SSC-218

# DESIGN CONSIDERATIONS FOR ALUMINUM HULL STRUCTURES

## STUDY OF ALUMINUM BULK CARRIER



SHIP STRUCTURE COMMITTEE

1971

# SHIP STRUCTURE COMMITTEE

AN INTERAGENCY ADVISORY
COMMITTEE DEDICATED TO IMPROVING
THE STRUCTURE OF SHIPS

MEMBER AGENCIES:

UNITED STATES COAST GUARD
NAVAL SHIP SYSTEMS COMMAND
MILITARY SEALIFT COMMAND
MARITIME ADMINISTRATION
AMERICAN BUREAU OF SHIPPING

ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U.S. COAST GUARD HEADQUARTERS
WASHINGTON, D.C. 20591


SR 190

The Ship Structure Committee is sponsoring research to investigate the suitability of modern structural materials for ships' hull structures and to examine changes in design practices necessary to take advantage of the properties of these materials.

This report describes an investigation of the design of an all aluminum bulk carrier. Comments concerning this report are solicited.

W. F. REA, III
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-218
Final Technical Report
on
Project SR-190 "Aluminum Hull Feasibility Study"

# DESIGN CONSIDERATIONS FOR ALUMINUM HULL STRUCTURES
# STUDY OF ALUMINUM BULK CARRIER

by
C. J. Altenburg
R. J. Scott
Gibbs & Cox

under
Department of the Navy
Naval Ship Engineering Center
Contract No. N00024-70-C-5138

*This document has been approved for public release and sale; its distribution is unlimited.*

U.S. Coast Guard Headquarters
Washington, D. C.
1971

## ABSTRACT

The fabrication of a large aluminum hull with state of the art materials and construction techniques is shown to be technically feasible. Present 5000 series alloys have adequate properties, though additional research is required, particularly into fatigue characteristics. Experience to date with existing aluminum ships has been good, though instances of cracking at welds and corrosion have been noted. Criteria for the design of the aluminum hull structure are presented and justified. Methods of fire protection and system/equipment installation are evaluated, and operational characteristics of an aluminum bulk carrier are reviewed.

The designs of a large aluminum bulk carrier and an equivalent steel ship are presented and compared. The aluminum ship's structure weighs 43 per cent less than the steel ship, and its hull is about 50 per cent more flexible. Cargo deadweight is increased 7-1/2 per cent.

Cost studies indicate that for the same return on investment the required freight rate of the aluminum bulk carrier is higher than the equivalent steel ship, for all levels of procurement, assumed hull life, or voyage length considered.

Areas for further research are presented and further investigations of large aluminum ships are proposed.

CONTENTS



APPENDICES

## LIST OF TABLES

## LIST OF TABLES
(Cont'd)

## LIST OF FIGURES

LIST OF FIGURES
(Cont'd)

## SHIP STRUCTURE COMMITTEE

The SHIP STRUCTURE COMMITTEE is constituted to prosecute a research program to improve the hull structures of ships by an extension of knowledge pertaining to design, materials and methods of fabrication.

RADM W. F. Rea, III, USCG, Chairman
Chief, Office of Merchant Marine Safety
U. S. Coast Guard Headquarters

Capt. J. E. Rasmussen, USN
Head, Ship Engineering Division
Naval Ship Engineering Center

Capt. T. J. Banvard, USN
Maintenance and Repair Officer
Military Sealift Command

Mr. E. S. Dillon
Chief
Office of Ship Construction
Maritime Administration

Mr. C. J. L. Schoefer, Vice President
American Bureau of Shipping

## SHIP STRUCTURE SUBCOMMITTEE

The SHIP STRUCTURE SUBCOMMITTEE acts for the Ship Structure Committee on technical matters by providing technical coordination for the determination of goals and objectives of the program, and by evaluating and interpreting the results in terms of ship structural design, construction, and operation.

NAVAL SHIP ENGINEERING CENTER

Mr. P. M. Palermo - Chairman
Mr. J. B. O'Brien - Contract Administrator
Mr. G. Sorkin - Member
Mr. H. S. Sayre - Alternate
Mr. I. Fioriti - Alternate

MARITIME ADMINISTRATION

Mr. F. Dashnaw - Member
Mr. A. Maillar - Member
Mr. R. Falls - Alternate
Mr. Raymond F. Coombs - Alternate

AMERICAN BUREAU OF SHIPPING

Mr. S. G. Stiansen - Member
Mr. F. J. Crum - Member

OFFICE OF NAVAL RESEARCH

Mr. J. M. Crowley - Member
Dr. W. G. Rauch - Alternate

NAVAL SHIP RESEARCH & DEVELOPMENT CENTER

Mr. A. B. Stavovy - Alternate

MILITARY SEALIFT COMMAND

Mr. R. R. Askren - Member
Lt. J. G. Ervin T. Powers, USNR - Member

U. S. COAST GUARD

LCDR C. S. Loosmore, USCG - Secretary
CDR C. R. Thompson, USCG - Member
CDR J. W. Kime, USCG - Alternate
CDR J. L. Coburn - Alternate

NATIONAL ACADEMY OF SCIENCES

Mr. R. W. Rumke, Liaison
Prof. R. A. Yagle, Liaison

SOCIETY OF NAVAL ARCHITECTS & MARINE ENGINEERS

Mr. T. M. Buermann, Liaison

AMERICAN IRON AND STEEL INSTITUTE

Mr. J. R. Lecron, Liaison

BRITISH NAVY STAFF

Dr. V. Flint, Liaison
CDR P. H. H. Ablett, RCNC, Liaison

WELDING RESEARCH COUNCIL

Mr. K. H. Koopman, Liaison
Mr. C. Larson, Liaison

# I. INTRODUCTION

This report summarizes the results of a study of the present technical state of the art to determine the feasibility of economical construction and operation of a large high density deadweight carrier constructed entirely of aluminum.

The present level of technology in the aluminum industry is sufficiently advanced to warrant active consideration of the use of aluminum for a large bulk carrier. This study is given further impetus by the recent emphasis of life cycle cost, which has provided the techniques necessary to justify higher initial expenditures where the potential for long-term economic benefits exist.

## Background

Aluminum alloys suitable for use in a marine environment have been available for approximately 30 years, offering significant advantages in reducing structural weight and hull maintenance. However, the unit material cost of aluminum alloys is presently between 5 and 6 times that of mild steel. The use of aluminum alloys generally reduces hull structural weight by approximately 50 per cent relative to steel, so that the total material cost of an aluminum hull will be between 2-1/2 and 3 times that of a comparable steel hull. Since aluminum construction does not generally result in a significant reduction in the labor costs for hull construction, the higher material cost produces a corresponding increase in overall construction cost which must be passed on to the purchaser. This factor has generally restricted the use of aluminum to the following marine applications:

- High-speed hull forms, particularly planing hulls, where the higher hull cost can be justified on the basis of superior performance.

- Special applications where the resistance of aluminum to specific corrosive environments is required.

- Superstructures, where the reduction in topside weight justifies the higher material cost.

- Applications where light hull weight is essential to suit draft limitations or lifting requirements.

In addition to the foregoing restrictions, the introduction of aluminum alloys into the marine industry has encountered technical difficulties in some areas, resulting from either the basic characteristics of aluminum alloys, or from misuse of these alloys during fabrication. Among "the problems" experienced with aluminum marine applications are:

- Early problems with the introduction of aircraft-type alloys and fastening methods which were unsuited for a marine environment.

- Problems with welding prior to the introduction of the 5000 series alloys. Although these problems have been largely overcome, careful consideration must still be given to strength degradation, locked-in stresses and distortion in way of welds.

- Problems with isolation of dissimilar metals, particularly at mechanically-fastened joints between aluminum and steel structures exposed to salt water. Additional problems occur with installation of piping and equipment, shafting, propellers, mooring and anchor gear, etc.

- Low fire resistance of aluminum structures. This has required extensive investigation due to the low melting point of aluminum and gross loss of structural integrity resulting from fire.

- Exfoliation of the 5456 alloy in the Navy patrol and assault craft, and crevice corrosion in way of welds and discontinuities.

- Use of improper primer/paint systems.

- Improper fabrication of aluminum weldments due to lack of qualified welders. This problem has largely disappeared at facilities where a significant quantity of their production is of aluminum construction.

The aforementioned limitations and problem areas have tended to restrict the use of aluminum to smaller hulls and other specialized applications in the marine field until recent years. However, as the technical problems have been overcome and the state of the art in fabricating aluminum structures has advanced, aluminum has been considered and used in larger hulls, including:

- U. S. Navy 84 foot LCM-8 landing craft.

- U. S. Navy PGM high-speed patrol craft, 154 feet long.

- 244 foot oceanographic vessel SEA PROBE, now under construction.

- The shallow draft tanker "INDEPENDENCE", 118 feet long.

- The trailership "SACAL BORINCANO", 306 feet long.

- Commercial and military hydrofoils.

- 86 foot aluminum purse seiner, presently under construction.

- 223 foot aluminum barge "ALUMINIA".

- 160 foot ferry GTS "AVALON".

A major factor affecting the future of aluminum in marine applications is the recent trend toward evaluation of life cycle cost, in which all factors affecting the economics of a specific system are evaluated over the lifetime of the system to determine total cost throughout its life. The use of life cycle cost techniques permits the designer and economist to trade-off higher first cost of an aluminum ship against potential fuel savings or increased earning capacity resulting from lighter hull weight, as well as economies in hull maintenance and higher scrap or resale value. This factor, in conjunction with the recent advances in the state of the art in fabricating and maintaining aluminum, justifies consideration of aluminum in the construction of a large hull such as the bulk carrier presently under consideration.

Scope of Study

This program consisted of four phases:

- Material and Design Studies including a review of alloy properties, development of criteria, methods of fabrication, fire resistance, effect on systems and effects on operations.

- Comparative Ship Design and Evaluation, including modification of the selected steel bulk carrier to suit 1969 strength standards, and design of an equivalent aluminum bulk carrier: dimensions, midship section, weights, and construction cost.

- Cost Studies, wherein equivalent steel and aluminum bulk carriers are analyzed to determine relative required freight rates over several trade routes and for operating lives of from 20 to 30 years. These studies are conducted for both single hull and multi-hull procurement.

- Recommended Areas for Further Study wherein a research program is proposed for extending this study in areas requiring further investigation.

The study was originally specified to be based upon comparison to an existing US-built bulk carrier or a realistic design study reflecting ABS requirements. Since few, if any, large ocean going high-density bulk carriers have been built in this country in the past 20 years, this study is based on a hypothetical ship which is physically identical to a recent large foreign built bulk carrier approved by ABS. All cost factors are based upon construction in the United States and operation under the American Flag. This approach is considered preferable to basing this work on a design study, since the physical characteristics of the existing base line ship are well documented and fully proven in service.

Selection of Bulk Carrier

The ship selected as a basis for developing the hypothetical high density bulk carrier is the M.V. CHALLENGER. This ship is an ocean going flush deck bulk carrier with raised forecastle and poop, 6 cargo holds and machinery aft. The characteristics of the CHALLENGER are summarized in Table 1.

TABLE 1. Principal Characteristics - *M.V. Challenger*

| | |
|---|---|
| Length Overall | 632'-10" |
| Length Between Perpendiculars | 590'-6-1/2" |
| Beam | 88'-7" |
| Depth | 52'-2" |
| Draft | 35'-9" |
| Deadweight | 36,858 LT max. |
| Light Ship | 7,892 LT |
| Displacement | 44,750 LT max. |
| Shaft Horsepower | 9,600 max. (Diesel) |
| Design Speed | 14.8 Knots |
| Range | 10,400 statute miles |
| Built | 1965, Mitsubishi Heavy Industries, Ltd. |
| Classification | ABS ✠ A1 E "Bulk Carrier" ✠ AMS |
| | Strengthened for heavy cargoes |
| Registration | Monrovia, Liberia, No. 2373 |
| Gross Tonnage | 19,633 (Liberian) |
| Net Tonnage | 13,451 (Liberian) |

The M.V. CHALLENGER is of mild steel construction, and is longitudinally framed. The general arrangements and a typical midship section are shown in Figures 1 and 2 respectively.

This vessel was chosen for several reasons:

- The aluminum hull structure would be economically more viable for a smaller bulk carrier (30-40,000 tons deadweight) than with a larger vessel, since the effects of reduced hull weight are more pronounced.
- Sufficient data is available on the ship to produce a high level of confidence in the physical characteristics of the base line design.
- Incorporation of aluminum hull structure on a relatively small vessel represents less of a technical risk and results in scantlings which are not beyond the state of the art to fabricate.

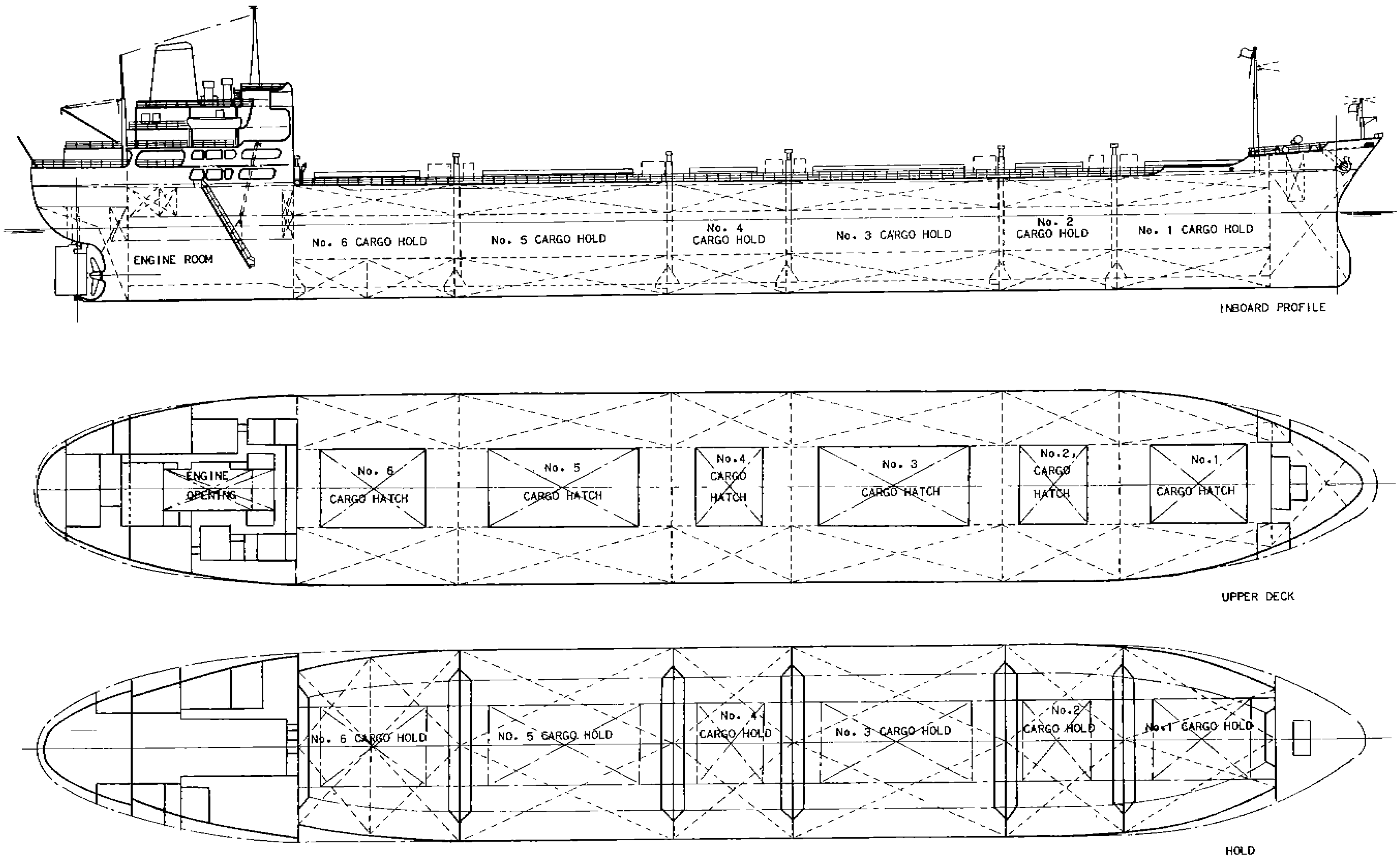



FIG. 1. General Arrangement *M.V. Challenger*

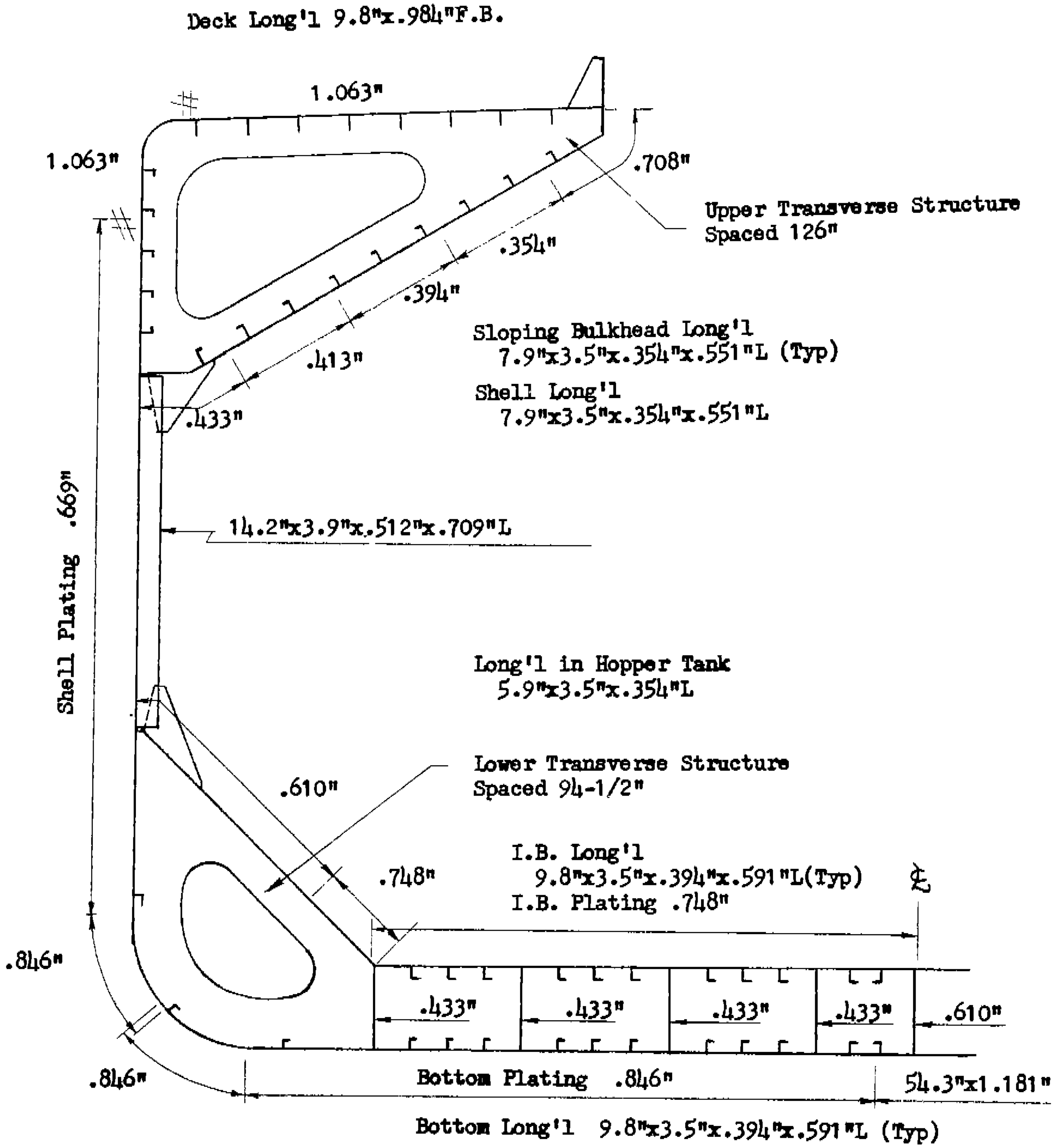



FIG. 2. Midship Section - *M.V. Challenger*

# II. MATERIAL AND DESIGN STUDIES

## IIA. REVIEW OF ALUMINUM ALLOYS

This section includes a comprehensive review of the properties of weldable aluminum alloys suitable for a marine environment and the selection of the most appropriate alloy or alloys for the construction of a large aluminum bulk carrier. In order to limit the scope of the study, only 5000 series alloys are considered for hull structure. Although 6000 series alloys, such as 6061, have excellent salt water corrosion resistance, their weldability is not considered suitable for welded structural applications. However, 6000 series alloys could be considered for catwalks, joiner panels and other similar applications.

The areas covered in this review include the following:

1. Mechanical Properties (Static and Fatigue)
2. Toughness
3. Buckling Strength
4. Corrosion and Abrasion
5. Weldability and Workability
6. Alloy Material Cost
7. Selection of Alloys

### Mechanical Properties (Static and Fatigue)

This phase of the aluminum bulk carrier feasibility study is a review of alloy properties including parent and welded static and fatigue strengths for 5000 series aluminum alloys.

The following factors have a primary effect on the static and fatigue strengths of parent and welded aluminum, and are herein evaluated quantitatively, where possible, or qualitatively: alloy temper, material thickness, weld procedure, filler wire alloy, type of weld - single vee butt, double vee butt, fillet, etc., weld process (MIG, TIG, etc.), weld defects, cold working, surface finish of parent metal and weld, stress concentrations such as notches, craters, welds, etc., service environment, differences in laboratory test specimens and test procedures.

Cumulative fatigue, low and elevated temperatures, composition and grain size are discussed. However, the effects of these latter factors on the static and fatigue properties of parent and welded aluminum alloys are beyond the scope of this study. Future required theoretical and experimental investigations are defined.

Numerous references have been reviewed and those pertinent to this study are References (1) through (36). The tables and curves presented were obtained from the references, and represent typical or average values. Some of the values are based on little data, while others are typical of the values obtained from numerous tests. In using these values or curves for design purposes, it is recognized that they often represent relative trends, and can be used only to compare materials and define those variables that affect the material properties evaluated. A more complete literature survey and evaluation of properties is being performed by the American Welding Society, in preparation for a major test program.

Static Properties

Table 2, obtained from Reference (1), presents minimum, maximum and typical static strength values for unwelded 5000 series aluminum sheet and plate. The values are obtained from many tests and are accurately representative of the material properties. Table 3 presents unwelded static strength limits for 5000 series aluminum extrusions. Table 4 presents values for the static strength of butt-welded 5000 series aluminum alloys tested in axial tension. The average values are obtained from both field and laboratory welded specimens of various thicknesses and dimensions, References (2) through (17). Values are presented for specimens in the as-welded condition with the bead on and for specimens with the weld bead machined flush with the parent material or bead off. Where undefined, the values correspond to specimens in the as-welded condition. Results for specimens with weld defects are not included, and no differentiation is made for filler wire, type of weld, weld process or specimen geometry since the effects of these variables are no more significant than normal test scatter. Several possible inconsistencies are noted in Table 4 relative to the average elongation figures. In some cases, bead on values are greater than bead off values, which is questionable. In other cases, the average values are equal to or slightly less than the minimum values of Tables 2 and 3. These inconsistencies reflect the relatively limited data available on average elongations, and the need for more consistent testing.

Comparison of Tables 2, 3 and 4 clearly indicates that, for all 5000 series alloys investigated, annealed parent material, butt-welded annealed material and butt-welded tempered material possess approximately the same ultimate and yield strengths under static load. The elongation of welded alloys, annealed or tempered, approaches that of tempered parent material, due to stress concentrations, residual stresses in the weld and metallurgical factors. These results establish that the static strength properties of 5,000 series aluminum welds are approximately equal to the static strength properties of annealed (O temper) parent material.

TABLE 2. Mechanical Properties of Aluminum Alloy Sheet and Plate

PART A - Property Limits ①

| ALLOY AND TEMPER | THICKNESS② in. | TENSILE STRENGTH—ksi (kg/mm²) ULTIMATE min | ULTIMATE max | YIELD min | YIELD max | ELONGATION percent min in 2 in. or 4D⑤ |
|---|---|---|---|---|---|---|
| | | **5050** | | | | |
| 5050-0 | 0.006-0.007 | 18.0 (12.7) | 24.0 (16.9) | 6.0 (4.2)⑥ | .. | .. |
| | 0.008-0.019 | 18.0 (12.7) | 24.0 (16.9) | 6.0 (4.2)⑥ | .. | 16 |
| | 0.020-0.031 | 18.0 (12.7) | 24.0 (16.9) | 6.0 (4.2)⑥ | .. | 18 |
| | 0.032-0.113 | 18.0 (12.7) | 24.0 (16.9) | 6.0 (4.2)⑥ | . | 20 |
| | 0.114-0.249 | 18.0 (12.7) | 24.0 (16.9) | 6.0 (4.2)⑥ | . | 22 |
| | 0.250-3.000 | 18.0 (12.7) | 24.0 (16.9) | 6.0 (4.2)⑥ | .. | 20 |
| 5050-H32③ | 0.017-0.050 | 22.0 (15.5) | 28.0 (19.7) | 16.0 (11.2)⑥ | .. | 4 |
| | 0.051-0.249 | 22.0 (15.5) | 28.0 (19.7) | 16.0 (11.2)⑥ | .. | 6 |
| 5050-H34③ | 0.009-0.031 | 25.0 (17.6) | 31.0 (21.8) | 20.0 (14.1)⑥ | .. | 3 |
| | 0.032-0.050 | 25.0 (17.6) | 31.0 (21.8) | 20.0 (14.1)⑥ | .. | 4 |
| | 0.051-0.249 | 25.0 (17.6) | 31.0 (21.8) | 20.0 (14.1)⑥ | .. | 5 |
| 5050-H36③ | 0.006-0.019 | 27.0 (19.0) | 33.0 (23.2) | 22.0 (15.5)⑥ | .. | 2 |
| | 0.020-0.050 | 27.0 (19.0) | 33.0 (23.2) | 22.0 (15.5)⑥ | .. | 3 |
| | 0.051-0.162 | 27.0 (19.0) | 33.0 (23.2) | 22.0 (15.5)⑥ | .. | 4 |
| 5050-H38 | 0.006-0.007 | 29.0 (20.4) | .. | .. | .. | .. |
| | 0.008-0.031 | 29.0 (20.4) | .. | . | .. | 2 |
| | 0.032-0.050 | 29.0 (20.4) | . | .. | . | 3 |
| | 0.051-0.128 | 29.0 (20.4) | . | .. | .. | 4 |
| 5050-H112 | 0.250-3.000 | 20.0 (14.1) | .. | 8.0 (5.6)⑥ | .. | 12 |
| | | **5052** | | | | |
| 5052-0 | 0.006-0.007 | 25.0 (17.6) | 31.0 (21.8) | 9.5 (6.7)⑥ | . | .. |
| | 0.008-0.012 | 25.0 (17.6) | 31.0 (21.8) | 9.5 (6.7)⑥ | .. | 14 |
| | 0.013-0.019 | 25.0 (17.6) | 31.0 (21.8) | 9.5 (6.7)⑥ | .. | 15 |
| | 0.020-0.031 | 25.0 (17.6) | 31.0 (21.8) | 9.5 (6.7)⑥ | .. | 16 |
| | 0.032-0.050 | 25.0 (17.6) | 31.0 (21.8) | 9.5 (6.7)⑥ | .. | 18 |
| | 0.051-0.113 | 25.0 (17.6) | 31.0 (21.8) | 9.5 (6.7)⑥ | .. | 19 |
| | 0.114-0.249 | 25.0 (17.6) | 31.0 (21.8) | 9.5 (6.7)⑥ | .. | 20 |
| | 0.250-3.000 | 25.0 (17.6) | 31.0 (21.8) | 9.5 (6.7)⑥ | . | 18 |
| 5052-H32③ | 0.017-0.019 | 31.0 (21.8) | 38.0 (26.7) | 23.0 (16.2)⑥ | .. | 4 |
| | 0.020-0.050 | 31.0 (21.8) | 38.0 (26.7) | 23.0 (16.2)⑥ | .. | 5 |
| | 0.051-0.113 | 31.0 (21.8) | 38.0 (26.7) | 23.0 (16.2)⑥ | . | 7 |
| | 0.114-0.249 | 31.0 (21.8) | 38.0 (26.7) | 23.0 (16.2)⑥ | .. | 9 |
| | 0.250-0.499 | 31.0 (21.8) | 38.0 (26.7) | 23.0 (16.2)⑥ | . | 11 |
| | 0.500-2.000 | 31.0 (21.8) | 38.0 (26.7) | 23.0 (16.2)⑥ | .. | 12 |
| 5052-H34③ | 0.009-0.019 | 34.0 (23.9) | 41.0 (28.8) | 26.0 (18.3)⑥ | .. | 3 |
| | 0.020-0.050 | 34.0 (23.9) | 41.0 (28.8) | 26.0 (18.3)⑥ | .. | 4 |
| | 0.051-0.113 | 34.0 (23.9) | 41.0 (28.8) | 26.0 (18.3)⑥ | .. | 6 |
| | 0.114-0.249 | 34.0 (23.9) | 41.0 (28.8) | 26.0 (18.3)⑥ | .. | 7 |
| | 0.250-1.000 | 34.0 (23.9) | 41.0 (28.8) | 26.0 (18.3)⑥ | .. | 10 |
| 5052-H36③ | 0.006-0.007 | 37.0 (26.0) | 44.0 (30.9) | 29.0 (20.4)⑥ | .. | 2 |
| | 0.008-0.031 | 37.0 (26.0) | 44.0 (30.9) | 29.0 (20.4)⑥ | .. | 3 |
| | 0.032-0.162 | 37.0 (26.0) | 44.0 (30.9) | 29.0 (20.4)⑥ | .. | 4 |
| 5052-H38③ | 0.006-0.007 | 39.0 (27.4) | . | 32.0 (22.5)⑥ | .. | 2 |
| | 0.008-0.031 | 39.0 (27.4) | . | 32.0 (22.5)⑥ | .. | 3 |
| | 0.032-0.128 | 39.0 (27.4) | . | 32.0 (22.5)⑥ | . | 4 |
| 5052-H112 | 0.250-0.499 | 28.0 (19.7) | | 16.0 (11.2)⑥ | .. | 7 |
| | 0.500-2.000 | 25.0 (17.6) | . | 9.5 (6.7)⑥ | .. | 12 |
| | 2.001-3.000 | 25.0 (17.6) | .. | 9.5 (6.7)⑥ | .. | 16 |

For all numbered Footnotes, see Page 13.

TABLE 2. Mechanical Properties of Aluminum Alloy Sheet and Plate

PART A - Property Limits① (cont.)

| ALLOY AND TEMPER | THICKNESS② in. | TENSILE STRENGTH—ksi (kg/mm²) ULTIMATE min | ULTIMATE max | YIELD min | YIELD max | ELONGATION percent min in 2 in. or 4D⑤ |
|---|---|---|---|---|---|---|
| **5083** | | | | | | |
| 5083-0 | 0.051-1.500 | 40.0 (28.1) | 51.0 (35.9) | 18.0 (12.7) | 29.0 (20.4) | 16 |
| | 1.501-3.000 | 39.0 (27.4) | 50.0 (35.2) | 17.0 (12.0) | 29.0 (20.4) | 16 |
| | 3.001-4.000 | 38.0 (26.7) | . | 16.0 (11.2) | . . | 16 |
| | 4.001-5.000 | 38.0 (26.7) | | 16.0 (11.2) | . . | 14 |
| | 5.001-7.000 | 37.0 (26.0) | . . | 15.0 (10.5) | . . | 14 |
| | 7.001-8.000 | 36.0 (25.3) | . | 14.0 (9.8) | . . | 12 |
| 5083-H112 | 0.250-1.500 | 40.0 (28.1) | . | 18.0 (12.7) | . . | 12 |
| | 1.501-3.000 | 39.0 (27.4) | | 17.0 (12.0) | . . | 12 |
| 5083-H321 | 0.188-1.500 | 44.0 (30.9) | 56.0 (39.4) | 31.0 (21.8) | 43.0 (30.2) | 12 |
| | 1.501-3.000 | 41.0 (28.8) | 56.0 (39.4) | 29.0 (20.4) | 43.0 (30.2) | 12 |
| 5083-H323 | 0.051-0.125 | 45.0 (31.6) | 54.0 (38.0) | 34.0 (23.9) | 44.0 (30.9) | 8 |
| | 0.126-0.249 | 45.0 (31.6) | 54.0 (38.0) | 34.0 (23.9) | 44.0 (30.9) | 10 |
| 5083-H343 | 0.051-0.125 | 50.0 (35.2) | 59.0 (41.5) | 39.0 (27.4) | 49.0 (34.4) | 6 |
| | 0.126-0.249 | 50.0 (35.2) | 59.0 (41.5) | 39.0 (27.4) | 49.0 (34.4) | 8 |
| **5086** | | | | | | |
| 5086-0 | 0.020-0.050 | 35.0 (24.6) | 42.0 (29.5) | 14.0 (9.8) | . . | 15 |
| | 0.051-0.249 | 35.0 (24.6) | 42.0 (29.5) | 14.0 (9.8) | . . | 18 |
| | 0.250-2.000 | 35.0 (24.6) | 42.0 (29.5) | 14.0 (9.8) | . . | 16 |
| 5086-H32③ | 0.020-0.050 | 40.0 (28.1) | 47.0 (33.0) | 28.0 (19.7) | . . | 6 |
| | 0.051-0.249 | 40.0 (28.1) | 47.0 (33.0) | 28.0 (19.7) | . . | 8 |
| | 0.250-2.000 | 40.0 (28.1) | 47.0 (33.0) | 28.0 (19.7) | . . | 12 |
| 5086-H34③ | 0.009-0.019 | 44.0 (30.9) | 51.0 (35.9) | 34.0 (23.9) | . . | 4 |
| | 0.020-0.050 | 44.0 (30.9) | 51.0 (35.9) | 34.0 (23.9) | . . | 5 |
| | 0.051-0.249 | 44.0 (30.9) | 51.0 (35.9) | 34.0 (23.9) | . . | 6 |
| | 0.250-1.000 | 44.0 (30.9) | 51.0 (35.9) | 34.0 (23.9) | . . | 10 |
| 5086-H36③ | 0.006-0.019 | 47.0 (33.0) | 54.0 (38.0) | 38.0 (26.7) | . . | 3 |
| | 0.020-0.050 | 47.0 (33.0) | 54.0 (38.0) | 38.0 (26.7) | . | 4 |
| | 0.051-0.162 | 47.0 (33.0) | 54.0 (38.0) | 38.0 (26.7) | . . | 6 |
| 5086-H38③ | 0.006-0.020 | 50.0 (35.2) | . . | 41.0 (28.8) | . . | 3 |
| 5086-H112 | 0.188-0.499 | 36.0 (25.3) | . | 18.0 (12.7) | . . | 8 |
| | 0.500-1.000 | 35.0 (24.6) | . | 16.0 (11.2) | . . | 10 |
| | 1.001-2.000 | 35.0 (24.6) | . | 14.0 (9.8) | . . | 14 |
| | 2.001-3.000 | 34.0 (23.9) | | 14.0 (9.8) | . . | 14 |
| **5154** | | | | | | |
| 5154-0 | 0.020-0.031 | 30.0 (21.1) | 41.0 (28.8) | 11.0 (7.7) | . | 12 |
| | 0.032-0.050 | 30.0 (21.1) | 41.0 (28.8) | 11.0 (7.7) | . . | 14 |
| | 0.051-0.113 | 30.0 (21.1) | 41.0 (28.8) | 11.0 (7.7) | . . | 16 |
| | 0.114-3.000 | 30.0 (21.1) | 41.0 (28.8) | 11.0 (7.7) | . . | 18 |
| 5154-H32③ | 0.020-0.050 | 36.0 (25.3) | 43.0 (30.2) | 26.0 (18.3) | . | 5 |
| | 0.051-0.249 | 36.0 (25.3) | 43.0 (30.2) | 26.0 (18.3) | . . | 8 |
| | 0.250-2.000 | 36.0 (25.3) | 43.0 (30.2) | 26.0 (18.3) | . . | 12 |
| 5154-H34③ | 0.009-0.050 | 39.0 (27.4) | 46.0 (32.3) | 29.0 (20.4) | . . | 4 |
| | 0.051-0.161 | 39.0 (27.4) | 46.0 (32.3) | 29.0 (20.4) | . | 6 |
| | 0.162-0.249 | 39.0 (27.4) | 46.0 (32.3) | 29.0 (20.4) | . . | 7 |
| | 0.250-1.000 | 39.0 (27.4) | 46.0 (32.3) | 29.0 (20.4) | . . | 10 |
| 5154-H36③ | 0.006-0.050 | 42.0 (29.5) | 49.0 (34.4) | 32.0 (22.5) | . . | 3 |
| | 0.051-0.113 | 42.0 (29.5) | 49.0 (34.4) | 32.0 (22.5) | . . | 4 |
| | 0.114-0.162 | 42.0 (29.5) | 49.0 (34.4) | 32.0 (22.5) | . . | 5 |
| 5154-H38③ | 0.006-0.050 | 45.0 (31.6) | . . | 35.0 (24.6) | . . | 3 |
| | 0.051-0.113 | 45.0 (31.6) | | 35.0 (24.6) | . . | 4 |
| | 0.114-0.128 | 45.0 (31.6) | | 35.0 (24.6) | . . | 5 |
| 5154-H112 | 0.250-0.499 | 32.0 (22.5) | . . | 18.0 (12.7) | . . | 8 |
| | 0.500-2.000 | 30.0 (21.1) | . | 11.0 (7.7) | . . | 11 |
| | 2.001-3.000 | 30.0 (21.1) | | 11.0 (7.7) | . . | 15 |

For all numbered Footnotes, see Page 13.

