 20, 1971.
3. Lloyd's Register of Shipping - Chapter D, Section 32 on Welding (PP. 124-pp. 130).
4. Personal communication with Mr. D. Hicks, Kaiser Steel Corporation, Oakland, California.