TABLE 2 Mechanical Properties of Aluminum Sheet and Plate

PART A - (cont.)

| ALLOY AND TEMPER | THICKNESS② in. | TENSILE STRENGTH—ksi (kg/mm²) ULTIMATE min | ULTIMATE max | YIELD min | YIELD max | ELONGATION percent min in 2 in. or 4D⑤ |
|---|---|---|---|---|---|---|
| **5252** | | | | | | |
| 5252-H24 | 0.030-0.090 | 30.0 (21.1) | 38.0 (26.7) | . | .. | 10 |
| 5252-H25 | 0.030-0.090 | 31.0 (21.8) | 39.0 (27.4) | . | . | 9 |
| 5252-H28 | 0.030-0.090 | 38.0 (26.7) | . | .. | . | 3 |
| **5257** | | | | | | |
| 5257-H241 ④ | 0.030-0.090 | 14.0 (9.8) | 22.0 (15.5) | | .. | 14 |
| 5257-H25 | 0.030-0.090 | 16.0 (11.2) | 23.0 (16.2) | . | .. | 10 |
| 5257-H26 | 0.030-0.090 | 17.0 (12.0) | 24.0 (16.9) | . | . | 9 |
| 5257-H28 | 0.030-0.090 | 20.0 (14.1) | | . | .. | 6 |
| **5454** | | | | | | |
| 5454-0 | 0.020-0.031 | 31.0 (21.8) | 41.0 (28.8) | 12.0 (8.4) | | 12 |
| | 0.032-0.050 | 31.0 (21.8) | 41.0 (28.8) | 12.0 (8.4) | | 14 |
| | 0.051-0.113 | 31.0 (21.8) | 41.0 (28.8) | 12.0 (8.4) | . | 16 |
| | 0.114-3.000 | 31.0 (21.8) | 41.0 (28.8) | 12.0 (8.4) | | 18 |
| 5454-H32③ | 0.020-0.050 | 36.0 (25.3) | 44.0 (30.9) | 26.0 (18.3) | . | 5 |
| | 0.051-0.249 | 36.0 (25.3) | 44.0 (30.9) | 26.0 (18.3) | . | 8 |
| | 0.250-2.000 | 36.0 (25.3) | 44.0 (30.9) | 26.0 (18.3) | .. | 12 |
| 5454-H34③ | 0.020-0.050 | 39.0 (27.4) | 47.0 (33.0) | 29.0 (20.4) | . | 4 |
| | 0.051-0.161 | 39.0 (27.4) | 47.0 (33.0) | 29.0 (20.4) | | 6 |
| | 0.162-0.249 | 39.0 (27.4) | 47.0 (33.0) | 29.0 (20.4) | . | 7 |
| | 0.250-1.000 | 39.0 (27.4) | 47.0 (33.0) | 29.0 (20.4) | . | 10 |
| 5454-H112 | 0.250-0.499 | 32.0 (22.5) | | 18.0 (12.7) | | 8 |
| | 0.500-2.000 | 31.0 (21.8) | | 12.0 (8.4) | . | 11 |
| | 2.001-3.000 | 31.0 (21.8) | | 12.0 (8.4) | . | 15 |
| **5456** | | | | | | |
| 5456-0 | 0.051-1.500 | 42.0 (29.5) | 53.0 (37.3) | 19.0 (13.4) | 30.0 (21.1) | 16 |
| | 1.501-3.000 | 41.0 (28.8) | 52.0 (36.6) | 18.0 (12.7) | 30.0 (21.1) | 16 |
| | 3.001-5.000 | 40.0 (28.1) | | 17.0 (12.0) | .. | 14 |
| | 5.001-7.000 | 39.0 (27.4) | | 16.0 (11.2) | | 14 |
| | 7.001-8.000 | 38.0 (26.7) | | 15.0 (10.5) | .. | 12 |
| 5456-H112 | 0.250-1.500 | 42.0 (29.5) | | 19.0 (13.4) | .. | 12 |
| | 1.501-3.000 | 41.0 (28.8) | | 18.0 (12.7) | . | 12 |
| 5456-H321 | 0.188-0.624 | 46.0 (32.3) | 59.0 (41.5) | 33.0 (23.2) | 46.0 (32.3) | 12 |
| | 0.625-1.250 | 46.0 (32.3) | 56.0 (39.4) | 33.0 (23.2) | 45.0 (31.6) | 12 |
| | 1.251-1.500 | 44.0 (30.9) | 56.0 (39.4) | 31.0 (21.8) | 43.0 (30.2) | 12 |
| | 1.501-3.000 | 41.0 (28.8) | 56.0 (39.4) | 29.0 (20.4) | 43.0 (30.2) | 12 |
| 5456-H323 | 0.051-0.125 | 48.0 (33.7) | 58.0 (40.8) | 36.0 (25.3) | 46.0 (32.3) | 6 |
| | 0.126-0.249 | 48.0 (33.7) | 58.0 (40.8) | 36.0 (25.3) | 46.0 (32.3) | 8 |
| 5456-H343 | 0.051-0.125 | 53.0 (37.3) | 63.0 (44.3) | 41.0 (28.8) | 51.0 (35.9) | 6 |
| | 0.126-0.249 | 53.0 (37.3) | 63.0 (44.3) | 41.0 (28.8) | 51.0 (35.9) | 8 |
| **5457** | | | | | | |
| 5457-0 | 0.030-0.090 | 16.0 (11.2) | 22.0 (15.5) | . | .. | 20 |
| **5557** | | | | | | |
| 5557-0 | 0.030-0.090 | 13.0 (9.1) | 20.0 (14.1) | . | . | 20 |
| **5657** | | | | | | |
| 5657-H241 ④ | 0.030-0.090 | 18.0 (12.7) | 26.0 (18.3) | | . | 13 |
| 5657-H25 | 0.030-0.090 | 20.0 (14.1) | 28.0 (19.7) | . | .. | 8 |
| 5657-H26 | 0.030-0.090 | 22.0 (15.5) | 30.0 (21.1) | . | . | 7 |
| 5657-H28 | 0.030-0.090 | 25.0 (17.6) | | . | | 5 |

For all numbered Footnotes, see Page 13.

TABLE 2 Mechanical Properties of Aluminum Sheet and Plate

PART B - Typical Properties[1]

| ALLOY AND TEMPER | TENSION: STRENGTH ksi (kg/mm²) ULTIMATE | TENSION: STRENGTH ksi (kg/mm²) YIELD | TENSION: ELONGATION percent in 2 in. 1/16 Inch Thick Specimen | TENSION: ELONGATION percent in 2 in. 1/2 Inch Diameter Specimen | HARDNESS: BRINELL NUMBER 500 kg load 10 mm ball | SHEAR: ULTIMATE SHEARING STRENGTH ksi (kg/mm²) | FATIGUE: ENDURANCE[2] LIMIT ksi (kg/mm²) | MODULUS: MODULUS[3] OF ELASTICITY ksi (kg/mm²) x 10³ |
|---|---|---|---|---|---|---|---|---|
| 5005-0 | 18 (12.7) | 6 (4.2) | 25 | ... | 28 | 11 (7.7) | ... | 10.0 (7.0) |
| 5005-H12 | 20 (14.1) | 19 (13.4) | 10 | ... | ... | 14 (9.8) | ... | 10.0 (7.0) |
| 5005-H14 | 23 (16.2) | 22 (15.5) | 6 | | ... | 14 (9.8) | ... | 10.0 (7.0) |
| 5005-H16 | 26 (18.3) | 25 (17.6) | 5 | | ... | 15 (10.5) | ... | 10.0 (7.0) |
| 5005-H18 | 29 (20.4) | 28 (19.7) | 4 | ... | ... | 16 (11.2) | ... | 10.0 (7.0) |
| 5005-H32 | 20 (14.1) | 17 (12.0) | 11 | | 36 | 14 (9.8) | ... | 10.0 (7.0) |
| 5005-H34 | 23 (16.2) | 20 (14.1) | 8 | | 41 | 14 (9.8) | ... | 10.0 (7.0) |
| 5005-H36 | 26 (18.3) | 24 (16.9) | 6 | ... | 46 | 15 (10.5) | ... | 10.0 (7.0) |
| 5005-H38 | 29 (20.4) | 27 (19.0) | 5 | | 51 | 16 (11.2) | ... | 10.0 (7.0) |
| 5050-0 | 21 (14.8) | 8 (5.6) | 24 | ... | 36 | 15 (10.5) | 12 (8.4) | 10.0 (7.0) |
| 5050-H32 | 25 (17.6) | 21 (14.8) | 9 | ... | 46 | 17 (12.0) | 13 (9.1) | 10.0 (7.0) |
| 5050-H34 | 28 (19.7) | 24 (16.9) | 8 | ... | 53 | 18 (12.7) | 13 (9.1) | 10.0 (7.0) |
| 5050-H36 | 30 (21.1) | 26 (18.3) | 7 | ... | 58 | 19 (13.4) | 14 (9.8) | 10.0 (7.0) |
| 5050-H38 | 32 (22.5) | 29 (20.4) | 6 | ... | 63 | 20 (14.1) | 14 (9.8) | 10.0 (7.0) |
| 5052-0 | 28 (19.7) | 13 (9.1) | 25 | 30 | 47 | 18 (12.7) | 16 (11.2) | 10.2 (7.2) |
| 5052-H32 | 33 (23.2) | 28 (19.7) | 12 | 18 | 60 | 20 (14.1) | 17 (12.0) | 10.2 (7.2) |
| 5052-H34 | 38 (26.7) | 31 (21.8) | 10 | 14 | 68 | 21 (14.8) | 18 (12.7) | 10.2 (7.2) |
| 5052-H36 | 40 (28.1) | 35 (24.6) | 8 | 10 | 73 | 23 (16.2) | 19 (13.4) | 10.2 (7.2) |
| 5052-H38 | 42 (29.5) | 37 (26.0) | 7 | 8 | 77 | 24 (16.9) | 20 (14.1) | 10.2 (7.2) |
| 5056-0 | 42 (29.5) | 22 (15.5) | ... | 35 | 65 | 26 (18.3) | 20 (14.1) | 10.3 (7.2) |
| 5056-H18 | 63 (44.3) | 59 (41.5) | ... | 10 | 105 | 34 (23.9) | 22 (15.5) | 10.3 (7.2) |
| 5056-H38 | 60 (42.2) | 50 (35.2) | | 15 | 100 | 32 (22.5) | 22 (15.5) | 10.3 (7.2) |
| 5083-0 | 42 (29.5) | 21 (14.8) | ... | 22 | ... | 25 (17.6) | ... | 10.3 (7.2) |
| 5083-H321 | 46 (32.3) | 33 (23.2) | | 16 | ... | ... | 23 (16.2) | 10.3 (7.2) |
| 5086-0 | 38 (26.7) | 17 (12.0) | 22 | ... | ... | 23 (16.2) | | 10.3 (7.2) |
| 5086-H32 | 42 (29.5) | 30 (21.1) | 12 | | ... | ... | ... | 10.3 (7.2) |
| 5086-H34 | 47 (33.0) | 37 (26.0) | 10 | | ... | 27 (19.0) | ... | 10.3 (7.2) |
| 5086-H112 | 39 (27.4) | 19 (13.4) | 14 | | ... | ... | ... | 10.3 (7.2) |
| 5154-0 | 35 (24.6) | 17 (12.0) | 27 | | 58 | 22 (15.5) | 17 (12.0) | 10.2 (7.2) |
| 5154-H32 | 39 (27.4) | 30 (21.1) | 15 | ... | 67 | 22 (15.5) | 18 (12.7) | 10.2 (7.2) |
| 5154-H34 | 42 (29.5) | 33 (23.2) | 13 | | 73 | 24 (16.9) | 19 (13.4) | 10.2 (7.2) |
| 5154-H36 | 45 (31.6) | 36 (25.3) | 12 | | 78 | 26 (18.3) | 20 (14.1) | 10.2 (7.2) |
| 5154-H38 | 48 (33.7) | 39 (27.4) | 10 | | 80 | 28 (19.7) | 21 (14.8) | 10.2 (7.2) |
| 5154-H112 | 35 (24.6) | 17 (12.0) | 25 | | 63 | ... | 17 (12.0) | 10.2 (7.2) |
| 5252-H25 | 34 (23.9) | 25 (17.6) | 11 | | 68 | 21 (14.8) | ... | 10.0 (7.0) |
| 5252-H38, -H28 | 41 (28.8) | 35 (24.6) | 5 | ... | 75 | 23 (16.2) | ... | 10.0 (7.0) |
| 5257-H25 | 19 (13.4) | 16 (11.2) | 14 | ... | 32 | 11 (7.7) | ... | 10.0 (7.0) |
| 5257-H38, -H28 | 23 (16.2) | 19 (13.4) | 8 | ... | 43 | 12 (8.4) | ... | 10.0 (7.0) |
| 5454-0 | 36 (25.3) | 17 (12.0) | 22 | ... | 62 | 23 (16.2) | ... | 10.2 (7.2) |
| 5454-H32 | 40 (28.1) | 30 (21.1) | 10 | ... | 73 | 24 (16.9) | ... | 10.2 (7.2) |
| 5454-H34 | 44 (30.9) | 35 (24.6) | 10 | ... | 81 | 26 (18.3) | ... | 10.2 (7.2) |
| 5454-H111 | 38 (26.7) | 26 (18.3) | 14 | ... | 70 | 23 (16.2) | ... | 10.2 (7.2) |
| 5454-H112 | 36 (25.3) | 18 (12.7) | 18 | | 62 | 23 (16.2) | | 10.2 (7.2) |
| 5456-0 | 45 (31.6) | 23 (16.2) | ... | 24 | ... | ... | ... | 10.3 (7.2) |
| 5456-H111 | 47 (33.0) | 33 (23.2) | ... | 18 | ... | ... | ... | 10.3 (7.2) |
| 5456-H112 | 45 (31.6) | 24 (16.9) | ... | 22 | ... | ... | ... | 10.3 (7.2) |
| 5456-H321 | 51 (35.9) | 37 (26.0) | ... | 16 | 90 | 30 (21.1) | ... | 10.3 (7.2) |
| 5457-0 | 19 (13.4) | 7 (4.9) | 22 | ... | 32 | 12 (8.4) | ... | 10.0 (7.0) |
| 5457-H25 | 26 (18.3) | 23 (16.2) | 12 | ... | 48 | 16 (11.2) | ... | 10.0 (7.0) |
| 5457-H38, -H28 | 30 (21.1) | 27 (19.0) | 6 | ... | 55 | 18 (12.7) | ... | 10.0 (7.0) |
| 5557-0 | 16 (11.2) | 6 (4.2) | 25 | ... | 28 | 11 (7.7) | ... | 10.0 (7.0) |
| 5557-H25 | 23 (16.2) | 20 (14.1) | 12 | ... | 40 | 14 (9.8) | ... | 10.0 (7.0) |
| 5557-H38, -H28 | 28 (19.7) | 24 (16.9) | 7 | ... | 50 | 15 (10.5) | ... | 10.0 (7.0) |
| 5657-H25 | 23 (16.2) | 20 (14.1) | 12 | ... | 40 | 14 (9.8) | ... | 10.0 (7.0) |
| 5657-H38, -H28 | 28 (19.7) | 24 (16.9) | 7 | | 50 | 15 (10.5) | ... | 10.0 (7.0) |

For all numbered Footnotes, see Page 13.

FOOTNOTES

(Part A - Pages 9-11)

(1) Mechanical test specimens are taken as detailed under "Sampling and Testing", pages 52-54 of Reference (1).

(2) Type of test specimen used depends on thickness of material; see "Sampling and Testing", pages 52-54 of Reference (1).

(3) For the corresponding H2 temper, limits for maximum ultimate tensile strength and minimum yield strength do not apply.

(4) This material is subject to some recrystallization and the attendant loss of brightness.

(5) D represents specimen diameter.

(6) These yield strengths not determined unless specifically requested.

(Part B - Page 12)

(1) These typical properties are average for various forms, sizes and methods of manufacture, and may not exactly describe any one particular product.

(2) Based on 500,000,000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen.

(3) Average of tension and compression moduli. Compression modulus is about 2% greater than tension modulus.

TABLE 3 Mechanical Property Limits of Aluminum Alloy Extrusions

Part A - Extruded Rod and Bar

| ALLOY AND TEMPER | DIAMETER OR LEAST DISTANCE BETWEEN PARALLEL FACES in. | AREA sq in. | TENSILE STRENGTH—ksi (kg/mm²) ULTIMATE min | ULTIMATE max | YIELD min | YIELD max | ELONGATION percent min in 2 in. or 4D |
|---|---|---|---|---|---|---|---|
| **5083** | | | | | | | |
| 5083-0 | Up thru 5.000 | Up thru 32 | 39.0 (27.4) | 51.0 (35.9) | 16.0 (11.2) | .. | 14 |
| 5083-H111 | Up thru 5.000 | Up thru 32 | 40.0 (28.1) | . | 24.0 (16.9) | . | 12 |
| 5083-H112 | Up thru 5.000 | Up thru 32 | 39.0 (27.4) | . | 16.0 (11.2) | .. | 12 |
| **5086** | | | | | | | |
| 5086-0 | Up thru 5.000 | Up thru 32 | 35.0 (24.6) | 46.0 (32.3) | 14.0 (9.8) | .. | 14 |
| 5086-H111 | Up thru 5.000 | Up thru 32 | 36.0 (25.3) | | 21.0 (14.8) | .. | 12 |
| 5086-H112 | Up thru 5.000 | Up thru 32 | 35.0 (24.6) | | 14.0 (9.8) | .. | 12 |
| **5154** | | | | | | | |
| 5154-0 | All | All | 30.0 (21.1) | 41.0 (28.8) | 11.0 (7.7) | .. | .. |
| 5154-H112 | All | All | 30.0 (21.1) | | 11.0 (7.7) | .. | .. |
| **5454** | | | | | | | |
| 5454-0 | Up thru 5.000 | Up thru 32 | 31.0 (21.8) | 41.0 (28.8) | 12.0 (8.4) | | 14 |
| 5454-H111 | Up thru 5.000 | Up thru 32 | 33.0 (23.2) | | 19.0 (13.4) | | 12 |
| 5454-H112 | Up thru 5.000 | Up thru 32 | 31.0 (21.8) | | 12.0 (8.4) | .. | 12 |
| **5456** | | | | | | | |
| 5456-0 | Up thru 5.000 | Up thru 32 | 41.0 (28.8) | 53.0 (37.3) | 19.0 (13.4) | | 14 |
| 5456-H111 | Up thru 5.000 | Up thru 32 | 42.0 (29.5) | | 26.0 (18.3) | . | 12 |
| 5456-H112 | Up thru 5.000 | Up thru 32 | 41.0 (28.8) | . | 19.0 (13.4) | . | 12 |

TABLE 4 Static Properties of Welded Aluminum Alloys (1)

| Material | Minimum Values, KSI $F_{TU}$ | $F_{TY}$ | Average Values $F_{TU}$ (KSI) | Elongation (%) | Condition |
|---|---|---|---|---|---|
| 5052-0 | 25 | 9.5 | 28.0 | 18.0 | - |
| -H34 | 25 | 13 | 29.9 | 17.6 | Bead On |
| | - | - | 28.4 | 22.2 | Bead Off |
| 5083-0 | 40 | 18 | 43.6 | 16.2 | - |
| -H321 | 40 | 24 | 45.2 | 14.0 | Bead On |
| -H321 | - | - | 43.4 | 14.1 | Bead Off |
| -H111 | 39 | 21 | - | - | - |
| 5086-0 | 35 | 14 | 36.0 | 20.0 | - |
| -H32 | 35 | 19 | 38.5 | 20.0 | Bead On |
| -H32 | - | - | 38.5 | 16.0 | Bead Off |
| -H111 | 35 | 18 | - | - | - |
| 5154-0 | 30 | 11 | 33.0 | 15.0 | - |
| -H34 | 30 | 15 | 35.5 | 17.0 | - |
| 5356-H321 | - | - | 41.2 | 17.3 | Bead On |
| -H321 | - | - | 39.2 | 16.8 | Bead Off |
| 5456-0 | 41 | 18 | 44.0 | 15.0 | - |
| -H321 | 42 | 26 | 46.8 | 17.1 | Bead On |
| -H321 | - | - | 44.4 | 12.2 | Bead Off |
| -H111 | 41 | 24 | - | - | - |
| 5454-0 | 31 | 12 | - | - | - |
| -H34 | 31 | 16 | - | - | - |
| -H111 | 31 | 16 | - | - | - |

(1) Minimum values are from "Welding Alcoa Aluminum" (Alcoa)(Reference (22)) while average values are from referenced test reports.

Test values of static ultimate and yield strengths for the parent material are generally higher than the minimum values in Tables 2 and 3. The following exceptions were noted during the evaluation of the referenced data. Yield strengths for 10 specimens of 5456-H321 alloy are approximately 10 per cent below the minimum value, Reference (9). Although significant, this is not critical since aluminum does not have a yield point and the yield strength is arbitrarily defined. Reference (10) lists yield strengths for 2 specimens of 5086-H34 alloy (0.064 inch thickness) that are approximately 3 per cent below the minimum value. The elongation of 5083-H113 alloy which is identical to H321 temper, is about 5 per cent less than the minimum value, Figure 25 of Reference (13). One specimen of 5086-H32 alloy has a yield strength in the transverse direction 2 per cent below the minimum value and one specimen of 5456-H321 has yield strengths both longitudinal and transverse about 7 per cent below the minimum value, Reference (21). These limited cases do not modify the conclusion that the properties presented in Tables 2 through 4 are considered satisfactory for general design purposes.

## Fatigue Strength

Figures 3 through 9 present typical S-N fatigue curves for 5000 series aluminum alloys and structural steel. The curves are based on average data from available references. Some of the curves have been verified by many tests while others were obtained using few specimens. Ranges of test scatter are not presented, and the curves are used to develop relative trends only. Generally, specimens with weld defects are not included in the development of the curves. Fabrication variables evaluated include butt-welds and weld bead. Environmental variables evaluated include stress ratio R, test loading procedure, notches and water spray.

Figure 3 describes fatigue curves for unwelded (parent) alloys subjected to zero and complete stress reversal. The values of endurance limit (EL) are the same, within normal experimental scatter, for all 5000 series aluminum alloys evaluated, although the static strengths vary from 33 to 51 KSI. Complete stress reversal (R = -1) reduces the endurance limit by 50 per cent from the value for zero stress reversal (R = 0). The endurance limit (EL) of mild steel is higher than that of 5000 series aluminum by approximately the same ratio as that for the average static strengths. Fatigue curves are not presented for annealed (O temper) alloys. However, the endurance limit of annealed alloys is the same as that of tempered alloys, References (4), (5) and (7).

Fatigue curves for butt-welded alloys in the as-welded condition are presented in Figure 4 for zero and complete stress reversal. As with the unwelded material, all butt-welded 5000 series aluminum alloys approach the same endurance limit, although the static strengths vary from 29.9 to 46.8 KSI. Complete stress reversal reduces the endurance limit by 40 per cent from the value for zero stress reversal. The endurance limit of butt-welded annealed alloys is the same as that of butt-welded tempered alloys, References (6) and (16). A significant observation from Figure 4 is that the fatigue strength of butt-welded 5000 series aluminum is less than half that of butt-welded structural steel, whereas the fatigue strength of unwelded aluminum is 70 to 80 per cent that of unwelded structural steel. Also significant is the magnitude of the fatigue limit of butt-welded aluminum subjected to complete stress reversal. The value, 6-7 KSI, leaves little room for the safety factors that are required because of environmental conditions, water spray, corrosion, notches.

Figures 5, 6, 7 and 8 present fatigue curves for 5083-H113, 5086-H32 and 5456-H321 aluminum as well as structural steel alloys. These curves evaluate the effects of stress ratio, weld bead removal and surface notches, to the extent of available test data. The letter M corresponds to the R.R. Moore rotating beam fatigue test, and the letter K refers to the Krouse reversed beam bending fatigue test. Axial tension-compression fatigue tests give results approximately equal to reversed beam bending results for complete stress reversal. Most complete reversal tests utilize the Moore or Krouse procedure. Where undefined, the curves for complete stress reversal are probably developed from axial or Krouse bending tests. The factor $K_T$ defines the stress concentration factor at the root of the notch.

Equivalent curves of Figures 5, 6 and 7 are nearly coincident, and the following discussion applies to the three aluminum alloys. The endurance limit fatigue band covers the range from 35 KSI to 6.5 KSI, the upper bound corresponding to a stress ratio of 0.5 and the lower bound corresponding to as-welded material or sharp-notched material subjected to complete stress reversal. The effect of stress ratio and notches on the fatigue strength of unwelded material is obvious from the curves. A very significant observation is that the fatigue strength of butt-welded specimens with the weld bead removed is 50 to 80 per cent greater than the fatigue strength of as-welded specimens, although the static strength of as-welded specimens is slightly higher than that of specimens with the bead removed. The reasons for this phenomenon and the different values from different test procedures for complete stress reversal will be discussed later in further detail.

The S-N curves for steel, Figure 8, follow the same trends as the aluminum curves. However, the magnitudes of the curves for butt-welded mild steel and high tensile steel are somewhat higher than the equivalent magnitudes for aluminum, the lower bound for steel being 15 KSI. This is to be expected, since welding of structural steel results in a 100 per cent efficient joint, whereas welded aluminum joints exhibit somewhat less than 100 per cent static efficiency. The metallurgical explanation for the different weld strengths is beyond the scope of this study; however, its effect is clearly described by the fatigue curves. The limited fatigue data presented for steel is obtained from References (29) and (30), and is used for comparison purposes only. A complete evaluation of the fatigue strength of structural steel is not intended for this study.

Figure 9 indicates the detrimental effect of fresh or salt water spray on the fatigue strengths of unwelded mild steel and 5083-H113 aluminum alloy, Reference (13). Both metals have large reductions in fatigue strength from water spray, but the reduction in the endurance limit of aluminum to 4.5 KSI is a major concern in the application of aluminum in marine environment. References (14) and (23) indicate that the extreme reduction in fatigue strength due to water spray is caused by surface oxidation leading to fine cracks. Some methods for minimizing the reduction in strength are protective coating, surface compressive stresses, etc., Reference (23). The fatigue limit of butt-welded aluminum alloy with notches, subjected to water spray and slow complete stress reversal in a corrosive atmosphere, is as yet undetermined, but it is expected that such a value would be very low.

The following paragraphs explain the reasons for the trends in Figures 3 through 9, and discuss the many variables that have not been evaluated quantitatively. The effects of alloy composition, grain size

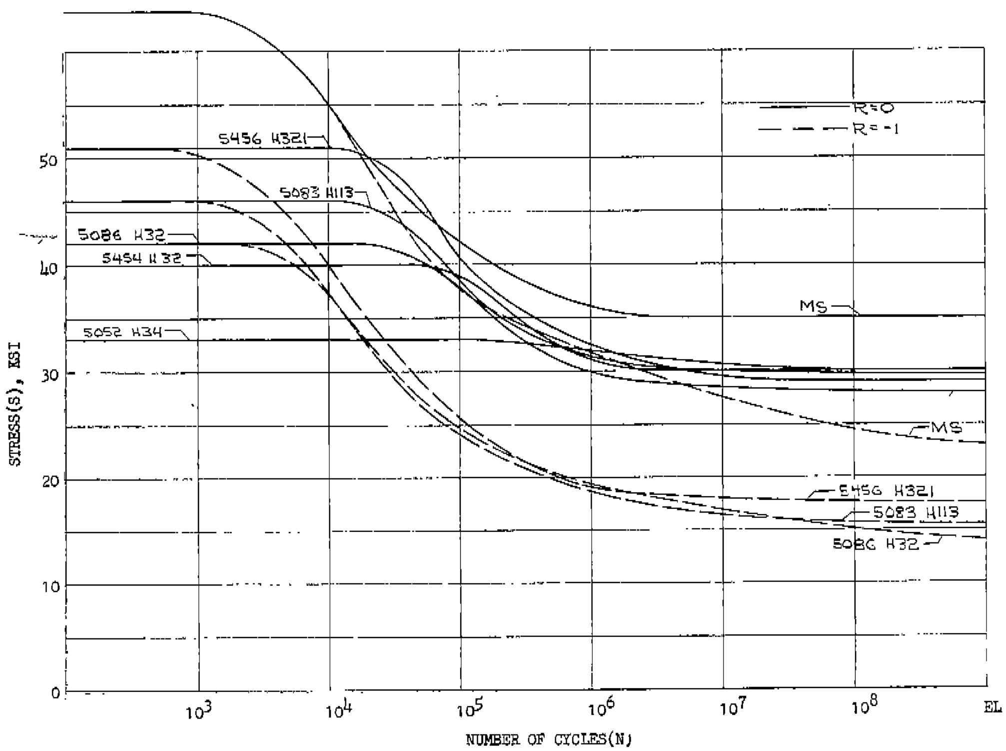



FIG. 3 S-N Fatigue Curves for Unwelded 5000 Series Aluminum Alloys and Structural Steel

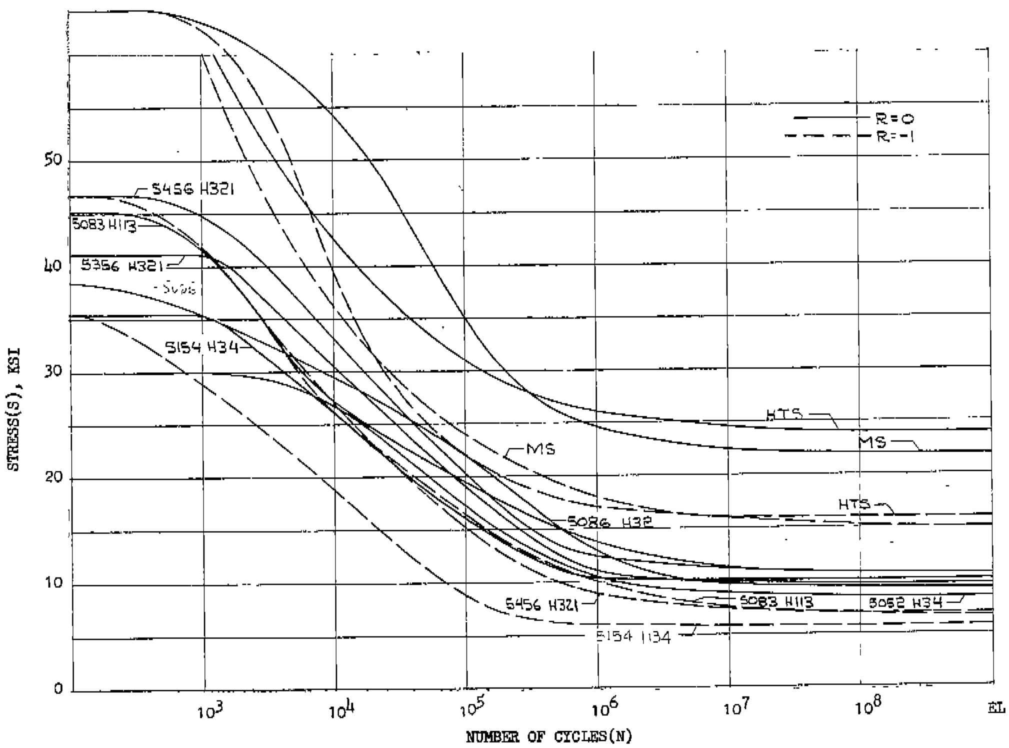



FIG. 4 S-N Fatigue Curves for Welded 5000 Series Aluminum Alloys and Structural Steel

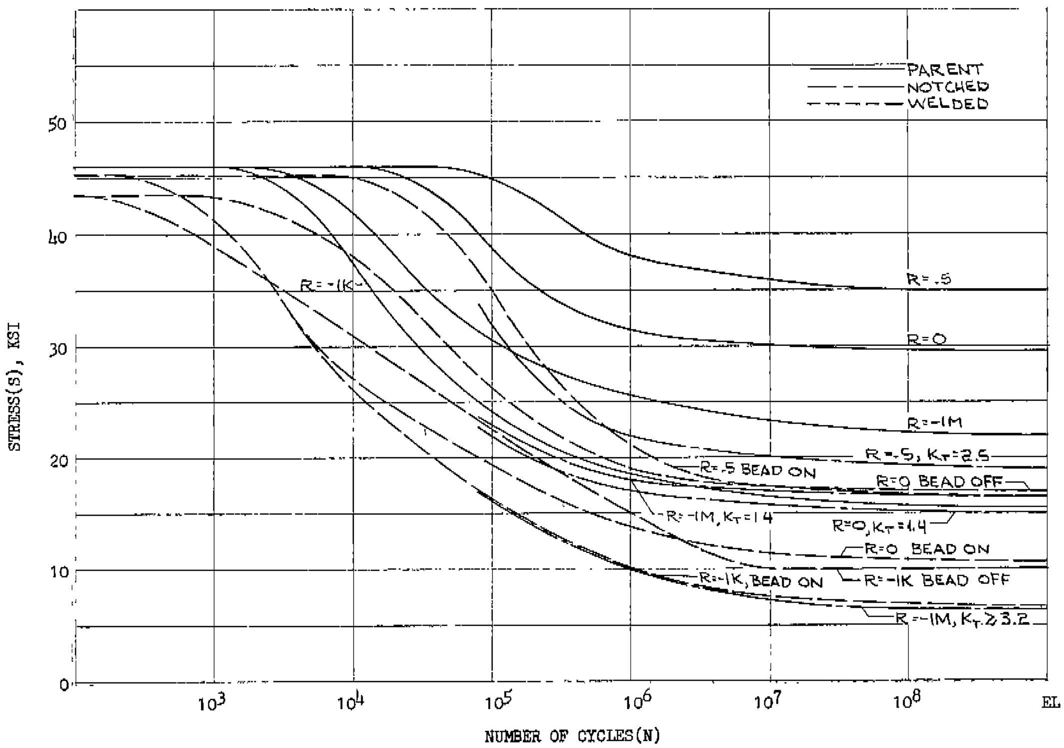



FIG. 5 S-N Fatigue Curves for 5083-H113 Aluminum Alloy

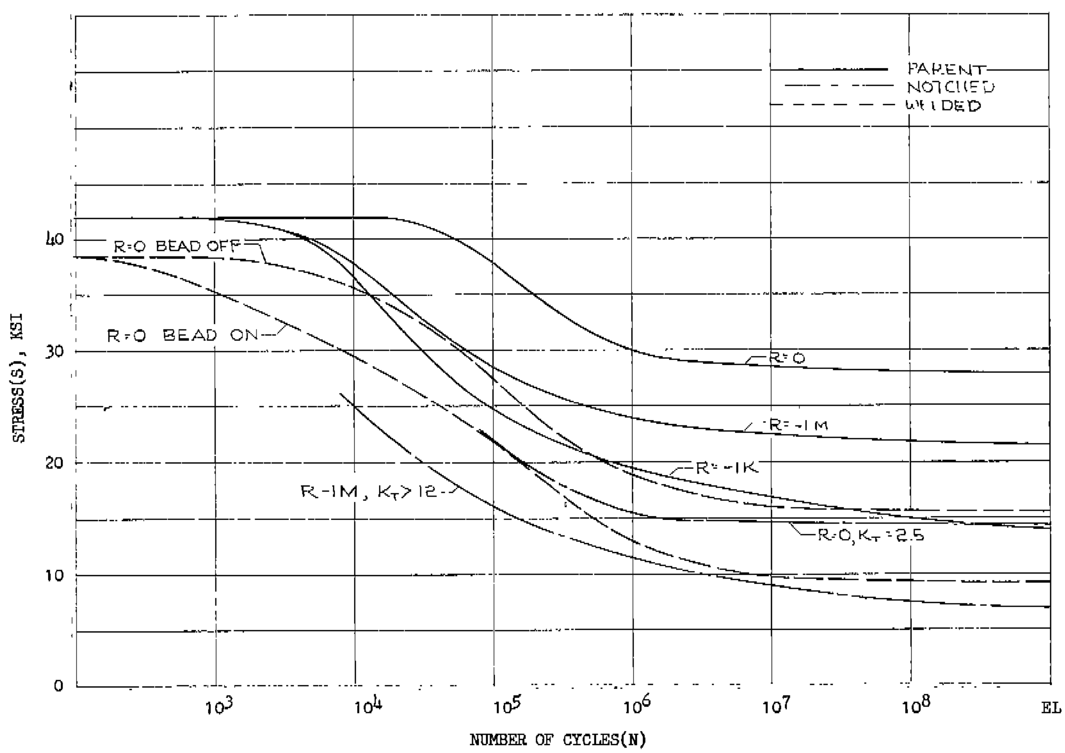



FIG. 6 S-N Fatigue Curves for 5086-H32 Aluminum Alloy

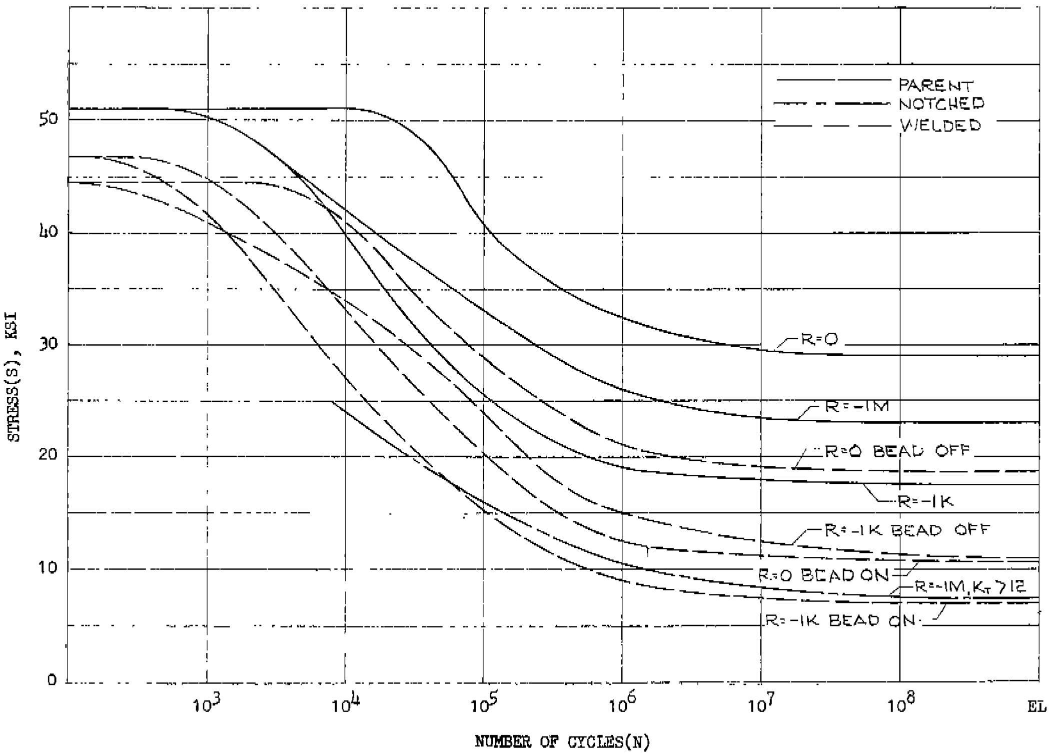



FIG. 7 S-N Fatigue Curves for 5456-H321 Aluminum Alloy

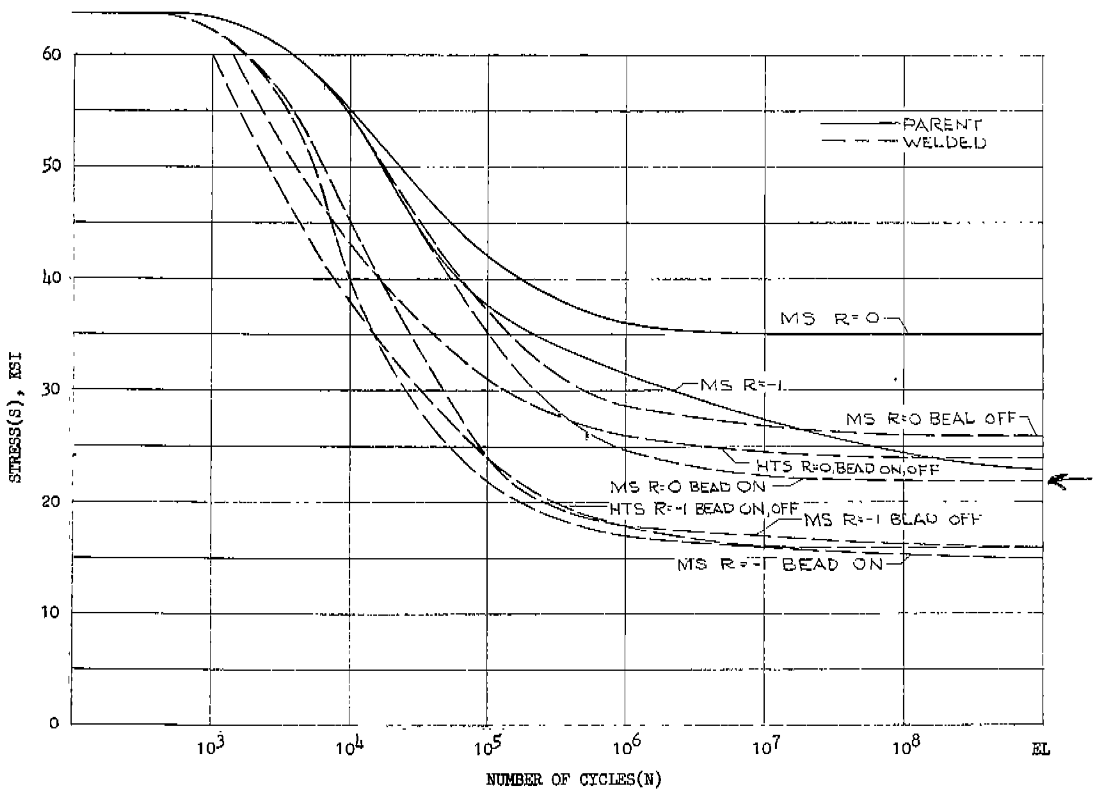



FIG. 8 S-N Fatigue Curves for Structural Steel

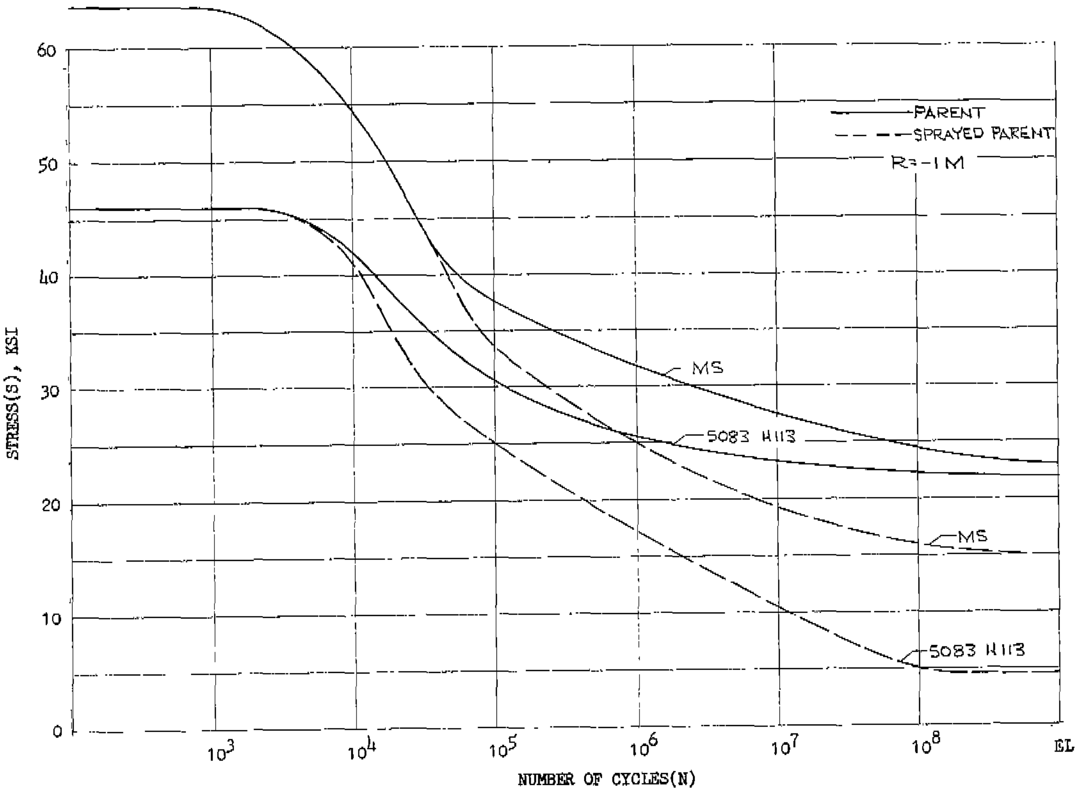



FIG. 9 S-N Fatigue Curves for 5083-H113 Alloy and Mild Steel Subject to Water Spray

and temper, weld process (including number of passes) and bead configuration, filler wire, specimen finish and thickness have not been analyzed in detail in this study. Although the references indicate variation in fatigue strength due to these variables, the magnitudes of variation are smaller than normal test scatter and are therefore considered negligible for this evaluation. It is sufficient to state that metallurgical and fabrication variables should be optimized to obtain maximum strength properties. Careful consideration should be given to complete removal of the weld bead in order to increase the endurance limit of welded aluminum structures. Stress concentrations and residuals at the weld bead accelerate fatigue failure of butt-welded specimens. Removal of the weld bead minimizes stress concentrations and residuals and strain hardens the weld region by the machining process, thus greatly increasing the fatigue strength of butt-welded aluminum alloys. However, this procedure is of questionable value for ship structures, because of the large number of fillet welds resulting from attachment of framing members and bulkheads.

A significant variable in this study is stress concentration due to fillet-welding structure to aluminum plate. Although there is no butt-welding in the parent plate, the introduction of stress concentrations and residuals at the fillets reduces the fatigue strength of the parent plate to values as low as or below values for butt-welded plate. Insufficient data is available for the presentation of curves; however, test results are presented in References (6) and (13) that verify the above statement. Test results for specimens with longitudinal butt-welds parallel to the direction of load are presented in References (6), (7) and (13). The fatigue strength of longitudinal weld specimens is approximately equal to that of specimens with transverse welds. However, the weld region covers the entire width of test specimens, but only a negligible width in full-scale structures. Further investigation is required to determine whether fatigue cracks will form at welds parallel to the direction of load in full-scale structures. The effects of temperature on the fatigue behavior of aluminum alloys are not included in this study. Test results at elevated temperatures are presented in References (1) and (5), and results at cryogenic temperatures are presented in References (1), (6), (10) and (12).

Fabrication, welding and inspection requirements for steel and aluminum ship hulls are defined in References (24) and (25). The critical variable relative to inspection is weld defects, which are more critical for aluminum than steel due to the inability of aluminum welds to develop 100 per cent efficiency. The effects of weld defects; cracks, incomplete penetration, lack of fusion, slag inclusions, porosity, etc. on the fatigue properties of aluminum, as yet undetermined, should be incorporated in inspection specifications. Weld defects relative to acceptance standards are discussed in References (26), (27) and (28).

Figures 3 through 9 present curves corresponding to ratios of minimum to maximum stress that vary from 0.5 to -1. Endurance limits for 0.5 stress ratio are reasonably higher than for zero stress ratio, which achieves higher endurance limit values than -1 stress ratio (complete reversal), as expected. Where available, S-N curves are presented for complete stress reversal obtained by rotating beam and reversed beam bending test procedures. The rotating beam test uses specimens with circular cross-section which subjects several fibers only at the top and bottom of the cross-section to maximum stress. The reversed beam bending test uses specimens with rectangular cross-section which subjects all fibers along the top and bottom edges of the cross-section to maximum stress, thus achieving lower fatigue strength values. The few available test results for complete stress reversal obtained using axial tension-compression tests give fatigue strength values approximately equal to those obtained from reversed beam bending tests. Since axial tension-compression tests stress all fibers equally, it is probable that the reversed beam bending test specimen has inherent stress concentrations or that incipient fatigue failure of beams occurs at the fatigue strength of the outer fibers.

The test values reported in the references are obtained from small specimens that are fabricated and tested in the laboratory and do not simulate full-scale structures that are fabricated in shipyards and subjected to marine environment. Pertinent variables, the evaluation of which is beyond the scope of this study, include the size, shape and configuration of full-scale structures, shipyard welding procedures, Reference (2), slow surface corrosion together with slow or rapid discontinuous fatigue loading, plate shear fatigue and section-on-plate bending fatigue, salt water and salt air environment such as waves, wake, barnacles, etc., protective coatings (References (15) and (23)), and cumulative fatigue. The effects of each of these factors on the static and fatigue strengths of unwelded and welded alloys may be reasonably greater than normal test scatter. Evaluation of these variables is required for accurate prediction of the structural behavior of alloys. References (33), (34), (35) and (36) define procedures for evaluating cumulative fatigue damage. Consideration of varying stress ratios, maximum stress magnitudes, number of cycles at each stress level, rate of load application and removal, and actual expected stress-frequency spectra determines the actual fatigue behavior of materials and structures.

The test data produces very wide scatter bands. Much of the scatter is typical for fatigue tests, and much is due to the many variables previously discussed. In cases where the data was considerably higher or lower than the general trends, it was usually possible to attribute this to variations in test procedure, specimen preparation, etc., in which cases the data was not included. Statistical evaluation of the data is required in order to develop design fatigue curves for aluminum alloys. This type of analysis is very important, since it appears that the scatter of aluminum fatigue data is greater than with steel, which could affect the selection of safety factors.

It now becomes necessary to reduce the data shown on Figures 3 through 9 to a set of design fatigue (S-N) curves for the various aluminum alloys under consideration, which will be suitable for use in comparing the hull structure of a large aluminum hull with that of an equivalent mild steel hull. This process involves reduction of the variables presented in Figures 3 through 9 to obtain a single curve for each alloy, for comparison to an equivalent steel S-N curve. Figure 10 contains such design curves, which are based upon the welded strength with bead on, using the average of $R = 0$ (zero to maximum stress) and $R = -1$ (complete reversal), and disregarding notch effects and salt water spray. The rationale for this approach follows.

The choice between welded and unwelded values is fairly straightforward, since the lower welded strengths would govern the design of a typical ship structure for both cyclic and short-term loading. This approach is somewhat conservative, in that the reduction in fatigue strength for aluminum due to welding is proportionally greater than that for steel.

The fatigue strength of both aluminum and steel is improved by removing the weld bead of full penetration butt welds. However, this represents an idealized condition which can not be economically achieved in ship construction. Cold working of fillet welds by peening will increase their fatigue strength, but again this represents an unreasonable fabrication requirement. Therefore it must be assumed that "bead on" values are more appropriate for typical ship structures.

For the idealized ship's hull girder bending on a trochoidal wave, it would be expected that fully reversed cyclic stress values ($R = -1$) would apply. However, as shown later, the actual life cycle-stress histogram of a bulk carrier lies between the cases of $R = -1$ and $R = 0$ (from zero stress to maximum tension or compression) because of the effects of the relatively high still water bending moment. Similarly, local structures seldom experience fully reversed stresses due to various combined loading conditions; i.e., bending plus compression or tension. Pending a more complete evaluation of this problem, it is proposed to use the average of the values for $R = 0$ and $R = -1$.

The quantity of data on the effects of notches of various types on fatigue strength is far too limited to derive general design curves at this time. In addition, it is not possible to relate the stress concentration factors prevalent in typical ship structures to the test data now available. The use of bead-on data reflects the notch problem; thus it is proposed to neglect additional stress concentration effects.

As noted previously, salt spray significantly reduces the fatigue strength of steel and, to a greater degree, aluminum. However, this effect is not being considered in this study for several reasons. First, the highly-stressed portions of the hull girder would be subjected to direct salt spray during relatively small percentage of their operating life. The bottom, for example, is totally immersed, while the deck would experience spray in the highly stressed midship portion only a small percentage of the time. Current salt spray fatigue data is based upon continuous exposure, and it is probable that the effects of salt spray are exponential. For a given reduction in exposure time, the reduction in strength degradation would be far less. Secondly, the relative depth of surface pitting and loss of thickness of thin test samples for a given period of exposure would be far greater than for the thick plates of a bulk carrier hull, which may reduce the net section loss in area. In conclusion, it does not appear that the salt spray data in Figure 9 is applicable to typical ship structures in a normal life-cycle sea environment. However, it is not intended to minimize the problem. As shown in Figure 9, a sufficient concentration of salt spray can effectively destroy the stress-carrying capabilities of aluminum alloys at a large number of cycles. Thus this problem warrants considerable future attention.

Figure 10 indicates that the S-N curves of the various aluminum alloys have approximately the same shape, with initial strength corresponding to the bead-on values of welded ultimate tensile strength of Table 4 reducing to between 6 and 9 KSI at $10^8$ cycles. Based upon the curves of Figure 10, the gross area under the S-N curves of the aluminum alloys relative to that of mild steel are as follows:

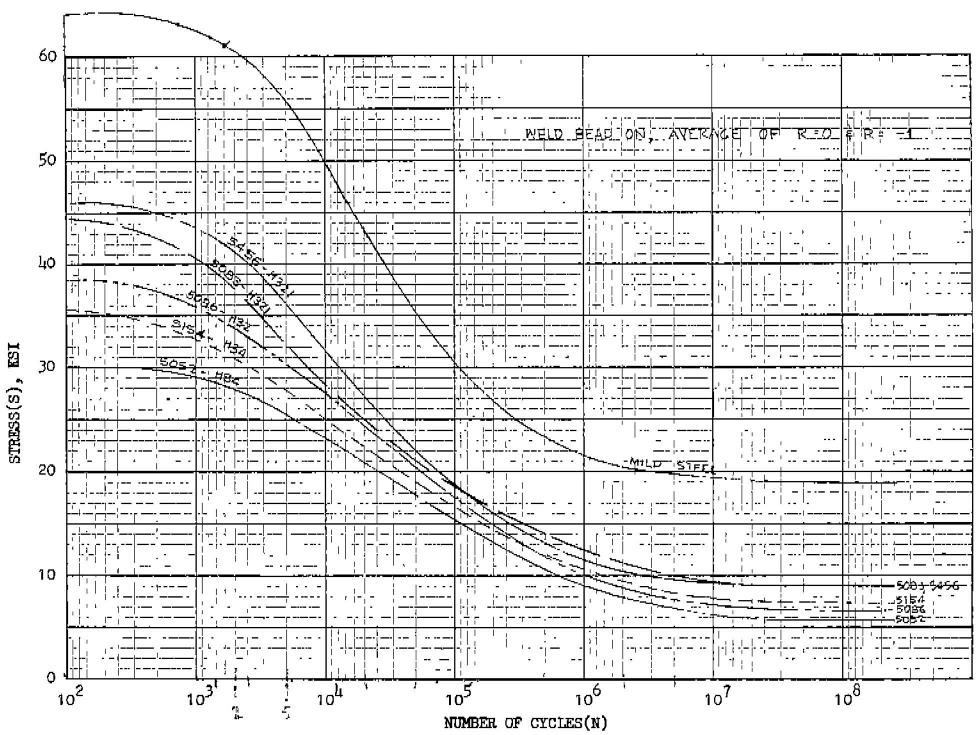



FIG. 10 Recommended S-N Fatigue Curves for Welded 5000 Series Aluminum Alloys and Mild Steel for Design of Ship Structure

| | | |
|---|---|---|
| 5456-H321 | = | 0.48 |
| 5083-H321 | = | 0.48 |
| 5154-H34 | = | 0.43 |
| 5086-H32 | = | 0.38 |
| 5052-H34 | = | 0.33 |

Thus 5456-H321 and 5083-H113 are essentially equivalent, with just under one-half the total life-cycle fatigue strength of mild steel, while 5154-H34 and 5086-H32 are essentially equivalent with three-eighths the life cycle fatigue strength of mild steel.

The foregoing discussion has been limited to plate and sheet tempers, with no consideration given to corresponding extrusion tempers, H111 or H112 in most cases, due to lack of data. A review of the data in Tables 2 through 4 indicates that the welded ultimate tensile strengths of plate and extrusion tempers are generally identical. Therefore, until further data can be developed, it is proposed to use the fatigue curves of Figure 10 for both plate and extrusion tempers.

Toughness

Test data used to evaluate the toughness of 5000 series aluminum alloys was obtained from References (10), (13), (16), (17), (18), (21), (37) and (38). Toughness describes the resistance of a material to fracture without reference to the specific conditions or mode of fracture and includes notch toughness, fracture toughness and tear resistance. Notch toughness is closely associated with the resistance of a material to the initiation of fracture, and describes the ability of a material to undergo local plastic deformation in the presence of stress-raisers, i.e., cracks, flaws or design discontinuities, without crack initiation; thus distributing loads to adjacent material or components. Fracture toughness describes the resistance of a material to unstable crack propagation at elastic stresses or to low-ductility fracture of any kind and does not generally involve resistance to crack initiation but only to the unstable propagation of an existing crack. The term tear resistance is generally applied to data obtained from tear tests and is a measure of the relative resistance of a material to the development of fracture in the presence of a tear-type stress-raiser.

Various dynamic tests are used to evaluate the toughness of 5000 series aluminum alloys. References (10), (16) and (17) present test results from tensile impact specimens; Reference (17) presents test results from Charpy keyhole impact specimens; Reference (18) gives test results from bending impact specimens; Reference (21) gives test results from notch-tensile specimens and tear specimens; Reference (13) gives test values from tear specimens. References (37) and (38) describe numerous theoretical and experimental procedures used to evaluate the toughness of aluminum alloys, correlation of the procedures, determination of relative toughness levels for aluminum alloys, and quantitative comparison of aluminum and steel fracture strengths which are beyond the scope of this study.

Figure 5 of Reference (21) presents the relative unit propagation energy, tear-yield ratio and notch-yield ratios of various 5000 series alloys, in both the unwelded and O-temper condition. The quantitative values are relatively unimportant for this study, since they can not be directly compared to equivalent values for steel. However, the qualitative toughness is meaningful in evaluating the relative merits of the various alloys. Table 5 presents the relative over-all tear and notch toughness of these alloys, based upon a maximum of 10.

TABLE 5 Relative Toughness of 5000 Series Aluminum Alloys

| Alloy and Temper | Relative Toughness | |
|---|---|---|
| 5083-0 | 8 | Avg = 6 |
| 5083-H321 | 4 | |
| 5086-0 | 8 | Avg = 7 |
| 5086-H32 | 6 | |
| 5154-0 | 10 | Avg = 8 |
| 5154-H34 | 5 | |
| 5454-0 | 10 | Avg = 8 |
| 5454-H32 | 6 | |
| 5456-0 | 7 | Avg = 6 |
| 5456-H321 | 5 | |

The following conclusions summarize the evaluation of toughness of the 5000 series aluminum alloys.

1. The notch toughness, fracture toughness and tear resistance are generally acceptable for structural applications.
2. Toughness of aluminum is inversely proportional to the ultimate or yield strengths of the various alloys, and increases with greater elongation.
3. Relative values of notch toughness, fracture toughness and tear resistance for unwelded and welded aluminum compare favorably with values for steel for single load applications.
4. Greater number of tests, standardization of theory and tests, and correlation of theory with tests are required to evaluate quantitatively the toughness of aluminum alloys.

## Buckling Strength

The column and panel buckling strengths of aluminum alloys are recognized as being significant design constraints under some circumstances, due to the lower elastic modulus of the material. However, the buckling behavior of aluminum is well documented, and can be readily incorporated into the design of ships structures based upon presently-available design procedures. Sources for design data on buckling include the design handbooks published by the various aluminum manufacturers and U.S. Navy Design Data Sheet 9110-4 "Strength of Structural Members" which presents curves of column strength versus slenderness ratio and plate panel buckling properties as a function of breadth/thickness ratio.

In the design of aluminum columns, the following applies:

(a) Members welded at the ends and butt-welded outside the middle 3/5 length may be designed on the basis of the yield strength of the prime (unwelded) metal.

(b) Members with butt-welds within the middle 3/5 length should be designed on the basis of 0 temper or annealed yield strength. In this case, the curve of column strength versus slenderness ratio has a horizontal cutoff in strength at the annealed yield strength of the material.

(c) Members with partial or continuous longitudinal welds may be designed on the basis of an average stress, where the annealed or O temper values apply to material within a 1-1/2 inch radius of the weld and the prime values apply elsewhere:

$$F_{c_{avg}} = F_{c_{prime}} - \frac{A_{annealed}}{A_{prime}} \left( F_{c_{prime}} - F_{c_{annealed}} \right)$$

where $A_{annealed}$ and $A_{prime}$ are the respective cross sectional areas.

Similar considerations could be applied to the design of aluminum plate panels subject to compressive buckling loads. In general, welding does not affect the buckling characteristics of plate panels, since there is seldom welding in the middle of a panel. However, for welded aluminum structure, the cut-off panel strength for low $k \frac{b}{t}$ ratios should be based upon the "welded" strength.

One aspect of buckling which is often overlooked in the design of ship structures relates to local instability of framing members. Because of the low modulus of elasticity of aluminum, normal proportions of beams and flanged plate girders which are commonly used for steel ship structures are unacceptable for aluminum sections, since local instability of the flange or web may result. In the selection of framing member scantlings, the following limitations should be met if the member is to be capable of resisting stresses approaching the yield strength of the material:

(a) $\left[\frac{\text{Flange width}}{\text{Flange thickness}}\right]$ for angles, flanged plates $\leq \frac{1}{2} \sqrt{\frac{E}{F_y}}$

(b) $\left[\frac{\text{Flange width}}{\text{Flange thickness}}\right]$ for tees (web at ℄ flange) $\leq \sqrt{\frac{E}{F_y}}$

(c) $\left[\frac{\text{Web depth}}{\text{Web thickness}}\right] \leq 2 \sqrt{\frac{E}{F_y}}$

where E is the modulus of elasticity ($10 \times 10^6$ PSI)
$F_y$ is the unwelded yield strength of the alloy

For structural sections meeting the foregoing requirements, the maximum span between supports should not exceed the following limits to prevent over-all lateral instability:

$$\frac{\text{span}}{b_F} \leq \frac{1.283 \sqrt{E / F_y}}{\sqrt{1 + 0.2\,(d/b_F) - 0.128\,(b_F/d)^2}}$$

where $b_F$ = flange width for tees; twice the flange width for angles and flanged plates
d = depth of section

This equation is derived from DDS 9110-4. If this distance is exceeded, an intermediate chock should be provided to prevent tripping of the section.

Corrosion Resistance

The 5000 series aluminum magnesium alloys are generally considered to have excellent resistance to corrosion in a salt air/salt water environment if reasonable precautions are taken to protect the metal. The characteristics of aluminum which might lead to corrosion are well documented, References (39) through (45). The following paragraphs briefly summarize the potential types of corrosion and the conditions leading to them.

Galvanic Corrosion is caused by dissimilar metals in contact in the presence of an electrolyte such as salt water. Aluminum is generally anodic to other materials and will be the metal to corrode. This corrosion is due to the different potential in electrical contact between the metals, which results in the transfer of ions through the electrolyte. Hull cathodic protection can be provided by sacrificial zinc or aluminum anodes on the shell, bilge areas, piping systems in tanks and sea chests or an impressed current system, as discussed later.

Deposition Corrosion is a special case of galvanic corrosion where particles of the more noble metal are deposited on the aluminum, which then pits. Copper and mercury are particularly bad in this respect, and contact of aluminum with these metals should be avoided.

Crevice Corrosion results from trapped water in crevices causing pitting due to the anodic reaction between the oxygen-free water deep in the crevice and the oxygen-saturated water at the mouth of the crevice. Crevice corrosion can be avoided by eliminating pockets, crevices, lapped joints and other similar conditions where water can become trapped. In areas where such a condition is unavoidable, such as the faying surface between aluminum foundations and equipment, the aluminum surface should be protected with a suitable paint system or sealant.

Pitting Corrosion occurs in water when only a small area of protective oxide or paint is removed from the aluminum surface. Once started, the pitting tends to continue, though at a diminishing rate. The damage to the aluminum oxide film is self-healing, even underwater. However, the loss in paint area might not be repaired for a long period of time. This leads to the conclusion that painting of the aluminum structure should be avoided except where required, such as anti-fouling paint for the bottom. As recommended later, a cathodic protection system is recommended to prevent pitting corrosion in way of scratched anti-fouling paint.

Stress Corrosion is cracking which occurs over a period of time as a result of a susceptible metallurgical structure, sustained surface tensile stress and a corrosive environment. The imposed stresses may be residual or externally applied. In strain-hardened Al-Mg alloys, precipitation occurs over the years, and in high-magnesium alloys (over 4 per cent), this susceptibility may develop in 5 to 10 years or less. Susceptibility to stress corrosion cracking (SCC) becomes worse at elevated temperatures. Reference (43) notes the following relative to 5000 series alloys: 5052, 5252 and 5454 have low susceptibility to SCC, and 5454 (Mg content 2.7 per cent) has low susceptibility at temperatures above 150 degrees F. Alloy 5154 (Mg content 3.5 per cent) is satisfactory at room temperature, but not at temperatures above 150 degrees F. Alloy 5086 (Mg content 4.0 per cent) is similar to 5154.

Alloys 5083 and 5456 (Mg contents 4.5 and 5.1 per cent respectively) are somewhat susceptible to SCC, particularly at elevated temperatures. In the O temper, thermal treatment for 4 hours at 450 degrees F is suggested to relieve residual stresses. H321 temper has no tendency toward SCC if cold formed to a sufficiently large radius. For smaller radii (less than 5t), hot forming or stress relief in way of cold forming is recommended for 4 hours at 450 degrees F. This method of stress relief is not recommended for welded assemblies inasmuch as it can lead to susceptibility to SCC. Temper H311 is only recommended for alloy 5456, subject to the forming limits and stress relieval practices noted for 5456-H321. Tempers H32 and H34 are susceptible to SCC with either alloy and are not recommended.

Microbiological Corrosion. Corrosion has been observed in aluminum aircraft fuel tanks due to accumulations of microbes found in the fuel residue at the bottom of the tank. These problems occurred with 7000 series alloys, and have been solved with fuel additives. Experience to date indicates no comparable problem with 5000 series alloys exposed to marine grade fuels.

Combustion Products. If soot is allowed to stand on the decks of an aluminum ship, the soot deposit will act as a cathodic metal and produce pitting of the aluminum. Experience to date with 5000 series alloys indicates that the intensity of pitting from combustion products is not severe, though frequent washdown of deck surfaces is recommended.

Exfoliation or intergranular corrosion results from excess magnesium precipitating into the grain boundaries causing separation of the material along grain boundaries. This form of corrosion is most pronounced in high magnesium alloys, primarily 5456, and appears to affect plates (temper H321) more than extrusions (temper H111). The problem was brought to light recently due to plating exfoliation in bilges and wet areas of U. S. Navy partrol boat hulls operating in Southeast Asia. The aluminum industry undertook a program to investigate the causes of exfoliation and means of preventing or inhibiting it, including the test program discussed in Reference (44). This program led to the development of the H116 and H117 temper, now available with alloys 5086 and 5456. These tempering processes are expected to eliminate the exfoliation problem, though service experience with the new tempers is very limited at this time.

Summary. In summary, it may be concluded that 5000 series alloys have satisfactory corrosion characteristics in a salt water environment when conventional precautions are taken to avoid conditions promoting corrosion. The lower magnesium content alloys such as 5052, 5454, 5154 and 5086 are somewhat less susceptible to stress corrosion and exfoliation than the high magnesium content alloys.

Tables 6, 7 and 8, derived from Reference (45) indicate that exposure of welded and non-welded samples of 5083 and 5086 alloys to sea water immersion for five years produced a maximum depth of attack of only .008 (8 mils) with no significant loss in tensile strength, yield strength or elongation. Other 5000 series alloys would yield results in this same range. For a ship's hull, assuming a 20 year life, the average loss in thickness would be between 10 and 12 mils, which is considered negligible.

TABLE 6 Sea Water Immersion Tests (5086-H34)

| Exposure Time | Average Depth of Attack Inches | Per Cent Change in Strength |
|---|---|---|
| 2 Years | .001 | 0 |
| 5 Years | .003 | 0 |

TABLE 7 Corrosion Resistance of Aluminum Alloys to Tide Range Sea Water Immersion - Seven Years' Exposure

| Alloy & Temper | Location Tensile Samples | Per Cent Change in Strength* | |
|---|---|---|---|
| | | Tensile Strength | Yield Tensile |
| 5083-0 | Totally Immersed | -2 | 0 |
| | Water Line | -3 | -2 |
| | Splash Zone | -6 | -2 |
| 5083-H34 | Totally Immersed | 0 | 0 |
| | Water Line | 0 | 0 |
| | Splash Zone | -3 | 0 |
| 5086-0 | Totally Immersed | -2 | 0 |
| | Water Line | -2 | 0 |
| | Splash Zone | -3 | 0 |
| 5086-H34 | Totally Immersed | 0 | 0 |
| | Water Line | 0 | 0 |
| | Splash Zone | -1 | 0 |

(* Per cent change negative (-) indicates apparent loss)

TABLE 8 Resistance of Aluminum Alloy Weldments to Corrosion In Sea Water - Five Years' Exposure

| Alloy & Temper | Test Condition * | Per Cent Change in Strength ** | |
|---|---|---|---|
| | | Ultimate Tensile | Yield Tensile |
| 5083-H113 | Beads Intact | -6 | 0 |
| | Beads Removed | 0 | -2 |
| | Non-Welded | -2 | -14 |
| 5086-H32 | Beads Intact | -2 | 0 |
| | Beads Removed | -8 | 0 |
| | Non-Welded | -2 | 0 |
| 5154-H34 | Beads Intact | 0 | 0 |
| | Beads Removed | -2 | -3 |
| | Non-Welded | -2 | 0 |
| 5356-H112 | Beads Intact | -2 | 0 |
| | Beads Removed | -1 | 0 |
| | Non-Welded | -2 | -1 |

* MIG welded with 5356 filler alloy.
** Per cent change negative (-) indicates apparent loss.

The previous paragraphs have dealt with the reaction of aluminum alloys to a salt water/salt air environment. It is also necessary to consider the corrosive effects of potential bulk cargoes on aluminum as well as the possibility of contamination of the cargo by the aluminum. Reference (46) reviews the compatibility of aluminum with a wide range of foods and chemicals, and Reference (47) summarizes extensive tests of the corrosion resistance and potential product contamination of 5000 series alloys.

In general, aluminum is superior to mild steel in resisting the corrosive effects of potential bulk cargoes, and in all cases would present less danger of product contamination. This results from the tenacity of the oxide film which forms on aluminum, which is extremely thin and self-healing when scratched or abraded. This film is attacked by some fluorides and chlorides, and heavy metals (tin, mercury and copper) are unusually harmful.

Table 9 indicates the corrosion resistance of 5000 series aluminum alloys relative to steel. The "A" rating indicates equal to or better than steel, while an AA rating indicates superior performance with no significant corrosion. A rating of U indicates that aluminum is unsatisfactory for this service.

In summary, aluminum is compatible with all potential dry bulk cargoes with the exception of copper, tin or mercury ores, potassium carbonate, potassium hydroxide and trisodium phosphate. Precautions should be taken with cargoes of aluminum fluoride, aluminum sulphate, lime and ferrous ores to minimize moisture within the hold, and the holds should be cleaned regularly to minimize build-ups of cargo residue.

Abrasion Resistance

Experience with bulk carriers indicates that abrasion can present a significant problem in several areas:

(a) The flat of bottom when the ship is engaged in a trade requiring navigation in shallow waters or across sand bars. An example of this is the bauxite trade in Surinam, where bulk carriers must cross a sand bar at the mouth of the Orinoco River and then navigate the shallow river. In this service, weardown of bottom plates occurs at an accelerated rate, generally resulting in renewal of bottom plates several times during the vessel's life.

(b) The bottom and sloping bulkheads in the cargo holds. Bulldozers and front end loaders are often used to consolidate and move the last of the cargo toward the center of the hatch to facilitate unloading by the grabs. In this process, the bottom and side bulkhead plating is subjected to severe abrasion, in addition to the impact loads resulting from unloading grabs and falling rock cargo.

The problem of bottom weardown due to abrasion is not recurrent except in a few specialized trades, such as the Orinoco River trade. Therefore this problem should not influence the design of a general service bulk carrier such as that presently being considered. For an aluminum bulk carrier in such a specialized trade, detailed studies of relative bottom weardown rates of aluminum and steel would be required, in conjunction with studies to determine the optimum balance between initial thickness and replacement costs.

TABLE 9 Relative Corrosion Resistance of Aluminum Alloys to Bulk Cargoes

| Product | Corrosion Resistance | Comment |
|---|---|---|
| Aluminum Fluoride | A | The presence of moisture can cause random attack when in contact over long periods (in excess of 2 weeks) |
| Aluminum Sulphate | A | Generally there is no problem since there is no free sulphuric acid present. Free acid would result in serious attack if moisture was present. |
| Ammonium Nitrate | A | - |
| Borax, Boric Acid | A | - |
| Cement | A | - |
| Coal, Coke | AA | Aluminum has a 2 or 3 to 1 advantage over steel, even with high sulphur content. |
| Fly Ash | A | Superficial surface attack only. |
| Forest Products | A | - |
| Grains | AA | Rice, wheat, corn, etc. cause no problem. |
| Gypsum | A | Slight localized attack if wet. |
| Lime | A | No problem with dry lime. Wet lime forms highly resistant protective film on aluminum. Should be satisfactory for intermittent service if the cargo is kept dry. |
| Limestone | A | It may be necessary to rinse residue from structure. |
| Nitrogen Fertilizers | AA | - |
| Oil (Crude and Refined) | AA | - |
| Ores | AA to U | Copper, tin and mercury ores should not be carried. In moist conditions, built-up residues of ferrous ores could cause corrosion. Bauxite, lead, phosphate, zinc and nickel ores present no problems. |
| Phosphate Fertilizers | - | Phosphate fertilizers cause mild etching. |
| Potash | A to U | Potassium chloride is similar to salt, causing no problems. Potassium carbonate and potassium hydroxide are highly corrosive and should not be carried. |
| Salt | AA | Highly concentrated salt water such as that found in bulk shipping cause less pitting than dilute solutions - no problem. |
| Sand, Gravel | A | - |
| Soda Ash | - | Initial attack on surface becomes arrested, and continued use in this service causes no major problems. |
| Sodium Chlorate | AA | - |
| Sodium Nitrate | A | - |
| Sodium Sulphate | A | - |
| Sugar | AA | - |
| Sulphur | AA | 3 to 1 advantage over steel. |
| Trisodium Phosphate | U | Not compatible. |

The problem of cargo hold abrasion is by no means limited, and must be considered carefully in the design of general service bulk carriers. Data on the relative weardown of aluminum and steel when abraded by sliding rock has been derived from References (48) through (51). These studies present weardown rates in heavy-duty aluminum dump truck bodies and compare the performance of aluminum and steel wear bars attached to the bottom of the truck body. This data is somewhat limited and must be extended to bulk carrier plating design with discretion. However, it serves as a basis for determining the ability of aluminum to resist abrasion from sliding rock cargoes relative to steel.

A typical heavy-duty aluminum truck body consists of aluminum plating between 3/4 and 1-1/4 inch thick. The bottoms are protected by a combination of steel plates and/or wear bars of steel or aluminum, on about 8 inch centers. The extent of protection is proportional to the hardness of the rock being handled. Actual truck body weardown rates are of questionable value due to the different nature of the services; however, relative weardown rates are meaningful in designing bulk carrier cargo areas.

The limited data presently available on the abrasion resistance of aluminum and steel indicates a relationship between increasing hardness and decreasing weardown rate. The trends are not yet well established, but it appears that the 5000 series alloys will abrade at approximately 4 to 5 times the rate of mild steel. There appears to be little difference between the abrasion resistance of the various 5000 series alloys, since their hardness values, noted in the following tabulation are not significantly different:

| | Brinell Hardness, 500-KG Load, 10-mm Ball | |
|---|---|---|
| Alloy | Unwelded (Hard) | O Temper |
| 5083 | 80 | 67 |
| 5086 | 72 | 60 |
| 5454 | 81 | 62 |
| 5456 | 90 | 70 |

As an indication of the relative abrasion allowance requirements of these various alloys, the equivalent of a .05 inch weardown in steel would vary from approximately .23 to .29 inches in aluminum depending on the hardness and chemistry of the alloy. The potential savings in thickness afforded by high-hardness 5000 series alloys does not appear to be sufficiently significant to warrant the use of one alloy in lieu of another solely on the basis of abrasion resistance.

The lower hardness in the O temper would imply that greater weardown would occur in way of welds, though no data has been found to confirm this.

Several of the 2000 series alloys having high unwelded hardnesses have proven to be about twice as abrasion resistant as the 5000 series alloys in truck body service. However, these alloys are not satisfactory in a marine environment and are much softer than 5000 series alloys in the heat affected zone.

Weldability and Workability

The welding of 5000 series alloys is accomplished with either the metal inert-gas (MIG) and tungsten inert-gas (TIG) process, both of which melt the aluminum at the weld line by heat from an arc struck between the electrode in the welding tool and the aluminum being welded. The weld area is protected from oxidation by a shield of inert gas such as argon, helium or a mixture of the two. Neither method requires flux, thus minimizing the possibility of porosity or corrosive residue. The methods are applicable to flat, horizontal, vertical and overhead welding, though downhand welding is fastest and of highest quality, as with steel. The fundamental differences between MIG and TIG welding is that with MIG welding, the aluminum filler wire serves as the electrode and is consumed, whereas the TIG process uses a non-consummable tungsten electrode, with filler metal provided in rod form, either manually or automatically. The MIG process is somewhat faster and more economical, but the TIG process produces a smoother bead, which is very important in maintaining high fatigue strengths.

Based upon discussions with aluminum fabricators and review of available literature, it appears that the weldability of 5000 series alloys improves as alloy magnesium content is reduced. The shipbuilding and boatbuilding industry presently favor 5086 alloys in preference to 5083 and 5456 alloys, which have approximately one-half and one per cent higher magnesium contents respectively.

Aluminum is somewhat more susceptible to weld distortion than steel, due to greater thermal conductivity. Heat fairing can be used to eliminate this distortion. However, when 5000 series aluminum alloys are heat treated to 150 to 200 degrees F for a sufficiently long period to allow heat fairing, the magnesium in the alloy migrates within the metal, which becomes susceptible to exfoliation. Heat fairing at higher temperatures for more limited periods may be used, providing the critical range is passed through quickly for both heating and cooling. However, this will result in the aluminum's properties being reduced to those of the annealed material, which may not be acceptable. Proper weld techniques (speed, heat input, number of passes, edge preparation, etc.) can minimize distortion problems.

It is generally preferable to use continuous welding for aluminum structures, even if strength considerations would permit the use of intermittent welding. Although intermittent welding reduces the quantity of electrode used and minimizes heat distortion, it can lead to crater cracking at the ends of beads and crevice corrosion if moisture is present. Therefore intermittent welding should be used only for secondary structures which are reasonably free from wetness, and are lightly loaded.

The problem of shrinkage in way of aluminum welds requires particular attention, since improper welding techniques can produce high residual stresses. These high stresses can lead to cracking, particularly when they occur in way of a poorly designed structural details. This is perhaps the most serious production problem to be overcome in the fabrication of large aluminum hulls, because experience in fabricating large aluminum weldments with thick plates is relatively limited. In nearly all cases of residual stress cracking of aluminum weldments, solutions can be found through improved design, testing and personnel training. Even with these precautions, however, it is vitally important that all structural details be very carefully designed and fabricated to eliminate sources of stress concentration. Among other things, this would require careful development of cuts in the hull girder, proper stiffener endings, elimination of excessive concentration of welding, including triaxial welds at intersections of three mutually perpendicular surfaces, avoidance of details which are difficult to properly fabricate, elimination of notches and hard spots, and location of welds away from highly stressed areas.

The question of residual stresses due to welding and fabrication presents a major problem area, in that they are difficult to predict and control. In the design of steel ship structures, the presently-accepted design loads and safety factors have provided a sufficient margin to account for most unknown factors in design, construction and life-cycle operation, including residual stresses resulting from welding. Unfortunately, there is no precedent to indicate that the relationship between residual and material yield stress will be comparable for steel and aluminum structures. In fact, the past experience with large aluminum weldments tends to indicate that the effects of residual stresses may be more severe with aluminum than with steel, because of the cracking that has been observed in way of improperly designed welded connections.

Proper cleaning of aluminum in way of welds is very important, to prevent porosity or contamination of the weld. The area must be cleaned just prior to welding, preferably by wire brushing or equal, to prevent reformation of the aluminum oxide film.

Most manufacturers of aluminum boats and structures find it desirable to accomplish welding in a protected environment, since moisture is detrimental to proper welding of aluminum and wind tends to disturb the shield of gas around the arc. Further investigation must be undertaken to determine the extent of environmental protection required for a large aluminum hull, since data is presently too limited to draw firm conclusions. These factors can not be overemphasized since nearly all cases of structural cracking of aluminum which have been observed have been the result of improper design or fabrication rather than an inherent weakness in the material. Consequently, it will be necessary to achieve a high level of quality control in designing and building a large aluminum hull.

Aluminum alloys of the 5000 series possess good workability characteristics, and can be easily formed, punched, cut, flanged, ground, and otherwise processed. In general, the ease with which alloys may be cold formed decreases with higher magnesium content. In cold bending aluminum, it is very important to maintain minimum bend radii in accordance with manufacturer's recommendations, to prevent cracking of the cold-worked area.

In summary, the weldability and workability of 5000 series aluminum alloys are considered satisfactory for large aluminum hulls subject to the following limitations:

(a) Additional investigation will be required to develop proper welding procedures to minimize residual stresses.

(b) Structural details must be very carefully designed and fabricated, as discussed previously, to eliminate hard spots, stress concentrations and other deleterious factors.

(c) The necessary environment for proper production of a large aluminum hull must be established. Pending proof to the contrary, it must be assumed that the environment in which an aluminum hull is fabricated must be more carefully controlled than with steel construction. However, the extent to which it must be controlled, including temperature and humidity limits, are not known at this time.

(d) Quality assurance procedures, particularly for checking welds, must be developed. It will be necessary to determine the level of weld porosity which can be accepted as degrading the strength of the weldment to a lesser degree than would a repair.

Alloy Material Cost

The final factor which must be considered in selecting an alloy is the raw material cost. A survey of aluminum manufacturers indicates that the base price of all common 5000 series plate or sheet alloys in large quantities will vary from about $0.50 to $0.55 per pound, depending upon width, length, thickness and manufacturer. However, all manufacturers questioned indicated that their individual base prices for 5000 series plates are identical.

The base price of all 5000 series extrusions except 5456-H111 will vary from about $0.62 to $0.66 per pound, with 5456-H111 costing about $0.04 per pound or about 6 per cent more. Since extrusions generally represent less than 15 per cent of the weight of an aluminum hull, this 6 per cent differential for 5456-H111 alloy has a negligible effect on the selection of alloys.

In conclusion, alloy material costs do not have a measurable effect on selection of alloys for the construction of a large bulk carrier. It is noted that specific instances will arise in which a fabricator can obtain low-priced plates or shapes of a particular alloy from a specific manufacturer's warehouse, based upon utilizing current inventory rather than placing a special order. This should not be a factor in this study, however, since the quantities, thicknesses, widths and lengths required for constructing a bulk carrier would warrant a direct shipment from the mill to the fabricator.

Selection of Alloys

The selection of an alloy or series of alloys for use in designing an aluminum bulk carrier, or, for that matter, any aluminum hull, is a very difficult process, particularly if the availability and basic cost per pound of the alloys is identical. This is due primarily to the fact that each alloy's advantages in a particular area are usually balanced by disadvantages of some type. For example, the alloys with high magnesium content such as 5083 and 5456 have high strength and would thus produce a lighter hull with lower material procurement cost and life cycle operating cost. However, these alloys present more problems in welding, cold working and corrosion than do the low-magnesium alloys such as 5052 and 5086. Achieving a proper balance between these factors is difficult, since it depends upon the individual designer's assessment of their relative importance.

In the process of selecting an alloy or series of alloys for the design of a bulk carrier hull, an assumed relative importance has been established for each of the factors considered in evaluating the alloys: static strength, including buckling, fatigue strength, corrosion and abrasion resistance, toughness, weldability and workability. Alloy costs were not included because of their similarity, and weight was not included directly since this factor is directly related to material strength, and is thus implicitly incorporated in the evaluation.

Each alloy was given a relative quantitative rating against these factors, based upon an evaluation of its relative merits, and a total rating was derived as shown in Table 10. Because of the necessarily arbitrary selection of weighting factors and relative ratings, a brief sensitivity study was conducted in which these factors were varied within reasonable limits. Although quantitative ratings did change, the qualitative results remain relatively consistent.

The values in Table 10 indicate that all of the alloys investigated are remarkably close in over-all scoring, which is consistent with the foregoing observation about the advantages of an alloy in one area being offset by its disadvantages in another. Based upon this, the selection of an optimum alloy becomes somewhat arbitrary. As a result of this study, the following alloys have been selected for plates and shapes respectively:

- 5083-H321 and 5083-H111 for all material in the primary hull structure. This is based upon its high ranking and the relatively low hull weight and material cost resulting from its relatively high strength. It is this material's properties which will determine required hull girder section modulus.

- 5086-H32 and 5086-H111 may be substituted for 5083 alloy for local structures if desired based upon its ease of fabrication, good corrosion resistance and good toughness characteristics.

- 5454-H34 and 5454-H111 for casings, stack and other areas subjected to high temperature (in excess of 150 degrees) unless these surfaces can be thermally insulated, in which case 5086 alloy can be used.

It should be noted that most of the 5000 series alloys considered could be satisfactorily used for the construction of the hull of an aluminum bulk carrier, though the alloys at the extreme ends of the spectrum (5052 and 5456) would not be recommended for use in the primary girder. The low welded strength of 5052 is not considered adequate for this application, and the high magnesium content of 5456 alloy creates potential problems such as susceptibility to stress corrosion cracking, potential corrosion problems, greater difficulty in welding and working, etc.

TABLE 10 Evaluation of Aluminum Alloy Characteristics

| Factor | Max.% | 5052 | 5083 | 5086 | 5154 | 5454 | 5456 |
|---|---|---|---|---|---|---|---|
| Static Strength (Welded) | 25 | 14 | 24 | 21 | 19 | 18 | 25 |
| Fatigue Strength (Welded) | 20 | 13 | 20 | 16 | 18 | 14 | 20 |
| Weldability and Workability | 25 | 25 | 17 | 21 | 22 | 24 | 16 |
| Corrosion Resistance | 15 | 15 | 10 | 12 | 12 | 15 | 10 |
| Impact Strength and Fracture Toughness | 10 | 9 | 8 | 10 | 9 | 8 | 6 |
| Abrasion Resistance | 5 | 2 | 5 | 3 | 3 | 3 | 5 |
| Total | 100 | 78 | 84 | 83 | 83 | 82 | 82 |

## IIB. OPERATIONS OF EXISTING ALUMINUM SHIPS

At this time, there are many vessels of various types in service which are constructed either partially or wholly of aluminum alloys. The service experience gained with these vessels is extremely helpful in predicting the long-term performance of an aluminum hull bulk carrier, and in avoiding problems which were incorporated in early designs.

One of the fundamental challenges in such a study is to separate problems which are inherent to the material from those which result from lack of experience, improper design or poor workmanship, and then to predict which are readily solved and which might reasonably be expected to occur under normal ship building or operational environments.

In conducting this phase of the study, the following primary sources of information were considered:

(a) U. S. Navy experience with deckhouses on destroyer type vessels.

(b) U. S. Navy experience with aluminum PGM gunboats, landing craft, "SWIFT" patrol boats and hydrofoils.

(c) U. S. Coast Guard experience with aluminum deckhouses on HAMILTON class cutters and others.

(d) Aluminum deckhouses on ocean liners and cargo ships.

(e) The aluminum cargo vessel INDEPENDENCE, operated in the Caribbean Sea.

(f) The aluminum trailership SACAL BORINCANO operated between Caribbean ports and Florida.

(g) Aluminum crew boats and fishing craft.

(h) Specialized applications, such as barges, LNG tanks, etc..

In evaluating the performance of these vessels, all available published reports were reviewed and in-depth discussions were held with owners, operators and builders,to determine the performance of aluminum alloy structures in a marine environment. Since much of the data derived in these discussions is considered proprietary, it will be necessary to present general comments and conclusions, without citing specific examples. However, where a specific observation appears to be unique to a particular service or set of circumstances, it will be so presented. In general, this review has been limited to applications in which 5000 series alloys and state-of-the-art design and fabrication techniques have been incorporated. Thus, for example, early problems with welded 6061-T6 deckhouses on Navy dstroyers have not been specifically considered. The problems associated with these deckhouses have been well documented and have been avoided in subsequent designs. They need not be reiterated as part of this study.

GENERAL OBSERVATIONS

Prior to a detailed review of the performance of existing aluminum structures in a marine environment, it is appropriate to make a few general remarks.

The basic metallurgy appears to be quite compatible with the salt water/salt spray environment when compared to competitive metals. To date, the problems which have occurred which relate to the basic metallurgy of the material are in three basic areas: corrosion, impact and abrasion, and localized cracking in way of structural hard spots or poorly developed details. Each of these areas is discussed in some detail below.

In general, all problems which have been encountered in the past have been or could be improved upon or solved by modifications to alloy properties, design or construction techniques. Unfortunately, it is not possible to fully extrapolate these observations to ships as large as the bulk carrier design presently being considered, based solely upon the performance of past designs. However, these observations will prove to be essential tools in deriving overall conclusions as to the feasibility of such a design.

CORROSION

As expected, a number of problems have occurred in existing aluminum vessels or steel ships with aluminum deckhouses, related to corrosion, particularly where the aluminum is in contact with a dissimilar metal. In general, these problems have occurred as a result of improper isolation of aluminum structures from either steel structures or non-aluminum piping or equipment, and/or inadequate cathodic protection, all of which have been or could be solved. The principal exception to this was the exfoliation problem experienced with the Navy's "SWIFT" boats.

The most prevalent corrosion problem to date has been in way of the connection between aluminum deckhouses and steel hulls. This joint is generally made quite close to the steel deck, so that it is often subjected to salt water spray. As the joint works due to relative hull-deckhouse motion, the fasteners loosen, allowing salt water to enter and corrosion to initiate. This problem was greatly reduced when the isolating material at the interface was changed from zinc chromate impregnated burlap cloth to neoprene or equal.

A further potential improvement is afforded by the bimetallic strips which are presently becoming available. These strips consist of layers of aluminum and steel which are explosively or chemically bonded together, to which the respective aluminum and steel ship structures can be welded. These strips offer a number of advantages:

(a) Joint efficiencies of 100 per cent based on the O-temper properties of the aluminum.

(b) Minimum joint slippage.

(c) Corrosion characteristics which have been shown experimentally to be very good, even at the interface of the steel and aluminum.

The use of these bimetallic connection strips should be given very careful consideration in future designs involving permanent connections to steel and aluminum. Present indications are that the initial cost of such a connection is somewhat higher than a conventional mechanically fastened joint, but life-cycle cost considerations may favor bimetallic strip connections if sufficiently large quantities of material are involved.

The exfoliation problem was discussed previously, and is well documented in numerous reports. At this time, it can be concluded that this problem has been solved by the introduction of new tempers for the high-magnesium alloys which exhibited the problem. The survey conducted in conjunction with this study found no significant evidence of exfoliation in commercial aluminum hulls. All of the known hulls which have experienced exfoliation were of 5456-H321 alloy, while the commercial hulls have generally been constructed of 5083, 5086 or alloys with lower magnesium content. Crew boats which were fabricated with 5086-H32 plating and were subjected to a relatively rugged operating environment and high panel stress levels have reportedly stood up very well, with no apparent evidence of exfoliation. This would lead to the tentative conclusion that 5086-H32 alloy is superior to 5456-H321 alloy with regard to exfoliation resistance, which is consistent with the higher magnesium content of the latter alloy. Fortunately, the foregoing discussion is now of academic interest only, since the recent introduction of the H116 and H117 tempers for both alloys has apparently solved the exfoliation problem.

Other areas in which corrosion has occurred as a result of improper isolation of aluminum from other metals include the following:

(a) Black iron piping systems in ballast tanks connected to aluminum bulkhead spools via rubber lined stainless steel sleeves. If the rubber lining is not properly installed, severe corrosion can be expected on the aluminum sleeves. Adequate cathodic protection is required within the ballast tank to protect the hull structure.

(b) Steel deck machinery must be well isolated from aluminum foundations, using butyl rubber, neoprene gaskets, plastic chocking, or equal. Painting both surfaces with red lead is not recommended.

(c) Miscellaneous minor details are often developed without consideration of isolation requirements. Minor piping systems, connections of hose racks and other miscellaneous outfit, etc., must consider these requirements, since minor details often create problems with critical structures.

(d) Corrosion and pitting has been observed in way of overboard discharges, indicating the need for local inserts. Other instances of localized pitting have generally been restricted to areas in which known galvanic couples have existed.

ABRASION AND IMPACT

Several instances have been noted in which steel mooring cables and anchor chains have caused moderate to severe abrasion of aluminum hull structures. Minor abrasion has also resulted from contact with wharves and pilings. This appears to be an inherent design problem with aluminum hulls which must be overcome by the proper location of mooring gear and ground tackle, as well as provision of expendable chafing strips where required. Abrasion of cargo decks has been a concern on crew boats, where heavy equipment and pipe is being handled. This is generally solved by fastening wooden protection strips to the aluminum deck.

The question of comparative impact resistance of steel and aluminum hulls is difficult to evaluate because there are relatively few cases in which a direct comparison is possible. However, the general opinion of crew boat operators and Navy personnel involved with equivalent aluminum and steel landing craft is that steel hulls possess somewhat greater resistance to impact loads than aluminum hulls. It is very difficult to evaluate such qualitative opinions. However, the lower modulus of elasticity of aluminum will result in greater apparent damage in aluminum than with steel, i.e., deeper dents and more gouging for similar impact loads. Since these factors do not necessarily relate to the residual strength of the structure after damage, it is very difficult to compare aluminum and steel in this regard. However, it can be concluded that sufficient impact resistance can be designed into an aluminum hull for a normal life cycle environment without an unacceptable penalty on weight or cost.

## LOCALIZED CRACKING OF STRUCTURE

A number of instances of cracking of aluminum ship structures have been observed, both in deckhouses and hulls of various sizes. In all cases which could be studied in detail, these cracks could be attributed to poorly designed or fabricated structural details rather than a fundamental weakness in the material. Among the cracking problems observed, the following examples are of particular interest.

(a) Plate cracks originating in the radius corners of uptake, vent and door cuts in aluminum deckhouses on destroyer type hulls.

(b) Weld cracking at the connection of highly loaded framing members where conventional merchant ship type details have been used, such as flanged plates lapped back to back. In many cases, the crack originated at the end of the weld beads where such beads could not be carried up into the intersection of the two members, as shown in Figure 11.

It is noted that such details can lead to cracking of steel structures also.

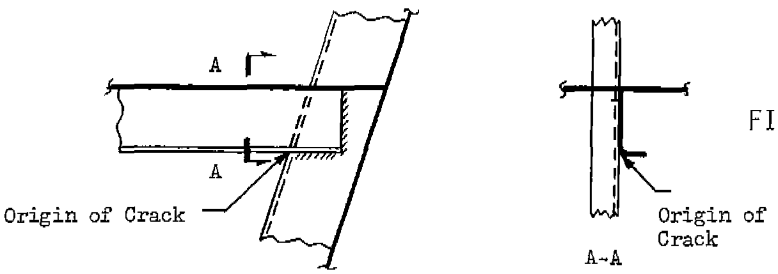



FIG. 11 Cracking in Way of Lapped Joint Between Flanged Plates

(c) Plate cracking at the end of stiffners where the hard spot was not relieved.

(d) Plate cracking in bulkheads where intercostal longitudinal girders were not aligned fore and aft of the bulkhead.

(e) Weld cracking at the ends of stanchions in the heat affected zone where the load transfer into the stanchion was not fully developed.

(f) Weld and plate cracking in way of impact damage on bottom or side shell.

(g) Cracking in the welds attaching highly loaded fittings, i.e., bitts, chocks, etc. to the hull.

These instances of structural cracking on existing aluminum ships or deckhouses lead to the following conclusions:

(a) Aluminum is more susceptible to such problems than steel, since the hardspots, discontinuities and poor welding details producing the stress concentrations invariably occur in either the weld of lower strength heat affected zone.

(b) Proper attention to the design of aluminum structural details is of paramount importance, particularly if the structure is to be highly stressed. Details should be designed so that access for welding is adequate all around. Continuous welding should be used in way of all connections of framing members, stanchions, etc. to avoid, or at least minimize, undercutting and radial shrinkage stresses at the end of the bead.

(c) Conventional merchant ship details for frame and beam connections should be avoided in aluminum construction since lapped brackets or overlapped framing members are hard to weld properly, and high stress concentrations can result at the discontinuity of these members. Navy-type details, though more expensive initially, should be less expensive in the long run, since failures are less likely to occur.

(d) Careful attention must be paid to the stress flow in aluminum deckhouses. Discontinuities such as large openings and inadequate attachment to the steel hull will result in stress concentrations which will produce structural failure even when the theoretical stress levels are relatively low. The transfer of loads between deckhouse and hull must receive special attention, particularly at the fore and aft ends of long deckhouses.

(e) All longitudinally effective structure in an aluminum hull or deckhouse must be continuous through transverse structure.

## REPAIRS

Several owners or operators have noted the difficulty in obtaining high quality repairs of aluminum structures. In many cases, the repair work does more harm than good, since bad welding applied to a cracked or highly stressed structure seldom remains sound. The basic problems seem to relate to the following factors:

(a) Unqualified welders working in a bad environment.

(b) Lack of proper surface or edge preparation in way of welds.

(c) Insufficient access for the welding gun.

(d) Poor quality welds due to moisture inclusion or porosity, often resulting from wind disturbing the shielding envelope of gas around the weld arc.

(e) Improper weld sequence resulting in high residual stress.

MAINTENANCE

General maintenance of aluminum hulls has reportedly been excellent. In many cases, the aluminum above the water line is unpainted, and only requires an occasional washdown with fresh water. The tendency of unpainted aluminum to streak and spot often leads to painting for aesthetic reasons, which can lead to problems if the coating breaks down locally, thereby tending to concentrate any corrosive or electrolytic attack. Hulls are generally painted with antifouling paint below the water line. Primer and tributyl tin oxide AF paint or other paints not containing cuprous oxide are generally used. These paint systems have stood up well, and when repainting is required, a careful sand washing is employed to remove old paint and barnicles.

SUMMARY

The operational experience with existing aluminum vessels and deckhouses has generally been satisfactory. All problems encountered in design, construction and operation to date have been or can be satisfactorily solved, and the practical experience gained can be applied to large aluminum hulls such as the bulk carrier under consideration. Undoubtedly, the most serious challenge to be faced in designing large aluminum ships is to avoid conditions which might lead to stress concentrations and subsequent cracking, since larger hulls will be more highly stressed than those now in operation.

## IIC. DESIGN CRITERIA FOR HULL STRUCTURE

The development of acceptable design criteria for the hull girder and local structure of an aluminum bulk carrier represents one of the most challenging and important considerations in this study. These criteria are fundamental in developing a technically feasible design, and require a thorough evaluation of the empirical and theoretical considerations leading to the steel scantlings presently required by regulatory bodies.

Design criteria have been developed for the primary hull girder structure and secondary structure to the extent necessary to fully demonstrate technical feasibility, including the following:

1. Hull girder section modulus at midships.

2. Hull girder moment of inertia at midships.

3. Primary hull structure: deck, tank top, shell plating and framing, longitudinal floors and girders, center vertical keel and web frames.

4. Secondary hull structure: bulkhead plating and framing, deep tank structure, deckhouses, etc.

Additional consideration is given to crack arresting and thermal stresses.

EXISTING CRITERIA

As a prelude to developing design criteria for an aluminum bulk carrier, an extensive review was made of existing acceptable procedures for developing aluminum structure for merchant and Naval vessels, including discussions with the American Bureau of Shipping, Lloyds Register of Shipping, Det Norske Veritas, Bureau Veritas, Registro Italiano Navale and the United States Navy. In general, these criteria are based upon conversion of proven steel scantlings to aluminum on the basis of relative strength or stiffness, particularly where steel scantlings are based upon emperical considerations. In the following paragraphs, these existing criteria are briefly presented and evaluated. It is noted that the Regulatory Body comments are very preliminary and subject to further review, and thus do not necessarily represent official policy.

American Bureau of Shipping - The first large aluminum vessel designed to ABS criteria was the trailership SACAL BORINCANO, completed in 1967. The design criteria used in converting steel scantlings to aluminum were published in the July 1967 issue of Marine Engineering/Log magazine. These criteria have been extended to the design of the ALCOA SEAPROBE, and are as follows:

(a) FOR PLATING:

$$T_{alum} = T_{steel} \times .80 \times \frac{60{,}000}{\text{Ult. Str of Alum.}} \quad \text{(unwelded)}$$

(b) FOR BEAMS:

$$SM_{alum} = SM_{steel} \times .80 \times \frac{60{,}000}{\text{Ult. Str of Alum.}} \quad \text{(unwelded)}$$

$$\Delta Alum \approx 1.5 \quad \Delta Steel$$

(c) FOR HULL GIRDER ($L/D \leq 15$):

$$I_{alum} = 0.9 \times SM_{steel} \times \bar{Y} \times 2.0$$

$$\text{where } \bar{Y} = \frac{\text{Hull Depth}}{2.03}$$

$$SM_{alum} = \frac{I_{alum}}{\bar{Y}} = 0.9 \times SM_{steel} \times 2.0$$

The factor of 0.80 is apparently a steel corrosion allowance which is not required for aluminum. The relationships for hull girder inertia are intended to limit the deflection of the aluminum hull to approximately 1.7 times that of the steel hull.

These criteria were developed by ABS for relatively small hulls, and would be subject to reconsideration for larger hulls in the area of low cycle fatigue, welding degradation, corrosion allowances and hull stiffness requirements. During discussions with ABS, they indicated that the limitation on hull girder stiffness is somewhat empirical, and that greater deflections would be considered, though the effects on shafting, piping and draft/freeboard relationships must be evaluated.

The ABS criteria noted above were used in the preparation of a preliminary midship section for an aluminum bulk carrier. The resultant weight per foot was approximately 55 per cent of that of an equivalent steel hull, while hull girder deflections would be increased by a factor of 1.75.

During the design of the Fast Deployment Logistic (FDL) ships, one of the criteria developed and approved by ABS for aluminum deckhouses was as follows:

(a) For plating designed primarily for lateral loading from wave slap, deck loads, etc.:

$$T_{alum} = .9\ T_{steel} \sqrt{\frac{UTS_{steel}}{UTS_{alum}}}$$

(b) For plating designed primarily for edge loading as might be induced by longitudinal bending or axial loads:

$$T_{alum} = .9\ T_{steel} \left(\frac{UTS_{steel}}{UTS_{alum}}\right)$$

(c) Framing

$$SM_{alum} = SM_{steel} \times \left(\frac{UTS_{steel}}{UTS_{alum}}\right)$$

$$I_{alum} = 2\ I_{steel}$$

where $UTS_{alum}$ is in the unwelded condition.

Lloyd's Register of Shipping.- In 1956, Lloyd's conducted a limited study of a 670 foot aluminum bulk carrier, to be built of 5083 aluminum alloy. The basic criteria at that time were as follows:

(a) Local plate thicknesses were increased by the square root of the ratio of material ultimate tensile strengths to provide equivalent safety factors. Assuming an ultimate tensile strength of 17 tons/in.$^2$ for the 5083 alloy and 29 tons/in.$^2$ for steel, this factor was 1.31.

(b) Local beam section moduli were increased by the ratio of the ultimate tensile strengths of steel to 5083 alloy or 1.71.

(c) Hull girder section modulus was also increased by a factor of 1.71.

No consideration was given directly to corrosion allowances, fatigue or notch toughness properties, welding degradation or yield strength. The resultant aluminum hull girder deflection was about 83 per cent greater than the steel hull.

These criteria with some modifications have been adopted into Lloyd's latest Rules for Aluminum Yachts, Reference (52), which require a 15 per cent increase in plate thickness and a 70 per cent increase in stiffener section modulus when substituting aluminum alloy for steel. These rules apply to aluminum alloys with a 0.1 per cent proof stress of 8 tons/in.$^2$, an ultimate tensile strength of 17 tons/in.$^2$ and an elongation in a 2 inch and 8 inch gage length of 12 and 10 per cent respectively.

The Lloyd's Rules relative to aluminum deckhouses require the following increases in scantlings:

| | |
|---|---|
| Fronts, sides, aft ends and unsheathed decks | 20 per cent |
| Sheathed decks | 10 per cent |
| Beams and stiffeners | 70 per cent |
| Scantlings of small isolated houses | 0 per cent |

These requirements are consistent with those discussed previously, and reflect a consideration of ratios of ultimate strength.

Recent discussions with Lloyd's relating specifically to the Aluminum Bulk Carrier project resulted in the following observations:

(a) A reduction in steel section modulus of 5 per cent should be accepted as a basis for converting to aluminum.

(b) Consideration must be given to low-cycle fatigue properties in relation to the hull's life cycle stress spectrum.

(c) Extensive radiographing of welds will be required to ensure proper reliability. Butts should be staggered as much as possible.

(d) Notch toughness is not considered a problem, and no crack arresting riveted seams are required.

(e) Hull girder deflection should generally not exceed that of a steel hull of equal length but with an L/D ratio of 16, i.e., $I_{alum} = SM_{steel} \times .95 \times 3 \times$ half-depth of ship. This requirement might be modified for this specific case, though both wave and still water deflection must be considered.

(f) Deflection of local aluminum beams may be 50 per cent greater than that of equivalent steel section.

Det Norske Veritas - DNV has no rules relating directly to aluminum structure at this time. However, they indicate that the procedures used in selecting high strength steel scantlings would be applicable to aluminum. These requirements convert mild steel scantlings to high strength steel by a factor which is based upon the ratio of yield strengths. Ultimate tensile strengths do not enter into the conversion directly, though lower limits are placed on the ratio of ultimate tensile strength to yield strength. For aluminum alloys, they would consider both ultimate and yield tensile strength ratios, assuming welded strengths of aluminum alloys, and the entire area under the stress-strain curve. They would deduct an appropriate corrosion allowance from the steel scantlings before converting, and would not require a corrosion allowance for aluminum. They would also not require riveted crack arresting seams for an aluminum hull.

DNV would consider fatigue in establishing hull girder section modulus by comparing the life cycle histogram of the stress level for combined wave and still water bending versus the number of cycles, with the fatigue strength (S-N) curve of the material. The relative areas under these curves would establish a safety factor which would be the same for both steel and aluminum.

Relative to hull deflection, DNV noted the possibility of resonance between the natural frequency of a flexible hull and period of wave-induced forces. They also noted the possibility of problems with flexibility of the double bottom, particularly if its frequencies are in resonance with those of the hull. The effects of cargo mass and entrained water must be considered when determining these frequencies.

Registro Italiano Navale - RIN experience relating to aluminum is presently limited to deckhouses and large LNG tanks. However, they indicated that the following considerations would apply to designing a large aluminum bulk carrier:

(a) Deduct a 10 per cent corrosion allowance from the steel hull girder section modulus before converting to aluminum.

(b) For the hull girder, fatigue would be considered by comparing relative strength of steel and aluminum at $10^2$, $10^4$ and $10^6$ cycles. The combined wave and still water bending stresses over the life of the hull would be compared to the fatigue characteristics for both materials. Both ultimate tensile strength and welded yield strength should be considered.

(c) Unstable propagation of a fatigue crack in aluminum should not occur. Therefore, crack arresting should not be required.

(d) Limitations on hull girder deflection for an aluminum ship may not be necessary, though greater permissible deflections require more careful consideration of low-cycle fatigue behavior.

(e) Particular attention is required to ensure proper welding, with no undercutting, and to prevent excessive weld distortion.

Bureau Veritas - The Bureau Veritas suggests a 10 per cent reduction in steel thicknesses for corrosion, and conversion of effective steel scantlings to aluminum on the basis of yield strength ratios unless the yield strength exceeds 0.6 times the ultimate strength, in which case ultimate strength must also be considered. Unwelded characteristics of aluminum alloys should be considered as long as the welded connections are well checked, and butts in the sheer strake, bottom and deck plate are staggered.

Bureau Veritas recommends that the deflection of the aluminum not exceed that of a steel hull with a length-depth ratio of 16.1, which is the maximum they permit.

U.S. Navy - The Navy's general specifications provide a working stress based upon the following equation for design of secondary structures subject to normal loading such as wave slap, deck loads, etc. on aluminum deckhouses:

$$\sigma_{alum} = \frac{1}{2}\left[\frac{\text{Welded Y.S. of Aluminum}}{\text{F.S. on Y.S. of Steel}} + \frac{\text{Welded UTS of Aluminum}}{\text{F.S. on UTS of Steel}}\right]$$

No direct credit is given for the corrosion resistance of aluminum, since reliance is placed on maintenance or protective coatings to minimize corrosion in steel.

Recent Navy studies of aluminum destroyers have been based upon an allowable hull girder stress of 4.5 tons/in.$^2$ for 5086 alloy when the ship is balanced on a wave equal to the ship in length and equal to $1.1\sqrt{\text{length}}$ for its height. This provides equivalent margins for secondary stress for aluminum and steel. No consideration is given directly to fatigue although this matter is presently under investigation. The deflection of an aluminum destroyer hull designed for the above criteria was limited to 1.5 times that of an equivalent high strength steel hull. This is not expected to produce binding at shaft bearings or problems with piping or other systems.

The Navy's design criteria for small, high performance craft include a requirement that hull bottom structure be designed for the welded yield strength at $10^7$ cycles when considering wave impact loading.

PROPOSED CRITERIA - HULL GIRDER SECTION MODULUS

The required section modulus of the hull girder at midships for steel merchant vessels has traditionally been determined on the basis of balancing the vessel statically on a trochoidal wave and equating the resultant wave bending moment to an allowable stress. This stress, generally around 8 tons per square inch, was arrived at empirically, based upon the successful performance of many previous designs. During the last decade, rapid growth in the size and number of super tankers and large bulk carriers has prompted the regulatory agencies to reconsider their requirements for hull girder strength. This has been possible because of recent developments in the science of oceanography and sea spectrum analysis, which have made it possible to predict life-cycle hull girder stress patterns with acceptable accuracy, and to relate these to the fatigue characteristics of the material.

The state of the art in hull girder stress analysis has not yet advanced to the point where a truly classical structural design is possible. At this time, the process of hull design is essentially one of working backwards, comparing proven, acceptable scantlings with more sophisticated load inputs and resulting moments and shears to determine the range of safety factors which have provided satisfactory designs in the past.

Based upon the above limitations, it will be necessary to determine the aluminum hull section modulus on the basis of converting acceptable steel scantlings, maintaining equivalent safety factors. In this process, the following factors apply:

Steel Hull S.M. - For this study, the base line steel hull girder section modulus will be based upon the latest requirements of the American Bureau of Shipping.

Corrosion Allowance - Present data indicates that the loss in aluminum shell and deck thickness due to salt water corrosion will be negligible over a 20 year lifetime if the selection of alloys, cathodic protection and isolation of dissimilar metals are suitable. For the equivalent steel hull, the corrosion anticipated by ABS can be derived from the allowance which they permit for steel protected by an approved corrosion control system, such as inorganic coatings. This allowance is 10 per cent or 1/8 inch, whichever is less, for the exposed side shell and deck plating. It is noted that the ABS equations for converting mild steel to HTS steel consider corrosion allowances of .12 inch for tank top, deep tank and double bottom girder plating, and .17 inch for exposed shell and deck plating. Since these latter values are deducted from the mild steel scantlings prior to conversion and are then added back to the HTS, it is slightly conservative to apply the higher allowances in converting from MS to HTS. However, where an allowance is being deducted from steel which will not be added back to the aluminum scantlings, the 1/8 inch or 10 per cent allowance is more appropriate. Therefore, in converting from steel to aluminum, an "effective" steel midship section will be derived by deducting 1/8 inch or 10 per cent from bottom and side shell and exposed deck plate. A lesser allowance of 1/16 inch will be deducted from all other longitudinally effective structure.

Short-Term Loading - In considering short-term loading, it is desirable that the aluminum and steel hulls have the same safety factor when experiencing the maximum combination of wave and still water bending moments. For a constant hull girder bending moment, this can be expressed by the relationship in Equation (1):

Equation (1): $$\text{Hull } SM_{alum} = SM_{steel} \text{ (effective)} \times \frac{97,000}{Y + U}$$

Where Y is the minimum welded tensile yield strength at 0.2 per cent offset with 10 inch gage length of the aluminum alloy, in PSI, with bead on, from Table 3.

U is the welded ultimate tensile strength of the aluminum alloy plus one-half the specified range, in PSI, or the average ultimate tensile strength from Table 4.

For alloy 5083-H321 plate the minimum welded yield and average ultimate tensile strengths with bead on are 24 and 45 KSI respectively. Corresponding values for 5083-H111 extrusions are 21 and 45 KSI respectively. Using these values in the above equation results in the following relationship:

Hull S.M. for 5083-H321 = 1.40 x effective Steel Hull S.M.
Hull S.M. for 5083-H111 = 1.47 x effective Steel Hull S.M.

The above equation gives equal ranking to yield and ultimate strengths, and is based upon minimum values of Y and U of 32000 PSI (minimum) and 65000 PSI respectively for structural steel meeting ASTM A131-61. The relative importance of yield and ultimate strengths has been the subject of wide debate, and a review of the previous discussion on existing criteria indicates that there still are differences in opinions. Therefore, the equal ranking proposed above, which is consistent with present ABS criteria in converting mild steel scantlings to HTS, is considered appropriate at this time, but requires further study.

The one factor which has not been addressed in the above equation is the relative elongations of the two materials. For hull-grade steel, the minimum specified elongation in 2 inches is 24 per cent, while that of the 5000 series alloys is 12 per cent for the unwelded metal and 15-20 per cent for the welded condition. By inspection, therefore, the unwelded case would be more critical if elongation were to be considered as a limiting factor. Referring to the typical stress-strain curve in Figure 12 below, two areas are considered: The area under the curve in the elastic range, and the area between the yield and ultimate strengths, designated $A_1$ and $A_2$ respectively:

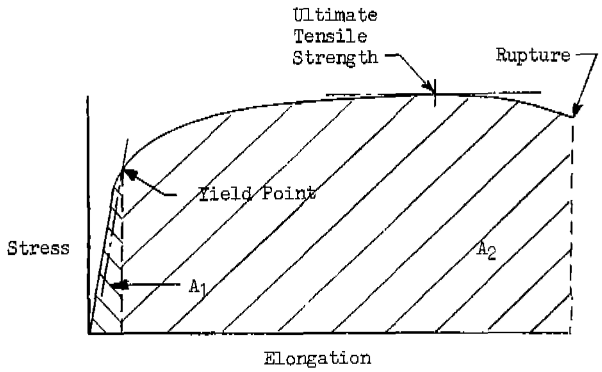



FIG. 12 Stress-Strain Relationships for Aluminum

The areas $A_1$ and $A_2$ are both important in studying the overall response of a material to loading, even though $A_1$ is far smaller than $A_2$. These areas represent the quantity stress times elongation, which is proportional to force times distance, or work. Area $A_1$ therefore represents the work required to exceed the elastic limit of the material, and falls within the area in which structures are normally loaded. Within this area, at any given stress level, aluminum has a 3 to 1 advantage over steel because of its lower modulus of elasticity.

The area $A_2$ represents the work associated with the plastic strain energy of the material, between the elastic range and rupture. In this area, due to its greater elongation, steel has an approximate 2 to 1 advantage over aluminum.

If it is assumed that the importance of areas $A_1$ and $A_2$ is identical, which is implicit in the Equation 1, it is apparent that aluminum's advantage in the elastic zone more than offsets its lower total elongation. Thus, differences in material elongation do not directly affect Equation 1.

Long-Term Loading - Long-term loading implies consideration of the anticipated stress levels which the hull will experience throughout its life, in conjunction with the low cycle fatigue strength of the hull material. For this specific study, the following procedure has been adopted:

(a) Estimate the life cycle histogram, bending moment versus number of cycles, for the steel bulk carrier, and convert this to equivalent bending stress, based on the steel hull girder section modulus as built.

(b) Develop a fatigue (S-N) curve for hull steel, ASTM A131-61.

(c) Determine the ratio of fatigue strength to hull girder bending stress throughout the life of the vessel. This can be considered a safety factor on fatigue failure.

(d) Apply these same ratios to the S-N curve of the selected aluminum alloy, thus establishing a curve of allowable life cycle bending stress for the aluminum hull girder.

(e) Determine the area (A) under the two life-cycle bending stress curves. The required hull girder section modulus to satisfy fatigue requirements is then as follows:

Equation (2): $\text{Hull SM}_{alum} = \text{Hull SM}_{steel} \text{ (as built)} \times \frac{A_{steel}}{A_{aluminum}}$

It is noted that the actual S.M. of the steel hull is used rather than the "effective" S.M., reduced for corrosion allowance, since the conversion of life-cycle moment to stress was based upon the actual S.M.

Considerable investigation is required to establish a general life cycle historgram of hull girder stresses for a bulk carrier, considering combinations of still water and wave bending moments, anticipated service, North Atlantic versus Pacific, etc., loading conditions, including per cent of time in ballast, operational profile and others. The scope of this study is not sufficient to investigate this problem in detail, although a general approach has been established which is sufficiently accurate to demonstrate feasibility. The results of this study are summarized in Appendix A.

Figure 13 illustrates the application of the foregoing criterion to the M/V CHALLENGER, where 5083 alloy is being used in lieu of mild steel. This figure indicates that the allowable stress for the aluminum hull would vary from 2.1 KSI (still water bending stress) at $10^8$ cycles to 13.5 KSI (extrapolated) at $10^0$ cycles. The corresponding values for the steel hull are 5 KSI and 19 KSI. The area under the steel and aluminum life-cycle stress curves between $10^0$ and $10^8$ cycles are $6.75 \times 10^8$ KSI and $3.56 \times 10^8$ KSI respectively, resulting in a required ratio of hull girder section moduli of 1.90.

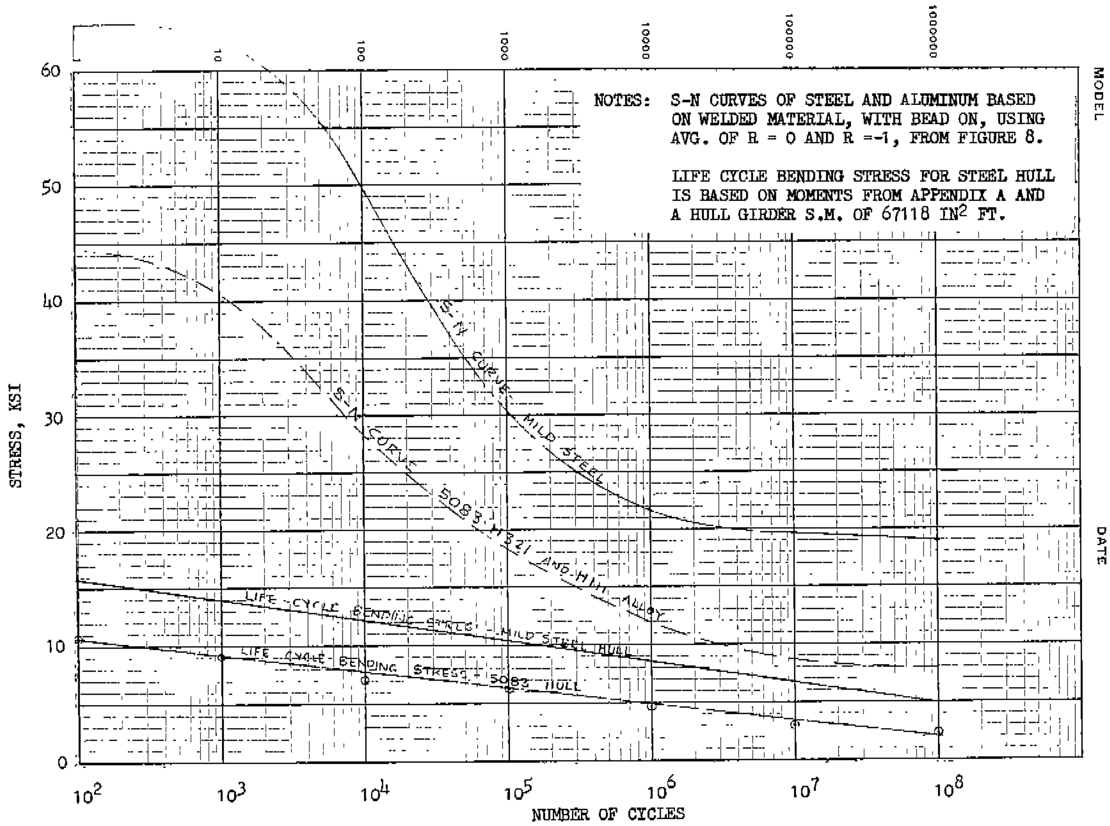



FIG. 13 Relationship Between S-N Curves and Life Cycle Hull Bending Stress for Steel and Aluminum Bulk Carrier

PROPOSED CRITERIA - HULL GIRDER MOMENT OF INERTIA

It appears obvious that the hull girder stiffness of an aluminum bulk carrier must be less than that of its steel counterpart if it is to be economically feasible. It now becomes necessary to establish the extent to which the hull girder deflection can be increased over that of a steel ship. As noted earlier, the only guidance in this area at present is the ABS requirement that the hull girder deflection of an aluminum ship shall not be more than 50 per cent greater than that of a "Rules" steel vessel while Lloyd's and Bureau Veritas suggest no increase. In justifying these recommendations or deviating from them, the following factors must be considered:

(a) Response to sea-induced forces.

(b) Hull girder vibrations, and possible resonances between the hull girder and other major structural components.

(c) Effects of deflection on draft.

(d) Effects of deflection on shafting, piping systems, etc.

(e) Stress-strain relationships of the material.

Sea-Induced Forces - Reference (53) indicates that reduced hull girder stiffness is beneficial in reducing dynamic bending moments associated with sea-induced forces. At the bow and midships, the reduction in maximum bending moment was approximately proportional to the square root of the ratio of hull rigidities, considering reductions in stiffness of as much as 50 per cent, though at the quarter points, the reduction was less. Although the studies discussed in Reference (53) were relatively limited and subject to further refinement, it appears that reduced hull stiffness will improve rather than degrade the hull's ability to withstand wave-induced forces.

Hull Vibrations - The hull girder frequency spectrum of a bulk carrier for vertical, lateral and torsional vibrations can be readily predicted either by empirical formulae or direct computation. Assuming that the overall weight distribution along the hull girder is identical for the aluminum and steel ship (i.e., reduced hull weight is fully compensated for by increased cargo deadweight), the variation in hull girder vibratory response will be approximately proportional to the square root of EI ratios, i.e.:

$$F_{n_{aluminum}} = F_{n_{steel}} \sqrt{\frac{10x10^6\ I_{alum}}{30x10^6\ I_{steel}}}$$

The ratio under the square root sign is the deflection ratio. Thus, if an increase of 50 per cent were accepted for the aluminum hull, its lower mode frequencies would be reduced by a factor of about 0.82. For a typical steel bulk carrier, the lowest hull frequency (1st mode vertical) is about 70 CPM, with the second mode vertical being at approximately 140 CPM. For an equivalent aluminum hull with a 50 per cent allowable increase in deflection, the corresponding values would be 60 and 120 CPM. The lower frequency spectrum of an aluminum hulled bulk carrier would have to be given consideration in selecting cruise and full speed shaft RPM and number of propeller blades to avoid resonances between either the shaft or blade forcing frequencies. However, this is not considered a design constraint since similar comments apply to steel hulls.

Another aspect of vibrations which must be given consideration in designing an aluminum bulk carrier is the possibility of resonance between the hull girder and major structural components such as the double bottom or deckhouse. The possibility of such resonances exists with steel hulls as well, so that similar design considerations apply in both cases. If all hull girder scantlings were to be converted to aluminum on the basis of the previous discussions, the relationship between frequency spectra of the hull and major structural components would remain essentially the same. Although this matter must be given consideration in selecting hull girder scantlings, it is not considered a design constraint for either a steel or aluminum hull.

Effects on Draft - The effects of hull girder deflections in still water on full load draft involves both technical and economic considerations. Excessive deflection can limit cargo carrying capacity both for freeboard requirements and for limiting drafts requirements entering harbors or crossing sandbars. The M/V CHALLENGER presently has still water bending stresses as high as 2.3 tons per square inch which may result in differences in draft between midships and the ends of approximately 1.9 inches (sag). However, these values correspond to conditions of partial loads. The maximum still water bending stress and corresponding sag for full load conditions are 1.7 tons per square inch and 1.4 inches respectively. For a similar, but 2,900 tons heavier, non-homogeneous cargo distribution the aluminum ship is expected to have a sag deflection of 3.1 inches. Such deflections correspond to losses of cargo carrying capacity due to freeboard requirements of 100 tons in the case of the steel ship and 220 tons in the case of the aluminum ship. However, with homogeneous cargo distributions in full load conditions, the sag deflections may be reduced to 0.7 and 1.7 inches respectively for steel and aluminum ships, with corresponding losses of cargo capability of 50 tons and 120 tons respectively.

Loss of cargo carrying capability due to effects of sagging on freeboard is expected to be a relatively rare occurrence in tramp operations. When picking up cargoes which are volume limited, a ship is not down to her marks and freeboard reductions due to sag are of no consequence. When picking up cargoes which are weight limited, in which case holds are only partially full, sagging stresses and deflections may be reduced by distributing cargo away from amidships. On few occasions when taking on cargoes of such densities to simultaneously fill the holds and load the ship to her marks, a loss of deadweight capacity would be experienced.

It is noted that when loading heavy cargoes partly at one port, and completing loading at another, it may not be feasible to limit the vessel's sag in full load and avoid loss of deadweight capacity.

Concerning navigational limitations on drafts to values less than full load draft, it is considered that the inch or so extra sag of an aluminum ship is not significant in the face of the inherent greater trim aft of an aluminum, machinery aft ship, as compared to a steel ship at a reduced draft.

In view of both the small percentage of cargo lift capacity that may be lost and the low frequency with which such losses may occur in tramp operations, it is not expected that reductions in cargo carrying capacity resulting from hull deflections can have measurable influence on the economic feasibility of an aluminum ship.

Effects on Shafting and System Runs - Greater hull girder deflection will have no effect on the design of the shafting of an aluminum bulk carrier, since the machinery is located aft, and the relative angular deflection along the length of the shafting is far less than with machinery amidships. For a hull with machinery amidships, the shaft bending stresses and bearing reactions would increase roughly in proportion to the hull girder deflection ratio, so that the question of shafting and bearing reactions would require serious consideration in this case.

The effects of greater hull girder deflection on longitudinally oriented bilge and ballast systems should be negligible, since the materials recommended for these systems have greatly reduced elastic modulus compared to conventional steel piping. Aluminum piping would be stressed to only 1/3 the level of equivalent steel piping for equal hull deflection, while the stress ratio for fiberglass piping would be only 1/10 to 1/15 that of steel. Thus an increase in hull girder deflection could be accepted without overstressing the pipe. Again, this presents a relatively simple design consideration which can be readily incorporated in the design of the piping system.

For longitudinal runs of steel piping, such as fuel oil piping, an expansion loop can be incorporated to absorb the additional deflection of the hull girder.

Stress-Strain Relationship - Consideration of design stresses, including fatigue, have been dealt with previously in detail, and it is these considerations which affect deflections rather than deflection considerations affecting stresses. Therefore, if previously established strength relationships have been satisfied, there is no apparent reason to impose a limit on hull girder deflection based upon consideration of material properties. It is noted, however, that increased hull deflection increases the strain energy in the post yield (plastic) range in way of stress concentrations.

The only area in which excessive deflection would affect structural design is in the design of hull longitudinals, where the secondary bending due to hydrostatic or deadweight loading should be augmented by the moment resulting from end loading being applied along an axis which is not in line with the neutral axis of the deflected beam, i.e.:

$$\left[\text{Additional secondary bending moment at midspan}\right] = \sigma_{Primary} \times A_{beam} \times \Delta_{beam}$$

Where $\sigma_{primary}$ is the hull girder primary bending stress
$A_{beam}$ is the area of the beam, including hull plate supported
$\Delta_{beam}$ is the midspan deflection of the beam

The stresses resulting from such secondary moments are usually negligible, but for an aluminum hull, where $\Delta_{beam}$ will be greater than with steel, this additional bending should be considered.

Conclusion - It is concluded that no limits should be placed on the hull girder deflection of an aluminum bulk carrier, but that the affects of the deflection resulting from normal structural design should be considered in the areas noted above.

## PROPOSED CRITERIA - PRIMARY HULL STRUCTURE

In this section, criteria are proposed for converting ABS steel scantlings to aluminum for application to the design of the primary hull structure of an aluminum bulk carrier. The following structural elements are considered:

- o Bottom Shell Plate
- o Side Shell Plate
- o Deck Plate
- o Tank Top Plate
- o Wing Bulkhead Plate (Upper and Lower)
- o Inner Bottom Floor and Girder Plates
- o Bottom Longitudinals
- o Deck Longitudinals
- o Tank Top Longitudinals
- o Other Hull Framing Members
- o Stanchions

In general, these criteria will establish minimum scantlings to resist combinations of primary and secondary stresses, local loads, impact, abrasion, slamming, etc., with consideration given to vibration and buckling problems. It will often be necessary to increase these minimum scantlings to suit hull section modulus requirements.

Design Criteria for Plates - In general, the approach to converting steel plate thicknesses to equivalent aluminum thicknesses requires the derivation of an "effective" steel thickness by deducting all corrosion or abrasion allowances, then increasing this thickness by a function of the relative strength ratios, and adding back any required corrosion or abrasion allowances.

The corrosion allowance to be deducted from steel will depend upon its anticipated exposure to salt water. An allowance of 1/8 inch or 10 per cent of the thickness, whichever is less, is proposed for the hull envelope (deck, side and bottom plate) with a 1/16 inch allowance for the internal plates. If the owner or Regulatory Bodies have added an additional margin for abrasion, such as on the flat of bottom or on the bottom of the hold, this should also be deducted.

The factor by which the "effective" thickness is to be modified is based upon the ratio of the sum of the welded yield and ultimate tensile strengths of the materials as in Equation (1) previously. For plates loaded primarily in shear, tension or compression, the full ratio should be used. However, for plates which are loaded primarily in tertiary bending (bending between stiffners due to applied normal load) the square root of this ratio should be used, since the section modulus of an element of plate is a function of $(\text{thickness})^2$. For plates subjected to a combination of tertiary bending and tension, compression or shear, an average factor should be used.

The allowance for abrasion to be added back to the resultant aluminum thickness is somewhat arbitrary. However, the previous discussion of aluminum alloy abrasion resistance indicates that aluminum will abraid about 4 times as fast as steel in a similar environment. Thus, for equal life, the steel allowance should be multiplied by four, unless a detailed economic analysis indicates that it is less expensive to renew the plate periodically or to provide steel chafing bars. However, neither of these approaches is considered economically or technically attractive at this time.

Summarizing the foregoing discussion, the conversion of mild steel plate thicknesses to aluminum would be as shown in Equation (3):

$$\text{Equation (3):}\quad t_{alum} = \left(t_{steel} - C_1 - C_2\right)\left(\frac{97{,}000}{Y+U}\right)^n + 4C_2$$

Where $t_{alum}$ = minimum required aluminum thickness

$t_{steel}$ = steel thickness required by ABS Rules without correction for corrosion control or increases for hull girder section modulus requirements

$C_1$ = corrosion allowance for mild steel

$C_2$ = additional allowance for abrasion

Y, U are as defined for Equation (1)

n is an exponent based on type of stress such as bending, shear or axial

Values of $C_1$, $C_2$, and n are as follows:

| Item | $C_1$ | $C_2$ | n |
|---|---|---|---|
| Minimum bottom thickness | 1/8" or .10t | As required by Owner | 1 |
| Side Plate | 1/8" or .10t | 0 | 1 |
| Deck Plate (exposed) | Determined primarily by hull girder S.M. requirements. Equation (3) not applicable. | | |
| Tank Top Plate | 1/16" | As required by Owner or ABS | 3/4 |
| Upper Wing Bulkhead Plate | 1/16" | 0 | 3/4 |
| Lower Wing Bulkhead Plate | 1/16" | As required by Owner or ABS | 3/4 |
| Floors and Girders | 1/16" | 0 | 1 |
| Shell Plates at Ends | 1/8" or .10t | 0 | 1/2 |

In addition to the foregoing, a safety factor of 1.25 on the critical panel buckling strength is recommended. The panel buckling analysis can be based upon the primary hull bending stress without considering the additional stress from secondary bending of the plate-stiffener combination, since the latter is generally quite small. For an aluminum hull equivalent to the M/V CHALLENGER, fabricated with 5083 alloy, this maximum hull bending stress will be 13.5 KSI at the deck and keel. This stress should be assumed to taper to 6.75 KSI at the neutral axis for the hull envelope and its framing, and to zero for other internal structure to account for stresses at an angle of heel.

Limitations on plate panel deflections are not considered necessary, since the increase in plate thickness in converting from mild steel to aluminum will generally provide a sufficient increase in inertia to offset the effects of differences in elastic moduli.

Design Criteria for Stiffeners - The design procedure for converting mild steel stiffener scantlings to aluminum consists of increasing the section modulus of the steel member by the relative strength ratio noted previously for plates:

Equation (4): $$SM_{alum} = SM_{steel} \left(\frac{97,000}{Y + U}\right)$$

Where Y and U are as noted previously for Equation (1).

Corrosion allowances are technically applicable to the above equation, but are neglected to provided an additional margin for member stiffness and high residual stresses in way of end connections. The additional weight resulting from this simplification is negligible, since the added area generally contributes to hull girder section modulus for longitudinally framed ships.

It is noted that longitudinal stiffeners on the shell and deck are subjected to a combination of axial load from hull girder bending and secondary bending from normal loads. Fortunately, however, the ratio of hull girder primary design stress to the quantity (Y + U) of steel and aluminum bulk carriers are essentially identical at about 0.20, so that this combined loading condition affects both materials similarly, and Equation (4) remains valid.

In addition to the foregoing, stiffeners should be checked for column buckling strength under the effects of longitudinal bending loads, and against local instability of flange and web as discussed in the previous section. It is suggested that the L/r ratio of the plate-stiffener combination be sufficiently low that the safety factor on column buckling failure would be 1.67, and that the web and flange proportions would permit development of full welded yield stresses in the member without local instability.

The deflection of aluminum stiffeners should be kept within reasonable limits, so that vibration problems and secondary bending effects are minimized. However, it is difficult to establish a specific deflection limitation, since this is a somewhat arbitrary decision, with little technical justification. Until a valid technical foundation for such a limitation can be developed, it is proposed to limit deflections of primary framing members (girders, web frames, hatch end beams, etc.) to 1-1/2 times that of the equivalent steel section, with no limits on the deflection of secondary stiffening. Equation (5) specifies the inertia required for primary hull framing members:

Equation (5): $$I_{alum} = 2\, I_{steel} \text{ (primary members only)}$$

Stanchions - Aluminum stanchions should have the same safety factor on column buckling as the equivalent Rules steel stanchion. The end connections, which will be at O temper, should be specially considered.

PROPOSED CRITERIA - SECONDARY HULL STRUCTURE

In designing such secondary structures as deckhouses, structural bulkheads, tanks, etc., the following criteria are proposed, which are essentially the same as those for primary hull structures:

For Plates:

Equation (6): $$t_{alum} = t_{steel} \left( \frac{97,000}{Y + U} \right)^{n}$$

Where n = 1 for plates loaded primarily on the edges (tension, compression or shear)

n = 1/2 for plates loaded laterally

For Stiffeners:

Equations (4) and (5) apply.

Crack Arresting - The various Regulatory Bodies and design activities with whom crack arresting requirements were discussed, indicated that aluminum alloys appear to possess sufficient fracture toughness, ductility and tear resistance that mechanically fastened crack arrestor seams may not be required for an aluminum hull. The investigation of fracture toughness and tear resistance of aluminum which was conducted for this study did not provide sufficient data to justify such a conclusion for a large, highly stressed hull subjected to cyclic loading. The data is particularly sparse in the area of crack propagation in way of the heat affected zone when subjected to high intensity cyclic loading. Therefore, it is concluded that a minimum number of mechanically fastened seams should be incorporated in the design of large aluminum hulls.

For this study, it is proposed to incorporate a single mechanically fastened seam at the lower edge of the shear strake port and starboard. This location reflects the fact that the deck is more highly stressed than the bottom, and subject to high stress concentrations at hatch corners. Mechanically fastened seams are not desirable below the water line due to possible stress corrosion problems at the faying surface.

Thermal Stresses - The thermal stresses induced in the hull of an aluminum ship with 5083 alloys will be no more critical than with an equivalent steel hull, based upon the following logic:

Thermal elongation $$\delta = L \alpha \Delta T = \frac{\sigma_T L}{E}$$

Where L is the length of the member

$\alpha$ is the coefficient of linear expansion per 100°F

= .00128 for aluminum

= .00065 for mild steel

$\Delta T$ is the change in temperature

$\sigma_T$ = Thermal stress

$E$ = Elastic modulus

Thus, $\sigma_T = E \alpha \Delta T$

Where $E \alpha$ = 12,800 for aluminum

= 19,500 for steel

For equal $\Delta T$, the thermal stresses for a steel member will be 1.52 times that of an aluminum member. Thus for any aluminum alloy with a welded yield strength in excess of 21 KSI, the safety factor on thermal stresses will be equal to or better than that of the equivalent steel structure. Since the welded yield strength of 5083 plate and shapes are 24 and 21 KSI respectively, thermal stresses are not considered as a design constraint. However, the effects of thermal expansion on hull deflection should be investigated, since limiting drafts might be affected.

## IID. FABRICATION OF LARGE ALUMINUM HULLS

The investigation of the effects of large scale aluminum construction on presently employed fabricating techniques and shipyard operations consisted of a series of discussions with representatives of four large U.S. shipyards with extensive experience in fabricating aluminum structures. The following paragraphs summarize these discussions.

### MATERIAL HANDLING

The material itself poses no particular storage problems. Handling however, requires greater care since the aluminum is more prone to damage than steel. Plates are handled with suction cups or vacuum lifts. This process requires additional labor. Aluminum requires no sand blasting or priming such as steel, but is washed with solvent to remove the oxide film or other contaminants. Since most yards presently do relatively small amounts of aluminum work per hull, this is generally done by hand. Present techniques could be updated for a large aluminum hull and mechanically controlled cleaning could be employed for plates and dipping for all shapes. Larger subassemblies can be handled in aluminum, due to lighter weight, which results in a cost savings.

### ENVIRONMENTAL CONTROLS

In general, most yards have no special environmental controls for temperature or humidity in the fabrication areas. To minimize thermal effects of the sun, it was generally felt that a shed type covering should be erected over the ways. This covering, in conjunction with other protective shielding, would also decrease welding time lost due to high winds and inclement weather.

### WELDING AND CUTTING

General yard experience with aluminum covers thicknesses up to and including one inch. The present techniques for handling and fabricating are generally based on material one-half inch thick and below. No special problems are envisoned in fabricating large quantities of thicker material.

Presently, sawing is the most common way of cutting aluminum since the finished edges need the least amount of dressing-up. Some amount of re-tooling for large quantities of thicker material would be necessary. Where modules of the hull are to be butted together, an allowance would be left to establish the "final cut" which could be done by a power saw mounted on a trackway.

Another common method of cutting, generally used for preparing access or lightening holes, is by plasma arc. This does not leave as smooth a finish as sawing and sometimes requires dressing.

MIG seems to be the preferred choice for welding, with a mixture of 75 per cent Argon and 25 per cent Helium. Small quantities of aluminum ship construction do not necessitate extensive use of automatic welding but it was felt that more automatic welding, perhaps as high as 70 per cent, would be in order for a large aluminum hull. A higher content helium-gas mixture was also proposed as a means of speeding up the welding process, but this would have to be evaluated against the additional cost of the helium.

A training program to qualify additional aluminum welders would be necessary for any shipyard undertaking the project, but no major problems were foreseen by any of the yards in either upgrading steel welders or in training new welders for this particular skill.

The general consensus of opinion seemed to dictate flat panel construction initially rather than three dimensional assemblies. The heavy scantlings proposed would in part minimize distortion problems and curved shapes would tend to remain as rolled. When fabricating aluminum, more care must be exercised since it has a shrinkage rate of two to three times that of steel. This is an area where a careful study should be made in the design stage to minimize any problem areas, particularly in way of shafting. Expansion tables could be developed for various combinations of plate thicknesses and weld sizes which would be an invaluable tool during construction.

Heavy stress should be placed on the development of the minimal welding sizes required. This will not only minimize distortion and expansion but reduce the total overall cost of welding. The sizes of aluminum fillet welds presently required by Navy welding specifications are considered excessive by the shipyards, and result in excessive distortion.

Intermittent welding is not recommended. Continuous welding is preferred since it results in smaller, better quality welds and hence lower rates of rejection, and minimizes cratering at the end of beads.

Experience has shown it is very difficult to meet an acceptable weld quality X-Ray standard when welding outside with high humidity. Further examination of possibly reducing this standard was proposed. Possible reductions in porosity standards were also viewed as another cost saving item.

ATTACHMENTS

Attachment of ferrous materials was another area which it was felt deserved special attention. Presently utilized methods for installing deck fittings and other hardware in the weather do not provide a completely satisfactory installation. It was proposed that flexible plastic sealers be used to cover all of these exposed joints over and above the normal tape and paint methods presently employed.

## SUMMARY

All parties contacted foresaw no insurmountable construction or fabrication problems and agreed that a satisfactory hull could be delivered by implementing three basic tools:

(1) Establishment of and rigid adherence to a proper welding sequence.

(2) Use of good welding equipment, continuously maintained.

(3) Use of properly trained and qualified welders with good on-line supervision.

## IIE. FIRE PROTECTION

### DEFINITION OF REQUIREMENTS

This phase of the study evaluates the problem of providing a satisfactory level of fire protection for a large aluminum bulk carrier, giving consideration to present requirements for steel ships, means of maintaining structural integrity in the face of a fire, and methods of detecting and extinguishing a shipboard fire. References (54) through (68), form the basis of this study.

Present Coast Guard Requirements - The basic document applicable to this study is the U. S. Coast Guard "Rules and Regulations for Cargo and Miscellaneous Vessels", Subchapter I, Part 92.07, Structural Fire Protection, excerpts of which appear in Appendix B.

It must be assumed that at present, compliance with the intent of the Rules is essential for certification of a U. S. Flag aluminum bulk ore carrier.

The standard fire test defined in paragraph 92.07-5(a) of the Rules, is essential in the development of a fire protection system. Appendix C contains a brief history of maritime fire testing and the reasons for adopting the standard fire test as a means of evaluating fire resistant constructions and materials.

The hull, superstructure, structural bulkheads, decks and deckhouses are specified by the U. S. Coast Guard to be of steel construction or, alternately, in special cases other equivalent materials. Metal equivalent to steel is defined as one which, by itself or due to insulation provided, has structural and integrity qualities equivalent to steel at the end of the applicable fire exposure. These composite structures are required to be of "A"-0 construction, which, when subjected to the standard fire test, are capable of preventing the passage of smoke and flame for one hour. For aluminum structural equivalence to steel, it is required that the temperature of the aluminum shall not rise 200 degrees C above ambient in the presence of fire.

In addition to the structure stated above, certain other structures are required to be of "A"-0 construction:

(a) The boundary bulkheads and decks separating the accommodations and control stations from the cargo and machinery spaces, galleys, main pantries and storerooms, other than small service lockers.

(b) Bulkheads of galleys, paint and lamp lockers and Emergency Generator Room.

(c) Stair towers, elevator, dumbwaiter and other trunks.

In summary, it must be concluded that all aluminum structures, specified to be of "A"-0 construction, must be capable of withstanding the passage of smoke and flame for a period of one hour while restricting the maximum temperature of the aluminum to 400 degrees F.

Fire Test of Aluminum Construction - An extensive test program of representative insulated aluminum bulkhead and deck assemblies is presently being conducted under the auspices of the Fire Test Ad Hoc Subgroup of Task Group HS-6-1 (Aluminum) of the Society of Naval Architects and Marine Engineers (SNAME). Reference (67) is a test report on the first bulkhead test by the National Bureau of Standards dated June 14, 1967. Ten additional bulkhead and ceiling configurations are now in the process of fabrication for testing during 1970. From these tests it will be possible to establish factual criteria for the protection of aluminum structures within the living, working and stores spaces.

In addition to the SNAME test many smaller tests have been conducted by materials manufacturers. Unfortunately, the results of these tests are of a proprietary nature. However, while these smaller tests lack official Government approval they do nevertheless contribute valuable information towards eventual solution of the problem of fire protective aluminum construction.

## AREAS REQUIRING PROTECTION

Living, Working and Stores Spaces - A study has been made of the living, working and stores spaces of a steel and equivalent aluminum bulk cargo ship, similar to the MV CHALLENGER, and built in strict accordance with current U.S. Coast Guard rules. The study included the complete after deckhouse down to and including the underside of the Upper Deck.

The construction utilized to afford the required protection is based upon tests, where available, or the construction considered most suitable at this time, based upon past experience, pending confirmation by test methods. In most cases, a conservative approach has been taken in order to realistically approximate the maximum additional cost and weight that might be required.

For both steel and aluminum ships, the stateroom and living space divisional bulkheads and the house side lining will be identical, i.e., 7/8 inch thick free standing marinite with steel "H" posts and joiner shapes with insulation if necessary. The normal application of thermal insulation on the surfaces of air-conditioned spaces results in an added degree of protection.

In general, the aluminum bulkheads requiring additional protection can be grouped in the following categories:

(a) The exposed surfaces within stair-towers.

(b) The engine room side of the machinery casing.

(c) The exterior side of the machinery casing, where this surface is normally exposed bare metal as in the crew stores and service areas.

(d) Bulkheads separating stores and service spaces which are normally exposed bare metal.

(e) Galley and pantry bulkheads require additional protection over that normally fitted for thermal conditions.

(f) Other minor cases.

With regard to the lower surface of the decks, it is apparent that with a maximum allowable aluminum temperature of 400 degrees F, and a required test of 1700 degrees F, an insulated construction is mandatory.

For the upper surface of aluminum decks in the presence of a fire within quarters, equivalent to the Standard Time Curve, the following observations are noted: The "Nantasket" tests, Reference (54) indicated that the deck covering restricted the downward propagation of flame, provided the covering was of an incombustible nature. This was largely due to the lack of oxygen at floor level, the products of combustion at this level, and the rising of heated air. This point was also illustrated by the Stateroom Fire Test Report, Reference (58). In this case with bare aluminum deck, the aluminum reached a temperature of 400 degrees F within 18 to 25 minutes. The maximum temperature reached was only approximately 675 degrees F at 35 minutes, after which the temperature declined. The British Test, "Fire Protection in Passenger Ships", Reference (59), with a 3/16 inch sand filled latex underlay and 1/8 inch thermoplastic resin bonded tiles, resulted in a maximum aluminum temperature of 425 degrees and 250 degrees on two isolated thermocouples at the end of 50 minutes.

From the above, it can be assumed that a lesser degree of protection can be permitted within the quarters to protect the upper surface of the decks than is required on the underside.

Therefore, the decks requiring additional protection can be grouped under the following categories:

(a) Above the normal stateroom ceilings, insulation must be added.

(b) Insulation protection must be added in those spaces exposed to the weather, in addition to that normally fitted with thermal insulation.

(c) Insulation must be fitted to the overhead of nonair-conditioned spaces when located under air-conditioned spaces in addition to the thermal insulation normally provided.

(d) Insulation is required in the overhead of stores and service spaces located under similar spaces.

(e) All topside surfaces must be protected.

The required protection resulting from the application of these criteria to the MV CHALLENGER of steel and aluminum construction are summarized in Tables 11 and 12. These tables indicate that the additional insulation required for the aluminum deckhouse would be about 110,000 pounds if the present U. S. Coast Guard requirements are fully satisfied.

TABLE 11 Aluminum Bulk Carrier - Summary of Joiner Bulkheads, Linings and Insulation in Living, Working and Stores Spaces

| THIS SPACE | ADJACENT TO | STEEL SHIP | | | ALUM. SHIP | | | SQ.FT. | ADDL WGT ALUM-LBS. |
|---|---|---|---|---|---|---|---|---|---|
| | | INSUL. | SHEATHG | LB./SQ.FT. | INSUL. | SHEATHG | LB./SQ.FT. | | |
| DK-HSE SIDE | WEATHER | 2"/1"-1# | 7/8" MAR 36# | 4.31 | 2"/1"-1# | 7/8" MAR 36# | 4.31 | 7,600 | NONE |
| DK HSE SIDE | WEATHER | 2"/1"-1# | SHT. MET. | 2.14 | 2"/1"-6# | SHT. MET. | 3.25 | 255 | 283 |
| PASSAGEWAY | S/RMS-ETC | NONE | 7/8" MAR 36# | 4.00 | NONE | 7/8" MAR 36# | 4.00 | 5,040 | NONE |
| S/RM | S/RM | NONE | 7/8" MAR 36# | 4.00 | NONE | 7/8" MAR 36# | 4.00 | 5,925 | NONE |
| STAIR TOWER | PASSAGE | NONE | 7/8" MAR 36#<br>SINGLE FACED | 4.00 | NONE | 7/8" MAR 36#<br>DOUBLE FACED | 8.00 | 1,265 | 5,060 |
| A.C. MACHY ROOM | TOILET | 2"/1"-1#<br>BARE STL | SHT. MET.<br>– | 2.14 | 2"/1"-1#<br>– | SHT. MET.<br>7/8" MAR 36# | 6.14 | 136 | 544 |
| MACHY CASING | WEATHER | 2"/1"-3# | SHT. MET. | 2.60 | 2"/4"-6# | SHT. MET. | 4.60 | 161 | 322 |
| MACHY CASING | PASSAGE, S/RMS, ETC. | 2"/1"-3#<br>- | SHT. MET.<br>7/8" MAR 36# | 6.60 | 2"/4"-6#<br>- | SHT. MET.<br>7/8" MAR 36# | 8.60 | 1,130 | 2,260 |
| MACHY CASING | STAIR TOWER, TOILET, PASSAGE | 2"/1"-3#<br>BARE STL | SHT. MET.<br>– | 2.60 | 2"/4"-6# | SHT. MET.<br>7/8" MAR 36# | 8.60 | 2,370 | 14,220 |
| A.C. MACHY RM | WEATHER | 2"/1"-1# | SHT. MET. | 2.14 | 2"/1"-6# | SHT. MET. | 3.25 | 161 | 178 |
| A.C. MACHY ROOM | FAN ROOM | 2"/1"-1#<br>2"/1"-1# | SHT. MET.<br>SHT. MET. | 4.30 | 2"/1"-6#<br>2"/1"-6# | SHT. MET.<br>SHT. MET. | 6.50 | 132 | 290 |
| STORE ROOM | STORE ROOM | BARE STEEL | -<br>- | 0.0 | 2"/1"-6#<br>2"/1"-6# | SHT. MET.<br>SHT. MET. | 6.50 | 765 | 4,973 |
| A.C. MACHY ROOM | MACHY CASING | 2"/1"-1#<br>2"/1"-3# | SHT. MET.<br>SHT. MET. | 4.70 | 2"/1"-1#<br>2"/4"-6# | SHT. MET.<br>SHT. MET. | 6.70 | 612 | 1,224 |
| MACHY CASING | GALLEY | 2"/1"-1#<br>2"/1"-3# | SHT. MET.<br>SHT. MET. | 4.70 | 2"/1"-1#<br>2"/4"-6# | SHT. MET.<br>SHT. MET. | 6.70 | 161 | 322 |
| STORES | GALLEY | 4"-1#<br>BARE STL | SHT. MET.<br>– | 2.29 | 4"-6#<br>2"/1"-6# | SHT. MET.<br>SHT. MET. | 7.20 | 323 | 1,583 |
| MESSRMS | GALLEY | 4"-1#<br>- | SHT. MET.<br>7/8" MAR 36# | 6.29 | 4"-6#<br>- | SHT. MET.<br>7/8" MAR 36# | 7.90 | 153 | 260 |
| STORES | REFRIG. STORES | 12"-1#<br>BARE STL | REEFERITE<br>- | 9.20 | 12"-1#<br>2"/1"-6# | REEFERITE<br>SHT. MET. | 12.50 | 800 | 2,640 |
| PANTRY | LOUNGE | 2"/1"-1#<br>- | SHT. MET.<br>7/8" MAR 36# | 4.31 | 2"/1"-6#<br>- | SHT. MET.<br>7/8" MAR 36# | 7.25 | 272 | 816 |
| PANTRY | WEATHER | 2"/1"-1# | SHT. MET. | 2.14 | 2"/1"-6# | SHT. MET. | 3.25 | 2,130 | 2,365 |
| PASSAGE | EMER. GEN. | 2"/1"-1# | SHT. MET.<br>7/8" MAR 36# | 4.31 | 2"/1"-6#<br>– | SHT. MET.<br>7/8" MAR 36# | 7.25 | 187 | 559 |
| LAUNDRY & STORES | PASSAGE | 2"/1"-1#<br>– | SHT. MET.<br>- | 2.14 | 2"/1"-6#<br>– | SHT. MET.<br>7/8" MAR 36# | 7.25 | 1,250 | 6,450 |
| | | | TOTAL - JOINER BULKHEADS AND INSULATION | | | | | 30,828 | 44,349 |

TABLE 12 Aluminum Bulk Carrier - Summary of Ceilings, Insulation and Deck Covering in Living, Working and Stores Spaces

| Upper Space | Lower Space | Steel Ship | | | Alum. Ship | | | Sq. Ft. | Addl Alu |
|---|---|---|---|---|---|---|---|---|---|
| | | Insul. | Sheathg | Lb/ Sq.Ft. | Insul. | Sheathg | Lb/ Sq.Ft. | | |
| Open Deck | Air Cond. Spaces | 2"/1"-1# | 3/16" Mar.Ven | 2.6 | 2"/1"-6# | 3/16" Mar.Ven | 3.7 | 6,188 | 6, |
| Open Deck | Refrig. Spaces | 8"/12"-1# | 1/4" Reeferite | 8.9 | 8"/12"-1# | 1/4" Reeferite | 8.9 | 532 | |
| Open Deck | Machy Casing | 2"/1"-3# | Sht. Met. | 2.6 | 2"/4"-6# | Sht. Met. | 4.6 | 685 | 1, |
| Air Cond. Spaces | Galley | 4" - 1# | Sht. Met. | 2.2 | 4" - 6# | Sht. Met. | 3.92 | 368 | |
| Air Cond. Spaces | Air Cond. Spaces | None | 3/16" MarVen | 2.3 | 2"/1"-6# | 3/16" Mar.Ven | 3.7 | 7,664 | 10, |
| Air Cond. Spaces | Non-Air Cond.Spaces | 2"/1"-1# | Sht. Met. | 2.14 | 2"/1"-6# | 3/16" Mar.Ven | 3.7 | 2,190 | 3, |
| Air Cond. Spaces | Pantry | 4" - 1# | Sht. Met. | 2.2 | 4" - 6# | Sht. Met. | 3.92 | 78 | |
| Open Deck | Emer. Gen. Rm. | 2"/1"-1# | Sht. Met. | 2.14 | 2"/1"-6# | Sht. Met. | 3.25 | 190 | |
| Stores Spaces | Steering Eng. Rm. | None | None | 0.0 | 2"/1"-6# | Sht. Met. | 3.25 | 1,240 | 4, |
| Stores, AC & Service Spaces | Machy Casing | 6" - 1# | Sht. Met. | 2.42 | 6" - 6# | Sht. Met. | 4.92 | 4,253 | 10, |
| | | Totals - Ceiling and Insulation<br>Total - Deck Covering | | | | | | 23,388<br>- | 37,<br>26, |

Machinery Spaces - Reference (68) lists 245 fire casualties on all classes of ships, of which only four were on bulk carriers. Three of the four fires originated in the machinery spaces and one in the accommodation spaces. Of those occurring in the machinery spaces, two were the result of fuel oil fires while combustible materials resulted in the accommodation space fire. This agrees with the expected assumption that these two types of combustibles are the primary sources of incipient fires, and that these locations must therefore be provided with the maximum protection against fires.

Within the machinery space, the most serious problem is the protection of the exposed aluminum structure to prevent the passage of smoke and flame and to restrict the maximum temperature of the aluminum to 400 degrees F for the required one hour time interval. The overriding requirement is the maximum temperature restriction in the presence of fire, since if this can be accomplished, the structure will prevent the passage of smoke and flame. One potential solution might be the use of sprinklers to form water walls on the vertical surfaces and the underside of the flats. However, this method is incompatible with an oil fire. A fixed fog system might be considered but to date there have been no physical tests to evaluate the time-temperature results of either of these proposals. A simple solution would be to construct the machinery space enclosing structure of steel. This, however, poses additional problems of added weight, connection of incompatible metals, and differential coefficients of expansion. For many local structures, such as machinery flats and small tanks, the use of steel in lieu of protected aluminum would appear to offer significant cost savings without a major weight penalty. Various types of fire-retardant intumescent paints are available, but these are primarily used to retard the spread of fire rather than to restrict the temperature rise on the surface to which they are applied for any appreciable time duration.

Of all the methods considered, the one chosen to best provide the desired protection to vertical surfaces and the crown of the machinery box is the application of a suitable thickness of insulation, sheathed with metal to protect the insulation against injury and abrasion.

The surface of tank top, while still requiring the same degree of protection, presents a rather different problem due to personnel access and abrasion from the movement of equipment. Of all the available materials considered, a composite construction consisting of an approved cellular glass incombustible material, expanded metal, Subkote No. 1 and a magnesia aggregate topping similar to MIL-D-23134 has been selected as the optimum after due consideration of weight, cost. abrasion, resistance, oil spillage, good housekeeping and other constraints.

Table 13 gives the approximate areas in each category together with the anticipated approximate added weight to protect the aluminum.

While not considered in detail at this time, other items that must be dealt with are structural stanchions and webs in the machinery spaces, together with exposed areas of main and auxiliary machinery foundations. It is also necessary to offset the deleterious effects of heat transfer.

TABLE 13 Aluminum Bulk Carrier Additional Insulation and Deck Covering in Machinery Space

INSULATION AND SHEATHING

| | | |
|---|---|---|
| Shell | | 8,000 Sq. Ft. |
| Forward Bulkhead | | 3,600 |
| After Bulkhead | | 1,600 |
| Underside - Upper Flat | | 3,720 |
| Underside - Lower Flat | | 3,340 |
| | Total | 20,260 Sq. Ft. |

With 2"/4"-6#/Ft$^3$ Insul. and Sheet Metal Sheathing at 5.1#/Sq.Ft. = 106,000 pounds additional weight

DECK COVERING

| | | |
|---|---|---|
| Top Surface - Upper Flat | | 3,730 Sq. Ft. |
| Top Surface - Lower Flat | | 3,340 |
| Top Surface - Tank Top | | 2,930 |
| | Total | 10,000 Sq. Ft. |

With 1" Cellular Glass, Expanded Metal, 1/4" Subkote, 3/8" Magnebond = 4.2#/Sq.Ft. = 42,000 pounds additional weight

preferable to utilize steel stanchions in lieu of insulated aluminum stanchions because of the disastrous results of stanchion failure.

Cargo Spaces - Within the cargo spaces, fire protection depends upon many variables, including the relative flammability of the anticipated cargo. If the cargo to be carried can be guaranteed to be non-flammable, the requirements for protection could ostensibly be reduced. However, in the course of the ship's general service it must be assumed that a flammable cargo will be carried. It is then necessary to either prevent a fire from starting, or to maintain the surface temperature of the aluminum structure at an acceptable level, by fighting the fire and/or protecting the surfaces.

The most promising method of preventing the start of a fire within the cargo spaces would be to fit a closed, pressurized nitrogen or carbon dioxide inerting system, although the effects of this on edible cargoes and means of exhausting the hold must be studied. This system will be discussed in further detail later.

Restricting the maximum temperature of the aluminum structure to 400 degrees F in the presence of a fire within the cargo spaces presents many problems. Of the many potential solutions considered, none have been actually tested. All methods are subject to the following constraints:

(a) The intensity of the fire for different type cargoes.

(b) Compatibility of the extinguishing agent with the type of cargo.

(c) Effectiveness of the extinguishing agent on fires of varying types of cargo.

(d) System weight.

(e) Potential damage to and loss of protection of the system, due to cargo handling whether by grab bucket, mechanized vehicles, conveyor system, or others.

(f) Additional cost.

One method considered for maintaining strength of the aluminum structure was the concept of a heat sink. A recent shore-side installation utilizes a water wall column system, with circulating pumps and expansion tanks to reduce the amount of insulation protection required for steel components (Reference (66)). Similar concepts might be utilized in constructing the wing tanks and inner bottom within the cargo holds. This method is not considered practical, however, since it is not desirable to carry water ballast in these tanks when cargo is carried. This system would require some type of double wall transverse bulkhead construction, with consequent loss of cargo cubic, or increased length of cargo holds for equivalent cargo cubic. An alternative method which reduces the quantity of water to be circulated would utilize double wall extrusions for wing tanks, bulkheads and tank top. While this is within the state-of-the-art, it must satisfy the constraints outlined above, and would present significant fabrication problems.

Constructing the inner surfaces of the wing and inner bottom tanks, and transverse bulkheads of aluminum clad with stainless steel might result in raising the allowable maximum temperature of the metal before structural strength is impaired. However, this would result in high cost and would present additional fabrication constraints. Further testing would be required.

There are several proprietary brands of intumescent paint that retard the spread of fire. However, it is extremely doubtful that these could effectively maintain the required maximum temperature of the structure in the face of cargo space fire. Within the current aerospace programs, many exotic ablative material constructions have been developed. The total effectiveness of these materials in maintaining required time-temperature relationships must be tested and studied to determine weight and cost constraints. At this time, it appears that ablatives would be relatively expensive to install and maintain, but warrant further consideration.

There is no doubt that suitable cargo hold insulation with some type of protective sheathing could be designed to meet the requirements. However, whatever components are selected, it appears that the added cost and weight would render this method unacceptable. Therefore, it is concluded that the cargo hold structure should not be protected. Rather, an inerting system should be installed which is compatible with the anticipated flammable cargoes, including coal and grain. This system, in conjunction with a proper detecting and extinguishing system, is considered to be the best solution to the somewhat low risk fire problem in the cargo holds of a bulk carrier.

DETECTION AND EXTINGUISHING SYSTEMS

The Rules and Regulations of the U.S. Coast Guard, for Cargo and Miscellaneous Vessels, Subchapter I, Part 95, sets forth various requirements regarding fire detection and extinction which are summarized as follows:

(a) Fire detecting, manual alarm and supervised patrol systems are not required, except in special cases.

(b) At least two fire pumps are required, located in separate spaces, each capable of delivering water at the two highest points in the ship at 50 pounds per square inch.

(c) Hose and hydrant sizes shall be 2-1/2 inches, with 7/8 inch nozzle and 50 foot length of hose, or, a 1-1/2 inch siamese hydrant with single hose, 75 feet long with 5/8 inch nozzle.

(d) Fire hydrants shall be of sufficient number and so located that any part of the vessel, other than the machinery spaces, accessible to persons on board while the vessel is being navigated, and all cargo holds may be reached with at least two streams of water from separate outlets, at least one of which shall be from a single length of hose. In main machinery spaces, all portions of such spaces shall be capable of being reached by at least two streams of water, each of which shall be from a single length of hose from separate outlets.

(e) Vessels engaged exclusively in the carriage of grain or coal in bulk, need not be fitted with a fixed carbon dioxide system in the cargo holds.

(f) A fixed carbon dioxide or other approved system shall be installed in all lamp and paint lockers.

(g) A fixed carbon dioxide system shall be installed in all spaces containing internal combustion main propulsion machinery and auxiliaries of 1,000 BHP or greater or their fuel oil units, including purifiers, valves and manifolds.

(h) If an enclosed ventilating system is installed for electric generators, a fixed carbon dioxide system shall be installed in such system.

(i) Spaces which are protected by a carbon dioxide system and are normally accessible to persons on board when the vessel is being navigated, other than paint and lamp lockers, shall be fitted with an approved audible alarm in such spaces which will be automatically sounded when the carbon dioxide is admitted to the space.

(j) Hand portable and semi-portable fire extinguishers shall be fitted of the type and number and in the locations specified.

Living and Working Areas and Stores Spaces - It is considered that the requirements outlined above are sufficient for the aluminum ship in these areas.

Machinery Spaces - Within the machinery spaces, consistent with the protection for the aluminum structure outlined previously, the requirements noted above are considered the minimum necessary to afford protection. Additional detection devices together with a fixed foam system would provide a greater margin, provided that it can be reconciled against the additional cost involved.

Cargo Spaces - For steel bulk carriers engaged in grain or coal trade, no detection or fixed extinguishing system is presently required in the cargo holds. This is assumed to be based on the premise that if a fire did start the provision of two fire hoses would permit sufficient fire control, together with the fact that steel does not lose its inherent strength in the face of an average fire. For some cargoes and arrangements, these fixed systems may not be effective.

The ignition temperatures of the dusts of the various types of bulk cargo vary approximately between 650 degrees F to 9000 degrees F. Thus a potential fire in the cargo spaces can not be disregarded. In view of the maximum temperature restriction of aluminum, this warrants the installation of a detection system within the cargo holds. A temperature rise sensing system would probably prove to be the most satisfactory.

In addition to the conventional cargo hold fire extinguishing system, an inerting system is recommended for all cargo spaces. This system could utilize either nitrogen or carbon dioxide, and would be activated when potentially dangerous cargoes are carried. Such systems are presently incorporated in a number of oil tankers to reduce the risk of explosion. The cargo holds must be gas-freed prior to unloading cargo, so that men may safely enter the hold, thereby requiring the installation of large suction fans serving the holds. In this regard, nitrogen offers an advantage in that it is slightly lighter than air and would tend to rise naturally from the hold when the hatch covers are open. However, this tendency of gas to rise would necessitate special techniques to maintain a satisfactory distribution of nitrogen throughout the cargo, such as circulating fans or continual bleeding of additional nitrogen at the lowest level of the hold. Carbon dioxide, being heavier than air, would be more difficult with regard to gas-freeing the hold, but would satisfactorily distribute itself throughout the cargo without resupply or recirculation. Neither gas would appear to be harmful to the range of cargoes being considered.

There are a number of unknowns concerning an inerting system such as that proposed, which preclude an evaluation of its cost. These include such factors as the required concentration of inerting gas to maintain a satisfactory level of fire protection, the residual concentration which could remain after gas-freeing the hold, recirculation requirements and so forth. The solution to these problems is beyond the scope of the present study, but warrants further consideration.

An alternative which might be preferable to an inerting system would include a high-capacity carbon dioxide smothering system in conjunction with fire detecting equipment of improved sensitivity. This system would incorporate the following features:

- Sufficient quantities of carbon dioxide to selectively flood any hold, or the engine room, with a high concentration of gas.

- A gas delivery system which would insure rapid flooding of the spaces and even distribution throughout the space.

- A detection system sensitive to rate of temperature rise and to ultra-violet emissions from open flame.

## IIF. INSTALLATION OF SYSTEMS AND EQUIPMENT

### MATERIALS

Propellers - For commercial ship application the majority of propellers have been of the following materials:

| Material-Alloy | Trade Name |
|---|---|
| Manganese Bronze | - |
| Nickel Manganese Bronze | Turbine Metal |
| Nickel Aluminum Bronze | Nialite and Nikalium |
| Manganese Nickel Aluminum Bronze | Superston |

When these materials are coupled to aluminum in sea water a galvanic cell is created and the aluminum hull plating, rudder, etc. will be anodic to the bronze and will act as an anode to protect this very large area of bronze cathode and the aluminum will corrode very rapidly. A cathodic protection system can be installed to protect the aluminum underwater structure.

Another material which is more compatible with aluminum in sea water should be considered. Such a material is 18 per cent chrome - 8 per cent nickel stainless steel alloy, similar in composition to the Alloy Casting Institute Specification CF-8 (corresponding wrought alloy type is AISI 304). This alloy has been used successfully for many years on the 29 ships built between 1962 and 1968 for Lykes Bros. and Gulf & South American Ships. These propellers vary from 52,000 to 76,000 pounds in weight and are about 21 feet in diameter.

The chemical, mechanical and physical properties of this CF8 material are as follows. (CF8 alloy is also similar to ASTM Specification A296-Grade CF8).

(a) Chemical

| Chemical | Per Cent |
|---|---|
| Carbon | 0.08 Max. |
| Manganese | 1.50 Max. |
| Si | 2.00 Max. |
| P | 0.04 Max. |
| S | 0.04 Max. |
| Chrome | 18 to 21 |
| Ni | 8 to 11 |

(b) Mechanical

| | |
|---|---|
| Tensile Strength | 65,000 PSI Min. |
| Yield Strength | 30,000 PSI Min. |
| Elongation in 2 Inches | 35 Per Cent |
| Brinell Hardness | 140 |
| Charpy Impact | 75 Ft-Lbs |

(c) Physical Constants

| | |
|---|---|
| Density | 0.280 Lbs/Cu.In. |
| Specific Heat | 0.12 |

(d) Welding Procedures

| | |
|---|---|
| Preheat | None |
| Postheat | None - if area is small |

These propellers are of the built-up type with the blade palms bolted to the cast hub. The propeller blades and hub are cast stainless steel CF8 alloy, while the studs for attaching the blades to the hub are monel K500 (K monel) and the nuts for studs are Armco 17-4PH condition H-1150.

The CHALLENGER propeller is presently a solid five-bladed of bronze material and is 18 feet 4-1/2 inches in diameter. An estimated weight and cost comparison is shown in the following table:

| Material | Type | Weight - Lbs. Approximate | Finished Cost Per Pound, $ | Total Cost, $ |
|---|---|---|---|---|
| Ni Al Bronze | Solid | 37,500 | 1.50 | 56,250 |
| CF8 - Cast Stainless Steel | Built-up | 48,000 | 1.25 | 60,000 |

The cast stainless steel propeller will weigh more since the hub has to be larger in diameter to accommodate the palms of the blades.

Based upon the foregoing, cast stainless steel, CF8 alloy is recommended for the propeller of a large aluminum-hulled vessel.

Shafting - The shafting for the CHALLENGER is presently made of American Bureau of Shipping Grade 2 steel and the diameters were based on the American Bureau of Shipping rules that were in existence at the time the vessel was constructed in 1965. This ship has an engine with a metric BHP of 9600 and a propeller RPM of 119. The diameter of the shafts are 16-3/4 inches (line shaft) and 19-1/2 inches (tailshaft). The tailshaft has no liner since an oil lubricated stern tube bearing was installed.

In this application it is suggested that the American Bureau of Shipping Grade 2 steel material be retained for the shafting.

Stern Tube, Bearings and Seals - The existing steel hulled ship, has a cast steel stern tube welded into the stern frame casting at the aft end and into the engine room aft watertight bulkhead at the forward end. The arrangement is generally as shown on Figure 14.

There are two stern tube bearings of the oil lubricated type (Waukesha type), one long bearing 43-1/2 inches long at the aft end of the tube and a shorter one, 17-3/4 inches long, at the forward end of the tube.

The materials of the existing assembly as installed in the steel hull ship and the suggested materials for the aluminum hull ship are shown in the table in Figure 14.

All bolts, nuts and studs for the seals and glands exposed to sea water should be made of a combination of 304 or 316 stainless steels, in other words, if the studs or bolts are 304 then the nuts should be 316, or vice versa, to prevent galling.

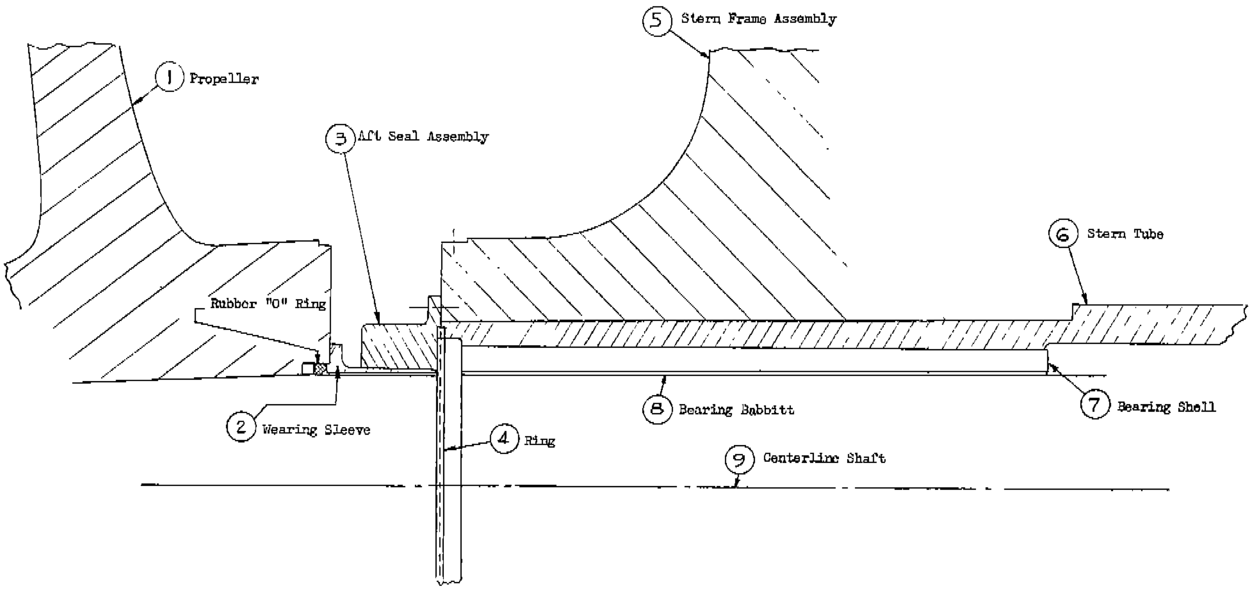
<u>Rudder Assembly</u> - The rudder and rudder stock of the aluminum bulk carrier should be made of steel, similar to that of the steel ship, for the following reasons:

(a) An aluminum stock would have an excessively large diameter, to suit torsional and bending loads, which would result in an unfavorable aspect ratio for the rudder. In addition, steel sleeves would be required in way of the bearings to resist abrasion. Therefore a high-strength steel stock is considered more practical.

(b) The use of a steel stock dictates that the remainder of the rudder be steel, to avoid problems of attachments of dissimilar metals.

(c) The use of a steel rudder minimizes abrasion and vibration problems.

The rudder stock should be isolated from the hull by the use of micarta or phenolic stave bearings. A cathodic protection system is also required, as discussed later. Details of the rudder bearing attachment to the hull will be similar to Figure 14.




| | Part | Existing Ship | Aluminum Hull Ship |
|---|---|---|---|
| (1) | Propeller | Mang Bronze | Stainless Steel - CF8 - Built-up |
| (2) | Wearing Sleeve | 12% Chrome Steel | 304 or 316 Chrome-Ni Stainless Steel |
| (3) | Aft Seal Assembly | Steel | Al - Alloy or 304 or 316 Chrome Ni Stainless Steel |
| (4) | Ring | Mild Steel | Al or 304 or 316 Chrome Ni Stainless Steel |

| | Part | Existing Ship | Aluminum Hull Ship |
|---|---|---|---|
| (5) | Stern Frame | Steel | Aluminum |
| (6) | Stern Tube | Cast Steel | Cast or Fabricated Al |
| (7) | Bearing Shell | Ductile Iron | Ductile Iron |
| (8) | Bearing Babbitt | White Metal | White Metal |
| (9) | Shaft | ABS Grade 2 Steel | ABS Grade 2 Steel |

FIG. 14 Stern Tube & Propeller Details *M. V. Challenger*

Sea Valves - The selection of aluminum alloys for the sea valves and shell connections is subject to specific approval by the American Bureau of Shipping and U. S. Coast Guard.

American Bureau of Shipping Rules - Article 36.25.5 on Page 249 of the American Bureau of Shipping - 1969 Rules is quoted for ready reference as follows:

> "36.25.5 Materials for Shell Valves and Shell Fittings - All shell valves and shell fittings required by this Subsection are to be of steel, bronze or other approved ductile material. Valves of ordinary cast iron or similar material are not acceptable. All pipes to which this subsection refers are to be of steel or other equivalent material, subject to special approval."

U. S. Coast Guard - Marine Engineering Regulations and Material Specifications, Subchapter F, CG-115, Part 56.50-95 Overboard Discharges and Shell Connections, Subchapter F is quoted for ready reference:

> "(f) Valves required by this section and piping system components outboard of such required valves on new vessel installations or replacements in vessels of 150 gross tons and over shall be of a steel, bronze, or nodular cast iron specification listed in Table 56.60-a(a). Lead or other heat sensitive materials having a melting point of 1,700°F, or less shall not be used in such service, or in any other application where the deterioration of the piping system in the event of fire would give rise to danger of flooding. Brittle materials such as cast iron shall not be used in such service. Where non-metallic materials are used in a piping system, and shell closures are required by this section, a positive closure metallic valve is required (see also Para. 56.60-25)."

In addition to cast aluminum alloys, other materials such as cast 25 per cent nickel - 20 per cent chrome and AISI 304 or 316 stainless steel could be considered for the sea valves. This 25 nickel - 20 chrome alloy is marketed under several trade names, Craneloy 20, Walworth Aloyco A-20.

25 Per Cent Nickel - 20 Per Cent Chrome alloy has been used for many years on the Lykes Bros. Gulf-Pride and Clipper Class freighters for sea valve suction and discharge services with good success. These stainless steel valves were fitted with monel trim. The following lists the properties of this alloy:

(a)

| Chemical | Per Cent |
|---|---|
| Carbon | 0.07 |
| Manganese | 0.7 Max. |
| Silicon | 1.5 Max. |
| Phosphorus | 0.04 Max. |
| Sulphur | 0.04 Max. |
| Nickel | 28 to 30 |
| Chromium | 19 to 21 |
| Molybdenum | 2 to 3 |
| Copper | 3.5 to 4.5 |

(b) Mechanical

| | |
|---|---|
| Tensile Strength (As cast) | 65,000 to 75,000 PSI |
| Yield Strength | 28,000 to 38,000 |

(c) Physical

| | |
|---|---|
| Elongation (Per cent in 2 inches) | 35 to 50 |
| Reduction in Area | 50 to 40 |
| Brinnell Hardness | 120 to 150 |

AISI 304 and 316 stainless steels could be used but are not considered to be as good for this service as the 25 per cent nickel - 20 per cent chrome stainless steel.

Aluminum Alloy 356-T6 has been used with apparently excellent results on the hydrofoil DENISON. This material has excellent corrosion resistance, good machinability and excellent pressure tightness. This alloy has the following properties:

| (a) Chemical | Per Cent |
|---|---|
| Silicon | 6.5 to 7.1 |
| Iron | 0.5 Max. |
| Copper | 0.2 Max. |
| Manganese | 0.10 Max. |
| Magnesium | 0.2 to 0.4 |
| Zinc | 0.20 Max. |
| Titanium | 0.20 Max. |
| Aluminum | Remainder |

| (b) Mechanical | Minimum |
|---|---|
| Ultimate Strength | 33,000 PSI |
| Yield Strength | 22,000 PSI |

This alloy has one disadvantage in that the elongation is only about 6 per cent for sand castings and perhaps 12 per cent for permanent molds. This material would have to be approved by the American Bureau of Shipping and the U.S. Coast Guard, since its use on DENISON was approved only for that specific case.

The trim material will have to be carefully selected, depending on the material used for the valve body. If aluminum valves are used, then 304 or 316 stainless steel can be considered. If the stainless steel valves are used then monel 400 could be considered as the trim material.

Valves of aluminum alloys suitable for use in sea water are not readily available and are very difficult to obtain.

Cost data is based on the actual aluminum alloy used, size and quantity. Valves of 25 Nickel - 20 Chrome, and 304 or 316 stainless steel are more readily available in sizes 1/2 inch to 6 inches. A cost comparison of aluminum alloy versus stainless steel valves is as follows:

| Size IPS | Pressure Service Lbs | Type | 304, 316 and 25 Nickel - 20 Chrome Stainless Steel $/Each | 356-T6 Aluminum Alloy $/Each |
|---|---|---|---|---|
| 3" Flgd | 150 | Gate | 263.00 | 268.00 |
| 4" Flgd | 150 | Gate | 376.00 | 389.00 |
| 6" Flgd | 150 | Gate | 610.00 | 622.00 |
| 8" Flgd | 150 | Gate | - | 809.00 |
| 3" Flgd | 150 | Globe | 407.00 | 273.00 |
| 4" Flgd | 150 | Globe | 478.00 | 512.00 |
| 6" Flgd | 150 | Globe | 809.00 | 891.00 |

Cast stainless steel, 25 Nickel, 20 Chrome valves are recommended. However, as stated above, special approval to use materials other than those listed in the Regulations will have to be obtained from the American Bureau of Shipping and the U.S. Coast Guard.

Ballast System - The ballast system for the steel CHALLENGER consists of four 14 inch mains through the tanks, one each in the port and starboard upper wing tanks and double bottom tanks, with 8 inch branches to each tank. The necessary piping connections are provided in the engine room to fill and empty the tanks. In addition, the upper wing tanks are fitted with 6 inch shell valves to permit rapid deballasting directly overboard by gravity. All pipe within the tanks is Schedule 80 galvanized steel.

Several different materials may be used in the ballast system for the aluminum hull ship, with the ultimate choice being based on the balance of installed cost versus compatibility with aluminum and reliability and maintenance cost. The different piping materials considered are aluminum, black steel, galvanized steel, fiberglass reinforced plastic, PVC coated steel pipe, 90-10 copper nickel alloy and stainless steel pipe. Each of these materials have advantages and disadvantages which will be discussed.

An aluminum pipe system with aluminum valves has the basic advantage of being completely compatible with the surrounding hull structure. It is weldable and bendable and there is extensive experience in its use and installation. Because of its corrosion resistance Schedule 40 thickness can be used for ballast piping service. Its major disadvantage is its high initial cost.

A black steel pipe system with black steel or nodular iron valves has the advantages of low material cost and is easily fabricated, bent and welded. However, it is not compatible with the aluminum hull structure, therefore, many measures have to be taken to protect the structure as follows:

(a) Each bulkhead penetration has to be a thick aluminum spool piece.

(b) On each side of this bulkhead spool piece another thick aluminum spool piece has to be fitted to act as a waster piece to protect the bulkhead fitting.

(c) Cathodic protection using expendable aluminum anodes must be fitted within the tanks to protect the aluminum structure.

(d) Pipe supports must be carefully insulated.

(e) The steel piping must be of Schedule 80 thickness to provide reasonably long life in the sea water environment.

A galvanized steel pipe system with galvanized steel or galvanized nodular iron valves has the advantage of being more compatible with the aluminum structure and reduces the corrosion effect of galvanic couple. However, this protection may last only a year since the zinc will waste away. Therefore, the protection of the aluminum structure suggested for the black steel system is also necessary for the galvanized steel system. The installed cost of this system will be somewhat higher than for the black steel system.

A fiberglass reinforced plastic pipe system has the advantage of the material being inert. Bulkhead penetrations would be with flanged aluminum spools. Valves could be either aluminum or 304 or 316 stainless steel. The fiberglass pipe can not be bent and only a few shipboard installations with U. S. Coast Guard approval have been made. U. S. Coast Guard approval would have to be obtained.

A PVC coated steel pipe system requires both the inside and outside of the pipe to be coated in order to provide full protection to the aluminum structure. Steel pipe systems with inner PVC lining only are used quite extensively on shore installations where contamination of the product being handled must be prevented, or where the product is quite active in attacking metals. It has the disadvantage of being costly, must be purchased in fixed lengths, can not be bent, and the coating is subject to mechanical damage. Any break in the coating will cause rapid corrosion of the steel.

An 18-8 stainless steel pipe system has the advantage of being compatible with the aluminum structure, can be readily bent and welded and is acceptable to the U. S. Coast Guard. It has the disadvantage of high initial cost.

A 90-10 copper nickel alloy is excellent for use in sea water applications but has the basic disadvantage that it is not compatible with aluminum and must be insulated and protected similar to the steel systems and, in addition, many heavy wall waster pieces are required.

An estimate of piping materials, quantities and costs has been made of the ballast system within the ballast tanks, Table 14. Certain items which are common to all systems such as bulkhead penetration spools, pipe hangers and valve reach rods have not been included. Installation costs are not included.

The welding, fabrication and assembly costs of the aluminum, carbon steel, 90-10 copper nickel alloy and 18-8 stainless steel piping systems are assumed to be approximately equal and the assembly costs of the plastic and PVC lined steel systems should be somewhat less.

As indicated in Table 14 it can be seen that the fiberglass reinforced plastic pipe system is the lowest in material costs as well as having the advantage of being compatible with the aluminum hull structure. Maintenance of this plastic material for the life of the ship should be very low in cost. It is recommended that this plastic material be used for ballast service in the ballast tank provided it is acceptable to the American Bureau of Shipping and U. S. Coast Guard. Nodular iron or bronze valves insulated from the hull can be used. If this plastic material is not acceptable to the American Bureau of Shipping and U. S. Coast Guard then consideration should be given to the use of an all aluminum ballast system.

TABLE 14 Material Cost - Ballast System (Dollars U.S.)

| Material | Aluminum | Black Steel | Galvanized Steel | Fiberglass Reinforced Plastic | Steel Pipe PVC Coated and Lined | Stainless Steel | Stainless Steel |
|---|---|---|---|---|---|---|---|
| Spec. | 6061 T6 | A53 | A53 | - | | AISI 304 | AISI 304 |
| Schedule | 40 | 80 | 80 | - | | 10 | 40 |
| Type | Seamless | Butt Weld | Butt Weld | "Bondstrand" or equal | Resisto-flex PP | Seamless | Seamless |
| 400 Ft 8" IPS Pipe | 2,940 | 2,962 | 3,554 | 3,180 | 7,900 | 4,744 | 12,732 |
| 2000 Ft 12" IPS Pipe | 31,585 | 22,893 | 27,442 | 29,000 | 59,500 | 41,740 | 124,600 |
| Bhd Penetration Conns. | 31,585 | 22,893 | 27,442 | 29,000 | 59,500 | 41,740 | 124,600 |
| 8" Alum Spool (Waster Piece) | - | 3,000 | 3,000 | - | | - | - |
| 12" Alum Spool (Waster Piece) | - | 12,600 | 12,600 | - | | - | - |
| 8" Flanges (92) | 4,048 | 3,220 | 3,551 | 1,509 | Included in Pipe | 5,300 | 5,300 |
| 12" Flanges (38) | 5,168 | 2,280 | 2,557 | 1,638 | Included in Pipe | 6,250 | 6,250 |
| 8" Valve (23) | - | - | - | - | - | - | - |
| 12" Valve (1) | - | - | - | - | - | - | - |
| 8" Ells (37) | 3,330 | 1,338 | 1,769 | 2,566 | 6,384 | 2,295 | 4,101 |
| 12" Ells (82) | 21,320 | 8,282 | 10,783 | 8,930 | 28,700 | 22,796 | 35,424 |
| 12" Tees (20) | 20,320 | 3,380 | 4,280 | 7,248 | 9,200 | 15,000 | 18,180 |
| Cathodic Protection | - | 3,400 | 3,400 | - | | - | - |
| 8" Couplings (4) | - | - | - | 58 | - | - | - |
| 12" Couplings (18) | - | - | - | 445 | - | - | - |
| Total Cost | 88,711 | 63,405 | 72,936 | 54,574 | 111,684 | 98,125 | 207,587 |

Other Piping Systems and Valves - The bilge system for the proposed ship would consist of a bilge main within the machinery space having the usual bilge suctions in the machinery space and two manifolds for the cargo hold suctions. The cargo hold bilge suctions go forward through the inner-bottom sea water ballast tanks and enter the bilge wells placed at the after end of the holds.

The selection of piping materials for bilge service within the sea water ballast tanks would be subject to the same restrictions as the ballast piping.

An estimate of the material cost exclusive of the check valves required for this service is shown in Table 15. This estimate shows that the material cost of Schedule 40 aluminum pipe system is almost the same as the low-cost Schedule 80 black steel system.

It is therefore recommended that this portion of the bilge system be made of aluminum provided it meets U. S. Coast Guard requirements.

TABLE 15 Material Costs - Bilge System In Ballast Tanks (Dollars U.S.)

| Material | Aluminum | Black Steel | Galv. Steel | Fiberglass Reinforced Plastic | PVC Lined |
|---|---|---|---|---|---|
| Specification | 6061T6 | A53 | A53 | "Bondstrand" or Equal | Resistoflex |
| Thickness | Schedule 40 | Schedule 80 | Schedule 80 | | |
| 2440 Ft 4" Pipe | 5,967 | 5,630 | 6,750 | 10,248 | 16,104 |
| Alum. Bhd Pen (50) | 5,967 | 5,630 | 6,750 | 10,248 | - |
| Alum. Spools (40) | - | 1,800 | 1,800 | - | - |
| Flanges (70) | 1,376 | 506 | 760 | 539 | Included |
| Ells (150) | 3,420 | 1,014 | 1,402 | 2,520 | 8,295 |
| Couplings (36) | - | - | - | 194 | - |
| Valves (10) | ← Not Included → | | | | |
| Cathodic Protection | - | 1,720 | 1,720 | - | - |
| Total Cost | 10,763 | 10,670 | 12,432 | 13,681 | 24,399 |

Firemain - The steel hull ore carrier has a firemain system composed of 90-10 copper nickel alloy piping with bronze valves and fittings. Since the U. S. Coast Guard probably would not approve the use of aluminum alloys or reinforced plastic piping for fire service, it is recommended that the 90-10 copper nickel alloy system be retained for the aluminum hulled ore carrier. Special precautions are necessary to insulate this material for the aluminum structure. The detail of bulkhead and deck penetrations through aluminum structure must be developed. However, there is good experience with this type of installation on the SS UNITED STATES.

Oil Systems - Black steel is usually used in the construction of oil piping systems. The U. S. Coast Guard will not approve the use of aluminum for these systems because of its low melting point. In addition, because of the non-conductive characteristics of fuel oil and the need for the fire protection provided by steel, it is considered that the fuel oil transfer and service systems, both heavy oil and diesel oil should be of all steel construction. Since lubricating oil has similar characteristics and requirements as fuel oils, it is considered that the lubricating oil service, transfer and purifying systems should also be of all steel construction. Special precautions are necessary where the steel piping penetrates the aluminum structure.

Diesel Engine Fresh Water Systems - The steel hull ore carrier has the diesel engine fresh water systems made of Schedule 40 galvanized steel pipe. For the aluminum hull ship it is recommended that the same material be used for these systems, with special precaution to insulate the system from the aluminum hull structure.

Sea Water Systems Within the Machinery Spaces - The systems under consideration are sea water cooling service systems for all heat exchangers, clean ballast system, oily ballast system and bilge system.

The steel hull ore carrier has the sea water service systems within the machinery spaces composed of 90-10 copper nickel alloy with bronze valves and fittings. Because of U. S. Coast Guard Regulations, it is recommended that these materials be retained for the sea water service systems in the aluminum hull ship. However, insulation of the entire system is required, particularly at the connections between the piping and the sea valves. If the U. S. Coast Guard would approve the use of aluminum for this service, it should be considered. However, it will be very costly in comparison to the 90-10 copper nickel alloy system, primarily due to the high cost of valves and fittings.

The steel hull ore carrier ballast system within the machinery spaces is of Schedule 80 galvanized steel pipe. For the aluminum hull ship it is recommended that the ballast system within the sea water ballast tanks be of fiberglass reinforced plastic. However, there is some question as to whether the U. S. Coast Guard will accept this material within the machinery spaces. If the U. S. Coast Guard accepts the use of fiberglass reinforced plastic, this will permit the use of standard materials for pumps and valves and reduce maintenance costs. The second choice would be aluminum pipe and valves. Since large capacity centrifugal pumps of aluminum are not available, special pump connections with replaceable waster pieces must be provided.

The steel hull ore carrier bilge system within the machinery spaces is of Schedule 40 galvanized steel pipe. For the aluminum hull ship it is recommended that the bilge system in the machinery spaces be of aluminum. This presents the same problem as noted above, namely, the requirement of heavy waster pieces at the pump connections. However, in this case they will be comparatively small (5 inch or 6 inch IPS) and their replacement is not too expensive. For this reason an all aluminum Schedule 40 piping system is recommended.

The weather deck and sanitary drainage systems for the steel hull ore carrier are all made of galvanized steel Schedule 80 pipe. It is recommended that all aluminum construction be used for these systems in the aluminum hull ship, using Schedule 40 aluminum piping to simplify the many connections and structural penetrations.

The tank venting system and sounding tubes for the steel hull ore carrier are all made of galvanized steel, Schedule 80 in way of the upper wing ballast tanks and Schedule 40 for the remainder of the piping. Because of the many connections to structure and structure penetrations of these systems, it is recommended that they be made of all aluminum construction for the aluminum hull ship. Schedule 40 aluminum piping should be used.

The steel hull ore carrier was fitted with independent potable water and sanitary water systems. The potable water system was made of copper tubing with bronze valves and fittings. The sanitary water system was made of 90-10 copper nickel alloy tubing with bronze valves and fittings. For the aluminum ship it is recommended that fresh water be used for flushing and the sanitary supply system be combined with the potable water systems. Although this would require an increase in the capacity of the distilling plant, the total cost would be reduced. In addition, the piping system should be made of PVC or aluminum, Schedule 40, whichever is the more economical.

The ship will be fitted with two compressed air systems, a 400 PSI system for diesel engine starting and a 100 PSI system for ship service. The diesel engine starting air system should be of all steel construction, to suit the high operating pressures. The low pressure ship service air system should be of all aluminum construction, because of exposure to salt laden air and multitude of contacts with the aluminum structure. Schedule 40 aluminum piping probably will be satisfactory for this 100 PSI air system.

Pumps - Pumps will be required to handle heavy fuel oil (Bunker C), diesel oil, lubricating oil, fresh water and sea water.

Steel is recommended for oil pumps, in order to meet U. S. Coast Guard Regulations, and because the piping systems are steel. Nodular iron may be used for the pump casings.

Casings - Steel or Nodular Iron
Rotors - Steel
Shafts - Steel

Fresh water piping systems are to be either steel or PVC. Standard materials should be used for the fresh water pumps. The materials are:

Casings - Bronze - Composition G
Impellers - Bronze - Composition G
Shafts - Steel with K Monel Sleeves

For the sea water pumps, the liquid handled is a good electrolyte, and aluminum should be preferably used. However, aluminum pumps are not readily available and, if used, the metal does not have adequate erosion resistant properties for this service. Also, for the sea water service and fire service the piping materials are not compatible. Therefore, for these pumps and the ballast pumps the recommended materials are:

Casings - Bronze - Composition G
Impellers - Monel
Shafts - Monel with K Monel Sleeves

For the bilge pumps, the liquids handled include sea water and the piping material recommended is aluminum. As noted above, aluminum pumps are not considered practical. The pumps could be made of a suitable stainless steel. However, it would appear to be more economically feasible to use pumps made of the same materials as recommended for the sea water pumps and provide extra heavy waster pieces at the piping suction and discharge connections.

SEA CHESTS

Sea chests and overboard discharge connections should be made of cast or fabricated aluminum of the same composition as the hull material. Aluminum pipe of heavy wall construction may be used for overboard discharge shell connections.

Cuts in the shell plating in way of the sea chests and overboard discharges should be compensated for by the use of heavy insert plates, since pitting has been observed in way of overboard discharges on some existing aluminum hulls.

Suction sea chests should be fitted with portable 304 or 316 stainless steel or approved type reinforced plastic strainer plates with 1/2 inch x 3 inch or 4 inch long slots placed in a fore and aft direction. All strainer plates must be recessed in such a way as to be removable with no part of the plate or securing studs and nuts projecting beyond the shell. All strainer plates should be secured in place with 304 or 316 stainless steel studs and nuts. All sea suctions should be fitted with the usual venting and air and steaming out connections.

If 25 nickel - 20 chrome sea valves are used, aluminum waster insert pieces should be installed in each sea chest and overboard discharge connection. If aluminum alloy sea valves are used then aluminum insert waster pieces are not required.

SUPPORTS FOR PIPING AND MACHINERY

Piping Supports - All dissimilar metal piping systems supports connected to the aluminum hull structure should be insulated from same. Non-absorbent type insulating materials such as plastic electric tapes, butyl rubber tapes, strips and sheets, and neoprene strips or sheet should be used as a lining between the pipe and the aluminum hanger.

Deck Mounted Machinery Supports - Most of the deck mounted machinery such as winches, anchor windlass, etc. are made of cast or fabrication steel parts, including the subbase which is normally bolted to a steel foundation. On the aluminum hull ship these foundations will be made of aluminum. Since it is not economically feasible to provide deck machinery with aluminum base plates, the joint must be insulated.

For light weight machinery or fittings, all faying surfaces should be cleaned and primed with zinc chromate. A butyl rubber type compound coating should be applied to the underside of the machinery or fitting base plates and allowed to dry. When the machinery or fitting is about to be installed, a second coat of such a compound should be applied. When the machinery or fitting is bolted down, a quantity of this coating will be squeezed out around the periphery of the base plate, and this excess material should be worked and formed into a large fillet thereby providing an effective seal. The bolting must be carefully considered and for deck service the use of 304 or 316 stainless steel bolting can be justified. If carbon steel bolting is used, it should be aluminized, galvanized or cadmium plated and plastic or neoprene bushings and washers should be used. As long as sea water spray can be kept out of the joint, no corrosion will occur. For this reason absorbent type materials should never be used and extreme care should be taken to make the bolted connection weathertight.

Large heavy type machinery must be handled in a different manner. All faying surfaces should be cleaned and primed with zinc chromate and coated with a good paint system. If metallic chocks are used they can be treated on both sides with a butyl rubber type compound as described above for light weight equipment, lined up and then bolted down. Bolting should be handled in a similar manner. Cast-in-place plastic chocks can also be used, together with special bolting arrangement and materials. The foundation must be designed so that the under portion of the steel based machinery and the top plate of the foundation can be inspected and maintained.

Enclosed Space Machinery Supports - Machinery installed in the Engine Room can be supported in a manner similar to that described previously for deck mounted machinery. In some instances non-metallic chocking materials such as plastic cast-in-place, can be used to insulate the engines, turbines, gears or other equipment from the aluminum foundation. In general, main machinery alignment requirements such as those for propulsion machinery and bearings limit the type of insulation to some of the more effective protective coatings, particularly along the faying surfaces of the connection. For this reason, it appears that the cast-in-place plastic type materials would be practical and beneficial. There has been extensive service experience with this type cast-in-place chocking material. On light weight equipment flexible type shock mounts could be used for insulating the machinery from the aluminum hull.

## HULL CORROSION CONTROL

The aluminum alloys under consideration are highly resistant to sea water and a marine environment. From a corrosion standpoint it is desirable not to paint the aluminum. However, an anti-fouling paint system will be applied and abrasions and scratches in the paint system will concentrate the corrosion attack in these relatively small localized areas. Thus, the corrosion which would have occurred over a very large area when the hull is not painted is now directed to these isolated spots. In addition, when aluminum alloys are combined with other metals normally used in shipbuilding and are in the presence of an electrolyte, such as sea water, galvanic action will result and the aluminum alloy will be subject to attack unless it is effectively protected.

The necessity of protecting a ship built of aluminum has therefore been investigated and evaluated. Since the underwater portion of the hull will be painted with an anti-fouling paint system and the rudder and propeller will be made of a material other than aluminum, it is considered essential that a hull corrosion control system should be installed to protect the underwater hull surface. Experience over many years duration has shown excellent results in protecting steel hull ships by use of controlled systems.

It is, therefore, recommended that an impressed current cathodic protection system be installed. The installation of a reliable automatically controlled, impressed current cathodic protection system will provide a long service life of aluminum hull ships even when the paint system has been broken. Service experience has proven an economic advantage for these systems.

The purpose of such a system is to eliminate the corrosion of metals and also to prevent the galvanic corrosion of dissimilar metals when they are immersed in sea water.

The system proposed herein is based on the protection of the exterior wetted hull surface of approximately 80,000 square feet. When properly installed, operated and monitored such a system will minimize the corrosion of the aluminum hull and rudder and the propeller. The interiors of sea chests, other intakes and discharges are only protected to a limited degree by the impressed current system. If it is necessary to protect these areas, then other special installation arrangements or coatings must be considered. The system under consideration has little effect on marine growth on the hull. However, the chlorine generated at the anodes acts as an effective sterilizing agent and it is quite normal for the hull areas in the immediate vicinity of the anodes to be completely free of marine growth.

The current necessary to protect the aluminum hull system is estimated to be approximately the same as that required for a steel hull system of the same amount of wetted surface and is estimated to be about 650 amps. The following basic components are required for such a system:

(a) Reference Cells - These units are mounted through the aluminum hull, below the light load or ballast waterline and are insulated from the hull and do not receive any anode current. These reference cells or electrodes are used to create a potential between themselves and the hull which prevents corrosion of the ship's hull.

(b) Anodes - The anodes are also mounted through the aluminum hull and are electrically insulated from the hull. Each anode is connected to a power supply and a current flows from the anode to the hull. This current suppresses the current flow from all the small anodic areas and puts the entire hull in a "cathodic" condition which stops the corrosion of the hull material.

(c) Controller - A controller is needed to control the power supply and consequently the anode output. This controller measures hull potential relative to the reference cells and adjusts the power supply as necessary to maintain the hull at some predetermined "corrosion free" potential.

(d) Power Supplies - The power supply converts the ship's AC power to low voltage - high amperage direct current which is delivered to the anodes and the hull and also provides means for automatically adjusting the direct current output as directed by the controller.

At least six anodes are required to protect the entire wetted surface of this aluminum hull. Each anode would be 4 feet long, and is a flush mounted strip type platinum anode molded in a rectangular glass reinforced polyester holder. The anode holder is approximately 4-3/8 inches wide and protrudes from the hull only one inch. The hull surface around each anode is covered with an insulating shield to prevent "short-circuiting" of the impressed current to only the immediate area of the hull.

The current required to protect the aluminum hull is about the same as that required for a steel hull of the same wetted surface. However, the shields that must be installed around the anodes for the aluminum hull application must be larger in area and must be very carefully installed in order to provide insulation to the aluminum plates in the immediate vicinity of the anodes. The shields must be applied without any gaps. This precaution is extremely necessary since aluminum is an amphoteric metal which suffers attack in an alkaline environment. Six epoxy shields would be required, one for each anode. An area of approximately 8 x 12 feet is coated with the epoxy after the anode is installed. Basically the shield material is built up of successive coats of a coal tar epoxy or tarset. Three to 4 layers are troweled on the cleaned aluminum surface. The final thickness of the shield film is about 12 mils minimum.

Shaft Ground Assembly - In addition to the hull protection system, the propeller shafting system must be provided with a grounding assembly, which is used to electrically connect the rotating shafting system to the hull. The propulsion shafting system is effectively insulated from the hull and this shaft grounding assembly is necessary to permit the anode current which flows through the water to enter the propeller blades and return to the hull. If the propulsion shafting system is not properly grounded, the protective current flow which enters the propeller must flow through the shafting system bearings to the hull and the current is greatly reduced due to the high resistance of the path that the current must follow. The proposed system consists of a silver alloy band strapped to the shaft, cast bronze brush holder and two brushes made of a silver graphite alloy (90 per cent silver - 10 per cent graphite).

A cathodic protection system suitable for the aluminum ship was discussed with Engelhard Industries. This Company has provided hundreds of such systems for protection of steel hull ships and has considerable knowledge in this area. Engelhard Industries believes that the aluminum hull under consideration can be effectively protected and recommended a system using the following equipment to protect a ship having a wetted surface of about 80,000 square feet:

| Description of Equipment | Number of |
|---|---|
| Transistorized Twin Controller | 1 |
| Saturable Reactor Power Supply - 450 Amps | 1 |
| Saturable Reactor Power Supply - 200 Amps | 1 |
| Anode Assemblies - Each 4 Feet Long (2 Anodes will be located forward, 2 Midship and 2 Aft) | 6 |
| Reference Cell Assemblies | 2 |
| Propeller Shaft Ground Assembly | 1 |
| Remote Ammeter Station | 1 |
| Shaft Hull Millivolt Meter | 1 |

The estimated cost of this equipment is $10,285.

Shore Power Transformer - Many partially immersed shoreside structures such as piers, retaining walls, pilings, etc. are of steel construction, and when an aluminum hull is brought into proximity with them, a strong galvanic couple exists, with the aluminum being anodic (or "sacrificial") to the steel. Actual corrosion of the aluminum requires a return path for corrosion currents, i.e., another conductive path from the steel back to the aluminum hull. Unfortunately, since most shore power systems are grounded, and shipboard power systems usually have a path to the ships hull through ground detection equipment, the shore power cables, when brought aboard provide this return path, and the aluminum hull corrodes rapidly and severely. In order to avoid this problem, aluminum-hulled vessels are usually provided with one-to-one isolating transformers at the shore power connection to effectively avoid creating a return path for galvanic corrosion current. It is also important to avoid providing metallic paths from the hull to ground at pierside by means of accommodation ladders, loading conveyors, etc. Auxiliary anodes may be dropped over the side when moored to provide added protection.

## IIG. OPERATIONAL CHARACTERISTICS OF AN ALUMINUM BULK CARRIER

The operational characteristics of a bulk carrier will be profoundly affected by the substitution of aluminum for steel as the hull material, particularly in the areas of hull maintenance, repairs, special surveys and insurance. In the following paragraphs, each of these factors will be briefly discussed.

### MAINTENANCE

Past experience with aluminum hulls and deckhouses indicates that it is feasible and desirable to keep the topsides and all internal surfaces unpainted, although antifouling paint will be required below the deep load line. The unpainted aluminum surfaces may eventually develop streaks and blotches and will become progressively darker. However, for a bulk carrier this consideration will be of secondary importance. Topside and internal painting or coating is not recommended, since any local breakdown in the surface of the paint will tend to localize corrosive attack.

In general, it appears that normal topside maintenance will be limited to an occasional water wash and scrubbing. However, the renewal of anti-fouling paint will be required periodically, as will bottom scraping. This, coupled with requirements for maintaining equipment, appendages and outfit, will result in essentially the same drydocking cycle for aluminum and steel hulls. It is noted that the removal of paint and marine growth from aluminum surfaces requires greater care than with steel. Conventional scraping and sandblasting methods must be modified to suit the lower abrasion resistance of aluminum. Sand washing has proven successful in removing old paint from aluminum surfaces.

During drydocking, special attention should be paid to the sacrificial anodes or components of impressed current systems, as well as to the condition of propellers, and other appendages, sea chests, overboard discharges, etc. where corrosion could be present. Anodes or waster pieces installed in fuel and ballast tanks should be reviewed periodically, and all piping and structure in the vicinity of bimetallic joints should be carefully checked for signs of corrosion.

The interface between all steel equipment (winches, windlass, etc.) and aluminum foundations should be checked periodically to ensure that the isolation material at the faying surfaces is intact and that no corrosion is taking place. Areas subject to chafing, such as in way of chocks and bitts, anchors and hatch coamings, should also be checked and renewed as required.

## REPAIRS

Obtaining proper repairs to hull damage, or minor structural modifications to an aluminum ship will be more difficult than with a steel ship, since the number of repair yards with qualified aluminum welders is relatively limited, as is availability of required materials in the alloys, tempers and thicknesses required. The lack of qualified welders is a particularly important factor, since the use of improperly trained welders can lead to significant problems. Downtime while awaiting arrival of necessary materials and skilled personnel to effect repairs could be a significant economic factor, though the effects of this factor will diminish as aluminum gains wider acceptance.

## SPECIAL SURVEYS

At this time, the Regulatory Bodies have no special policy relative to additional surveys for aluminum hulled vessels. However, based upon the large size of the aluminum bulk carrier being considered, as well as the problems with cracking of aluminum ship structures in the past, it would appear advisable to schedule additional structural surveys, at least for the prototype vessels. In order to be effective, these surveys should include close examination of internal structures, particularly in way of welded connections. Since this would entail gas freeing tanks and cleaning of all surfaces, it would be advisable to spot check in a limited number of tanks, and check others only if problems are uncovered. Additional items to be checked would include those noted in the previous discussion of hull maintenance, as well as a careful examination of shell and deck plates for signs of cracking or corrosion. It would be desirable to periodically re-Xray selected plate seams and butts in critical locations to ensure that internal fatigue cracks are not developing. It would also be desirable to remove selected pieces of equipment from their foundations to check the condition of the interface, the insulating material and the bolts.

## HULL INSURANCE

The cost of hull insurance for an aluminum bulk carrier will undoubtedly be higher than that of an equivalent steel hull, due to its higher replacement and repair cost and the greater risk of loss by fire. The relative increase is difficult to predict, since it is dependent upon the degree of fire protection provided, types of cargo to be carried, risk of fire as affected by type of machinery and equipment installed and other factors.

# III. COMPARATIVE SHIP DESIGN AND EVALUATION

In this phase of the study, equivalent hypothetical aluminum and steel bulk carriers are developed which are essentially identical to the M.V. CHALLENGER. This includes the following tasks:

- o Selection of principal dimensions.
- o Design of midship section.
- o Design of typical bulkhead.
- o Light Ship Weight Estimate.
- o Stability and Trim.

SELECTION OF PRINCIPAL DIMENSIONS

The principal dimensions of the steel bulk carrier will be identical to those of the M.V. CHALLENGER, as delineated in Table 1. The aluminum bulk carrier is assumed to be identical in full load displacement, with the reduction in light ship weight used to increase the cargo deadweight, and thus the earning capacity. The anticipated increase in available cargo deadweight is about 2,700 tons or 7-1/2 per cent, which means that the existing cargo hold dimensions would be satisfactory for all but the most volume-critical cargoes such as grain. For a new design, the hold volume could be increased accordingly. However, for this study, the volume of the cargo holds for the steel and aluminum ships will be kept identical to permit direct comparison.

All hull dimensions and form coefficients of the two ships are to be identical, so that speed-power relationships at full load displacement are similar. This means that the power plants of the two ships will be identical, thereby eliminating costs associated with the machinery system as variables.

It is recognized that this approach, although satisfactory for a feasibility study, will not necessarily result in an optimum aluminum hull. For example, the reduction in hull weight without a corresponding reduction in the machinery weights will result in greater trim by the stern in some conditions. It might also be desirable to increase the hull and double bottom depth to increase stiffness. However, these are the type of refinements which can easily be incorporated in the design if desired, but which should be excluded from this feasibility study if a direct basis is to be maintained for comparing the two designs.

Another feature of the M.V. CHALLENGER which bears consideration is the selection of propulsive power. The ship, as built, is powered by a 9,600 SHP diesel engine, which is questionable for U. S. Flag operation. A brief investigation was made of the feasibility of installing a steam plant within the present hull. This study indicated that the following changes would be required to facilitate installation of a steam plant:

(a) Increase the height and/or length of the machinery box.

(b) Modify the weight of the propulsive system.

(c) Increase the fuel capacity to maintain the present range, due to the higher specific fuel consumption of the steam system.

The magnitude of the above changes would necessitate a complete redesign of the ship, even for this preliminary feasibility study.

Since the machinery systems of both the steel and aluminum ships are to be identical, and thus do not directly affect the relative economic tradeoffs between the two designs, it appears preferable to retain diesel propulsion for this study in order to preserve the integrity of the existing design.

DESIGN OF MIDSHIP SECTION

The midship section of a steel bulk carrier equivalent to the M.V. CHALLENGER, designed to suit 1969 ABS Rules, is shown in Figure 15. This section differs slightly from that of the M.V. CHALLENGER shown in Figure 2, to reflect upgrading of scantlings to suit the latest Rules, and elimination of the additional bottom plate thickness requested by the owner as an abrasion allowance.

The design of the midship section of the aluminum bulk carrier has been carried out in two steps. The first design was developed in accordance with the criteria developed previously with the hull girder section modulus based upon the relative short-term or static strengths per Equation (1). The deck and bottom scantlings were then upgraded to suit the fatigue strength criteria (See Figure 13) to determine the relative effects of this more severe requirement. The resultant midship sections are shown in Figures 16 and 17.

These midship sections are based upon the welded properties of 5083 alloy as delineated in Table 4. Built-up sections have been used for the stiffeners at the extreme fibers of the hull girder so that the somewhat higher strength of the plate temper, H321, would govern the design. Extrusions have been specified for stiffeners in portions of the hull closer to the neutral axis.

The tank top and lower wing bulkhead plating reflect an allowance of about 0.80 inch for impact and abrasion in the hold. This is an increase of about 4 times the 0.20 inch allowances applied by ABS for steel bulk carriers, in accordance with Equation (3). As noted previously, this approach is considered to be more desirable and less costly than installing mechanically fastened steel chafing strips or steel doubler plates. In deriving the hull girder section modulus of the aluminum ships, a somewhat thinner "effective" thickness was used for this plating, based upon increasing the minimum required aluminum plating thickness by a factor equivalent to the addition of 0.20 inches to the minimum steel thickness for abrasion.

Throughout the design of the aluminum midship sections, the maximum plating thickness has been restricted to 1-1/2 inches, since the properties of thicker plate are less. This has created some difficulty in obtaining sufficient deck area for the midship section in Figure 17. For this study, the additional area has been included in the deck longitudinals, sheer strake and hatchside girder. Several alternatives are available:

(a) Use a cellular deck structure, with two skins about 1-1/4 inches thick separated by about 3-1/2 feet, tied together with longitudinal webs, about 3 feet apart. This structure might be more difficult to fabricate, but would provide a safety factor on cracking in that a crack initiating in the upper skin would probably not extend down to the lower skin except under extreme circumstances.

(b) The deck and longitudinal stiffener thicknesses could be reduced by installing a doubler on the deck. However, this could lead to possible crevice corrosion problems.

In accordance with the discussion of crack arresting in Section IIC., a mechanically fastened seam has been indicated at the lower edge of the sheer strake. However, the two additional seams per side incorporated at the deck and bilge of the steel ship have been omitted.

Several additional longitudinal stiffeners have been added to the bottom shell outboard and lower wing bulkhead to increase buckling strength.

Table 16 presents a comparison of the three midship sections shown in Figure 15 through 17. As indicated therein, the use of static strength design criteria results in a weight per foot ratio of approximately 0.47, while the more stringent fatigue strength criteria increases this factor to 0.62. In terms of overall hull structural weight, this fatigue strength criteria is expected to add about 435 tons or 15 per cent to the hull structural weight,

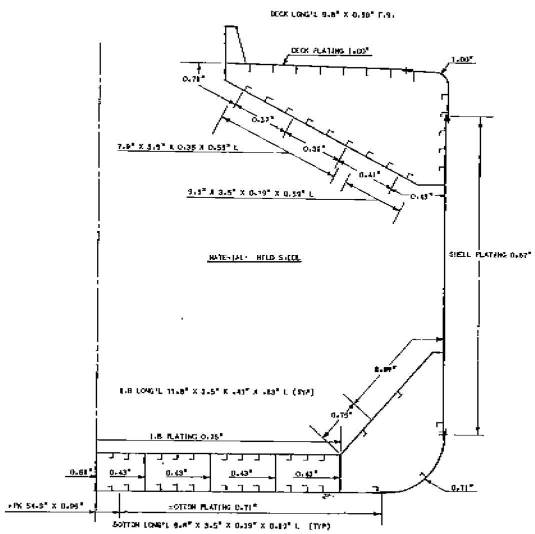


FIG. 15 Midship Section
Steel Bulk Carrier

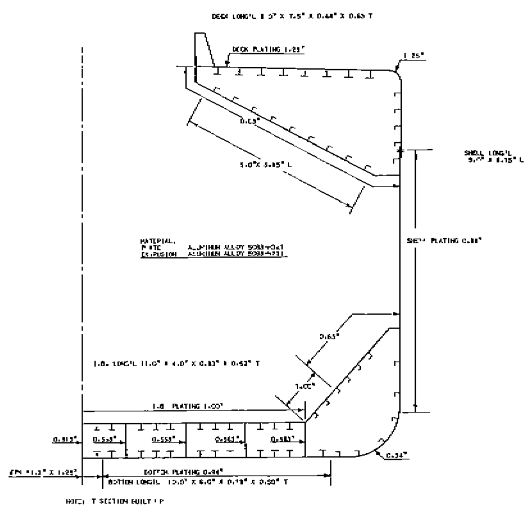


FIG. 16 Midship Section - Aluminum
Bulk Carrier Static Strength
Requirements

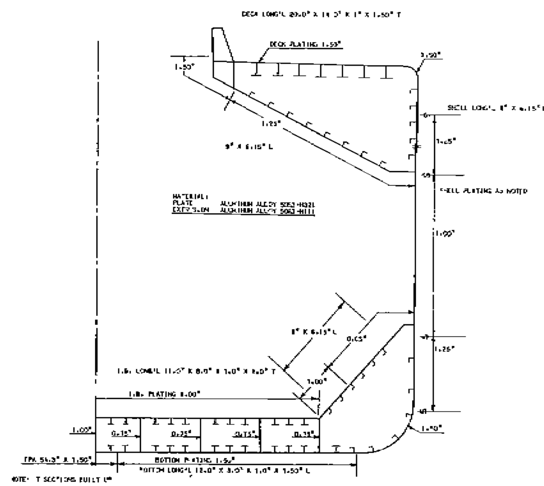


FIG. 17 Midship Section - Aluminum
Bulk Carrier Fatigue Strength
Requirements

assuming the increase is applicable throughout the midship 0.6 length. As will be noted later, the overall reduction factor for the primary aluminum hull structural weight is 0.57, corresponding to a weight savings of 43 per cent.

TABLE 16 Comparison of Aluminum and Steel Bulk Carrier Midship Sections

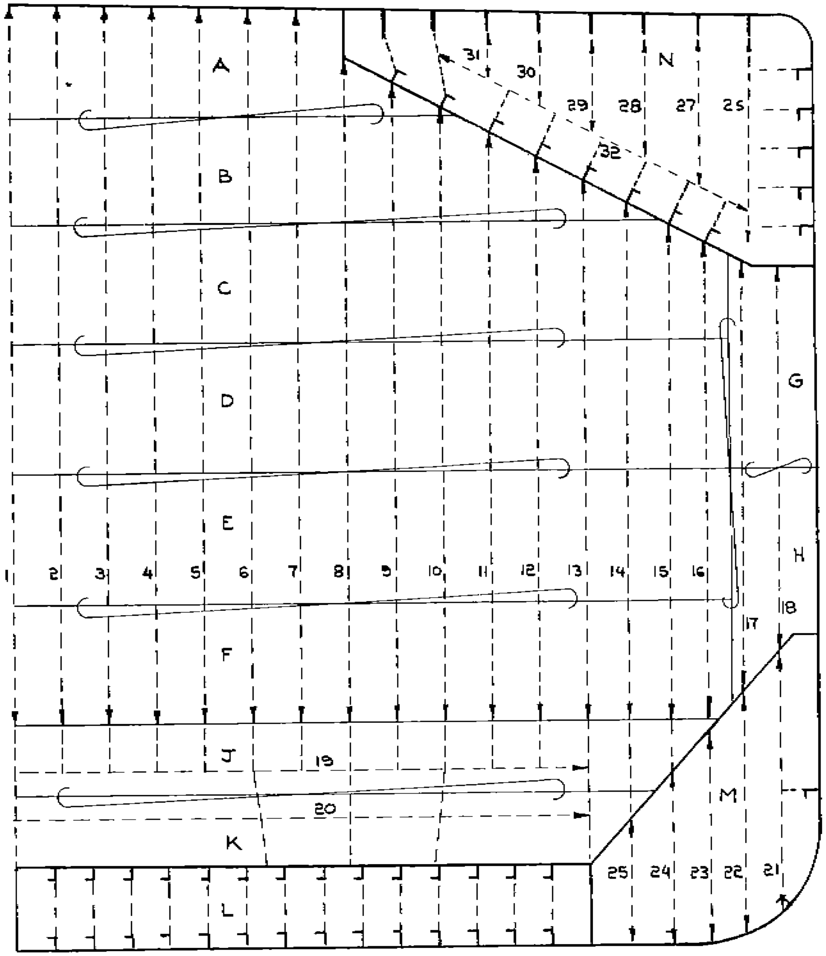
| Item | Steel Figure 15 | Aluminum Static Strength Figure 16 | Aluminum Fatigue Strength Figure 17 |
|---|---|---|---|
| Weight per foot*, tons | 7.99 | 3.718 | 4.930 |
| Weight/foot relative to steel | - | 0.465 | 0.617 |
| Section Modulus (Deck) $in^2ft$ | 67,090 | 88,757 | 135,890 |
| Section Modulus (Bottom) $in^2ft$ | 89,405 | 117,196 | 171,969 |
| Minimum S.M. relative to steel | - | 1.323 | 2.025 |
| Moment of Inertia, $in^2ft^2$ | 2,042,914 | 2,691,992 | 4,048,154 |
| EI, $in^2ft^2$ | $6.129 \times 10^{13}$ | $2.692 \times 10^{13}$ | $4.048 \times 10^{13}$ |
| EI, relative to steel | - | 0.439 | 0.660 |
| * Including transverse structure | | | |

The weight penalty resulting from the use of the fatigue criterion is considered more than offset by the benefits in long-term hull girder strength and stiffness which are gained. Therefore, the section shown in Figure 17 is proposed as the aluminum equivalent of the steel section in Figure 15.

The EI ratio of the proposed aluminum section is approximately 66 per cent of that of the steel ship, resulting in hull girder deflections being increased by a factor of 1.5. This is not considered excessive, based upon the discussion of hull girder deflection in Section IIC, and reaffirms the conclusion that the hull girder scantlings should be based upon strength requirements rather than an arbitrary deflection limitation for hulls of this type.

## DESIGN OF TYPICAL BULKHEAD

Figure 18 shows a typical transverse bulkhead utilizing mild steel and 5083 aluminum construction respectively. The steel bulkhead reflects current ABS requirements, and the conversion to aluminum was based upon the criteria presented in Section IIC. The ratio of aluminum to steel weights is 0.55, corresponding to a 45 per cent weight savings, which is consistent with the savings noted previously for the primary hull structure.




| ITEM | MILD STEEL | ALUMINUM<br>PLATE = 5083-H321<br>EXTRUSION = 5083-H111 |
|---|---|---|
| PLATING | | |
| A | 0.28 | 0.38 |
| B | 0.32 | 0.38 |
| C | 0.35 | 0.44 |
| D,G,N | 0.39 | 0.500 |
| E | 0.41 | 0.500 |
| F,H | 0.45 | 0.56 |
| J | 0.61 | 0.85 |
| K | 0.75 | 1.00 |
| L,M | 0.57 | 0.69 |
| STIFFENING | | |
| 1,8 | 27.2 X 9.8 X 0.43 X 0.50 T | 30.0 X 12.0 X 0.88 X 1.00 T |
| 2,3,4,5,6,7 | 27.2 X 7.1 X 0.43 X 0.50 T | 30.0 X 8.5 X 0.88 X 1.00 T |
| 9,10,11,12,13 | 19.7 X 10.6 X 0.39 X 0.50 T | 22.0 X 13.3 X 0.63 X 1.00 T |
| 14,15,16 | 19.7 X 7.1 X 0.39 X 0.50 T | 22.0 X 8.5 X 0.63 X 1.00 T |
| 17,18 | 15.8 X 3.9 X 0.51 X 0.71 L | 18.0 X 8.0 X 0.50 X 0.75 T |
| 19,20 | 7.9 X 3.5 X 0.35 X 0.55 L | 10.0 X 4.0 X 0.38 X 0.50 T |
| 21,22 | 11.8 X 3.5 X 0.43 X 0.63 L | 13.5 X 5.8 X 0.50 X 0.63 T |
| 23,24,25,26 | 9.8 X 3.5 X 0.39 X 0.59 L | 11.5 X 5.8 X 0.44 X 0.56 T |
| 27,32 | 7.9 X 3.5 X 0.35 X 0.55 L | 10.0 X 5.0 X 0.38 X 0.50 T |
| 28,29,30,31 | 5.9 X 3.5 X 0.35 X 0.35 L | S 8 X 5 X 5.07# L * |

* STANDARD SNAME ALUMINUM ANGLE

(ALL DIMENSIONS IN INCHES)

FIG. 18 Typical Bulkhead Steel and Aluminum Bulk Carriers

LIGHT SHIP WEIGHT ESTIMATE

In order to develop comparative light ship weights for the steel and aluminum ships the weight estimate and inclining experiment for the steel "CHALLENGER" were first combined and analyzed resulting in an "as inclined" light ship weight, as shown in Table 17.

| | Weight Long Tons | VCG Feet | Vert. Momt., Ft.Tons | LCG Feet | Long'l Momt., Ft.Tons |
|---|---|---|---|---|---|
| Steel | 5,920 | 29.9 | 177,008 | 4.0'A | 23,680A |
| Equip. & Outfit | 1,190 | 53.4 | 63,546 | 124.0'A | 147,560A |
| Machinery | 752 | 29.4 | 22,109 | 200.0'A | 150,400A |
| Light Ship | 7,862 | 33.4 | 262,663 | 40.9'A | 321,640A |

TABLE 17 Light Ship Weight Estimate - Steel Construction

Subsequent to the inclining, an additional margin of 30 tons was arbitrarily added to light ship in the Booklet of Loading Conditions.

Coefficients for converting the weight of the steel ship to an equivalent aluminum ship are shown in Tables 19, 20 and 21. Light ship for the aluminum equivalent to the CHALLENGER is summarized in Table 18.

| | Weight Long Tons | VCG Feet | Vert. Momt., Ft.Tons | LCG Feet | Long'l Momt., Ft.Tons |
|---|---|---|---|---|---|
| Hull Structure | 3,375 | 29.82 | 100,638 | 2.41A | 8,125A |
| Equip. & Outfit | 1,027 | 53.90 | 55,365 | 166.70A | 170,550A |
| Machinery | 720 | 29.60 | 21,312 | 200.00A | 144,000A |
| Total Without Margin | 5,122 | 34.62 | 177,315 | 63.00A | 322,675A |
| Margin | 78 | + .38 | | | |
| Total with Margin | 5,200 | 35.00 | 182,000 | 63.00A | 327,600A |

TABLE 18 Light Ship Weight Estimate - Aluminum Construction

It should be noted that some of the conversion factors ($C^{Al.}/Stl$) reflect engineering judgements based on previous studies and assumptions as to the percentage of items included in the original group weight breakdown which would be affected by the conversion between steel and aluminum.

The steel-to-aluminum weight conversion factors for hull structure, Table 19, are based upon the following considerations:

(a) Comparison of typical midship section in steel and aluminum, Figures 15 and 17. For hull framing, shell and decks; $C^{Al.}/Steel = 0.465$ for main structure (Table 16) with a 50 per cent increase for fatigue in the midbody.

(b) Comparison of typical bulkheads in steel and aluminum, for which $C^{Al.}/Steel = 0.546$ for bulkheads and similar major structures.

(c) Comparison of less significant items, based on samplings from previous studies, indicates that $C^{Al.}/Steel = 0.55$ for castings, forgings, miscellaneous weldments and minor structures.

(d) The allowance for welding was increased from 1.15 per cent for the steel CHALLENGER to 3 per cent for the aluminum ship based on the additional welding required for aluminum and the complications of dissimilar metals attachment.

TABLE 19 Aluminum Bulk Carrier
Hull Structure Weight Estimate

| Item | Weight Steel (Long Tons) | Sub-division | Weight Steel (Long Tons) | Basic Weight Coeff. | Weight Alum. (Long Tons) | Fat-igue Coeff. | Weight Alum. (Long Tons) |
|---|---|---|---|---|---|---|---|
| Shell Plating | 1,565 | Midbody (60%) | 939 | .465 | 436.6 | 1.50 | 655 |
| | | Ends (40%) | 626 | .465 | 291.0 | - | 291 |
| Framing | 325 | Midbody (60%) | 195 | .465 | 90.7 | 1.50 | 136 |
| | | Ends (40%) | 130 | .465 | 60.5 | - | 61 |
| Interbottom | 1,550 | All | 1,550 | .465 | 720.7 | - | 721 |
| Bulkheads | 925 | All | 925 | .546 | 505.0 | - | 505 |
| Deck | 1,035 | Midbody (70%) | 725 | .465 | 337.1 | 1.50 | 506 |
| | | Ends (30%) | 310 | .465 | 144.1 | - | 144 |
| Walls & Casing | 235 | All | 235 | .546 | 128.3 | - | 128 |
| Engine Seat | 50 | All | 50 | .55 | 27.5 | - | 28 |
| Forging & Castings | 50 | Fwd (Remains Steel) | 25 | 1.00 | 25.0 | - | 25 |
| | | Aft (Use Alum.) | 25 | .55 | 13.8 | - | 14 |
| Miscellaneous | 115 | | 115 | .55 | 63.3 | - | 63 |
| Sub Totals | 5,850 | | 5,850 | | 2,844 | | 3,277 |
| Riveting & Welding | 70 (1.15%) | | 70 | | 85 (3%) | | 98 |
| Structural Weight | 5,920 | | 5,920 | | 2,929 | | 3,375 |

Overall Weight Ratio for Hull Structure = 3,375/5,920 = 0.570

Significant moment shifts due to aluminum construction:
Castings Fwd = 10T x 200' = 2,000 Ft. Tons Fwd Moment
Neutral Axis for Midship Section (1,687 tons) shifts 0.2 feet up (say 400 ft.tons)

| | | | | | |
|---|---|---|---|---|---|
| Wt. with Original Centers = | 3,375 | 29.7 | 100,238 | 3.0A | 10,125 |
| Adjusted Moments | | | + 400 | | -2,000 |
| Aluminum Hull Structure | 3,375 | 29.82 | 106,638 | 2.41 | 8,125 |

TABLE 20 Aluminum Bulk Carrier - Equipment and Outfit Weight Estimate

| Item | Weight Steel (Long Tons) | Weight Coefficient | Weight Alum. (Long Tons) | Weight Diff. (Long Tons) | Explanation of Weight Coefficient |
|---|---|---|---|---|---|
| Hatch Covers | 235 | .55 | 130 | -105 | Sim. to bhd. study |
| Woodwork | 20 | - | 20 | - | No change |
| Joiner Work | 85 | - | 85 | - | No change |
| Deck Covering | 80 | Add 31 Tons | 111 | + 31 | Added fire protection |
| Insulation | 20 | Add 93 Tons | 113 | + 93 | Added fire protection |
| Painting | 60 | .30 | 18 | - 42 | No topside painting |
| Hull Attachments* | 150 | (100 x .55 | 55 | - 45 | Changed to alum. |
| " | | (50 x 1.00 | 50 | - | No change |
| Ventilation | 60 | (20 x .55 | 11 | - 9 | Change to alum. |
| " | | (40 x 1.0 | 40 | - | No change |
| Deck Machinery | 100 | 1.01 | 101 | + 1 | Dissimilar metals isolation |
| Piping | 190 | (100 x .60) | 60 | - 62 | Change to aluminum |
| " | | (90 x .75) | 68 | - | Optimized metals |
| Misc. Equip. | 130 | .80 | 104 | - 26 | Estimated |
| Elec. Plant | 60 | 1.02 | 61 | + 1 | Dissimilar metals isolation |
| Total | 1,190 | | 1,027 | | |

Overall Weight Ratio for Equipment and Outfit = 1,027/1,190 = 0.86

SHIFT IN V.C.G. AND L.C.G.

| Item | WT | VCG | $M_V$ | $LCG_F$ | $M_F$ | $LCG_A$ | $M_A$ |
|---|---|---|---|---|---|---|---|
| Orig'l Wt. E&O | 1,190 | 53.4 | 63,456 | | | 124.0 | 147,560 |
| Hatch Cover Reduction | -105 | 55.0 | -5,775 | 28.0 | -2,940 | | |
| Dk Cov'g Incr | + 31 | 60.0 | +1,860 | | | 210.0 | +6,510 |
| Insul'n Incr | + 93 | 38.0 | 3,534 | | | 210.0 | +19,530 |
| Paint Reduction | - 42 | 50.0 | 2,100 | | | 150.0 | - 6,300 |
| Hull Attach Reduction | - 45 | 60.0 | -2,700 | 200 | -9,000 | | |
| Vent Reduction | - 9 | 60.0 | - 540 | | | 210 | - 1,890 |
| Dk Machy Incr | + 1 | 60.0 | + 60 | - | - | - | - |
| Piping Reduction | - 62 | 15.0 | - 930 | | | 50 | 3,100 |
| Misc Eq. Reduction | - 26 | 60.0 | -1,560 | | | 150 | 3,900 |
| Elec Plant Incr | + 1 | 60.0 | + 60 | | | 200 | + 200 |
| Total - E&O | 1,027 | 53.90 | 55,365 | | | 166.07 | 170,550 |

* Assumed to include Masts, Spars, Rudder, etc.

TABLE 21 Aluminum Bulk Carrier - Machinery Weight Estimate

| Item | Weight Steel (Long Tons) | Weight Coef-ficient | Weight Alum. (Long Tons) | Weight Differ-ence (L.Tons) | Explanation of Weight Coefficient |
|---|---|---|---|---|---|
| Main Engine | 372.8 | - | 372.8 | 0 | No Change |
| Shaft & Propeller | 45.4 | - | 45.4 | 0 | No Change |
| Auxiliary Machinery | 51.9 | - | 51.9 | 0 | No Change |
| Auxiliary Boiler | 8.8 | - | 8.8 | 0 | No Change |
| Uptakes & Funnel | 18.0 | 0.75 | 13.5 | -4.5 | Some Alum. used |
| Piping, Valves | 115.0 | 0.95 | 109.3 | -5.7 | Some Alum. used |
| Machinery Space Equip. | 71.1 | .6 | 42.7 | -28.4 | Alum. Gratings, Etc. |
| Refrigerating Plant | 11.8 | - | 11.8 | 0 | No Change |
| Fire Extinguishing | 1.6 | 5.0 | 8.0 | +6.6 | Additional Fire Equip. |
| Margin and Miscellaneous | 56.0 | - | 56.0 | - | No Change |
| TOTAL MACHINERY | 752.4 | | 720.2 | | |

Overall Weight Ratio for Machinery = 720/752 = 0.96

Changes to Vertical Moment

| | | | |
|---|---|---|---|
| Uptakes, Funnel | -4.5 x 50 | = | -225 |
| Piping, Valves | -5.7 x 10 | = | - 57 |
| Machinery Space Equipment | -28.4 x 26 | = | -738 |
| Fire Extinguishing | +6.6 x 35 | = | +231 |
| TOTAL | -32.2 | = | -789 |

## STABILITY AND TRIM

A check of stability and trim was made for the full load (36'-11-3/8" draft) and the ballast condition. In the Full Load Homogeneous Cargo Condition, Table 22, stability of the aluminum ship was similar to the steel ship. Although trim was reasonable in the departure condition, the ship will trim further by the bow as fuel is consumed. This condition can be corrected by a slight change in underwater form to move the L.C.B. forward about 1.5 feet.

In the Ballast Condition, Table 23, drafts, trim and stability are equal to the steel ship. It is noted, however, that the design ballast capacity available in the steel CHALLENGER was marginal and is inadequate for the aluminum equivalent, where slamming or propeller racing might be expected even in relatively mild seas due to insufficient draft. To increase the ballast capacity in an economical manner, No. 4 Hold was used as a ballast tank. The increased ballast capacity permits the aluminum ship to equal or exceed the ballast drafts of the steel ship. Bending moments for the ship with ballast in No. 4 Hold were checked and found to be acceptable.

From Table 17, it is noted that the V.C.G. of the light ship for the aluminum bulk carrier is over a foot higher than that of the steel ship. This results from the weight savings in the hull being of a lower center of gravity than that of the ship as a whole. This has a negligible effect on stability in the loaded or ballast conditions, due to the relatively small ratio of light ship to displacement, and the low center of gravity of the added cargo or ballast. However, this higher light ship V.C.G. could be a problem in ships where the ratio of light ship to displacement is higher, such as cargo and naval ships.

TABLE 22 Trim and Stability
Full Load Departure Condition (Homogeneous Cargo)

| Item | STEEL SHIP WT. | STEEL SHIP VCG | STEEL SHIP LCG | ALUMINUM SHIP WT. | ALUMINUM SHIP VCG | ALUMINUM SHIP LCG |
|---|---|---|---|---|---|---|
| Light Ship | 7,892 | 33.4 | 40.9A | 5,200 | 35.00 | 63.0A |
| Crew & Misc. Dwt | 200 | 36.0 | 189.3A | 200 | 36.0 | 189.3A |
| Fuel | 1,029 | 6.8 | 159.5A | 1,029 | 6.80 | 159.5A |
| Fresh Water | 282 | 44.7 | 257.1A | 282 | 44.70 | 257.1A |
| Cargo | 35,849 | 28.8 | 31.0F | 38,541 | 28.80 | 31.0F |
| FULL LOAD CONDITION | 45,252 | 29.2 | 11.4F | 45,252 | 29.14 | 13.1F |

| Item | STEEL SHIP | ALUMINUM SHIP |
|---|---|---|
| Draft at LCF | 36'-11-5/8" | 36'-11-5/8" |
| KM | 36.10' | 36.10' |
| KG | 29.2' | 29.14' |
| GM Uncorrected | 6.90' | 6.96' |
| F.S. Correction | 0.40' | 0.40' |
| G.M. Corrected | 6.50' | 6.56' |
| LCB | 12.7' Fwd | 12.7' Fwd |
| LCG | 11.4' Fwd | 13.1' Fwd |
| LVR | 1.3' Aft | 0.4' Fwd |
| MT1" | 4,504' Tons | 4,504' Tons |
| Trim | 13" By Stern | 4" By Bow |
| Draft Fwd | 36'-5-1/8" | 37'-1-5/8" |
| Draft Aft | 37'-6-1/8" | 36'-9-5/8" |

TABLE 23 Trim an
Ballast - Arriva

| Item | STEEL SHIP WT. | STEEL SHIP VCG | STEEL SHIP LCG |
|---|---|---|---|
| Light Ship | 7,892 | 33.4 | 40.9A |
| Crew & Misc. Dwt | 200 | 36.0 | 189.3A |
| Fuel | 80 | 12.85 | 190.0A |
| Fresh Water | 30 | 46.70 | 246.7A |
| S.W. Ballast | 11,369 | 29.04 | 23.6F |
| BALLAST CONDITION | 19,571 | 30.8 | 5.9' |

| Item | STEEL SHIP |
|---|---|
| Draft At LCF | 16'-10" |
| KM | 44.7' |
| KG | 30.8' |
| GM Uncorrected | 13.9 |
| FS Correction | 2.3 |
| GM Corrected | 11.6' |
| LCB | 19.2'F |
| LCG | 5.9'A |
| LVR | 25.1'A |
| MT1" | 3,628' Tons |
| Trim | 11'-3-1/2" By St |
| Draft Fwd | 11'-5-3/4" |
| Draft Aft | 22'-9-1/4" |

* Used No. 4 Hold for additional ballast ca
** Includes Full F.S. for No. 4 Hold (4.4').

# IV. COST STUDIES

## OBJECTIVES

The objective of these studies was to compare the life cycle costs of an existing steel bulk carrier with an aluminum hulled ship of the same over-all dimensions to determine if the higher first cost of the aluminum hull can be justified on the basis of long term economics, including extended ship life.

## METHOD OF ANALYSIS

The initial step was to prepare single ship price estimates using an existing computer model based upon a vessel life of 20 years. The price for a steel bulk carrier of the CHALLENGER's characteristics was determined for construction in a U.S. shipyard in 1970. The steel ship price was then used as a reference in determining a price for the aluminum ship. Copies of the ship price breakdowns are included as Tables 24 and 25, which include notes to explain the derivation of cost details. The aluminum ship costs are not applicable to a prototype ship, but assume a state-of-the art equivalent to steel. A single prototype would undoubtedly cost far more, due to requirements for personnel training, contingencies, greater testing and development, and other factors beyond the scope of this study.

Next, data was gathered on fixed and variable operating and maintenance costs applicable to the two ships and the computer model was modified accordingly. This data appears as the Assumptions on Table 26.

Computations were made to determine the required freight rate (RFR, the standard economic measure of merit used) on realistic voyages for fifty-four separate cases, using the model. The RFR is based upon present values of vessel life cycle costs and includes a 10 per cent after tax return on investment to the Owner. The first thirty-six cases were based upon two of the four leg dry bulk carrier voyages which were represented in the previous dry bulk carrier study for the Maritime Administration, Reference (70). Results of these computations appear on Table 27. The cases which were studied included construction of steel and aluminum ships in flights of 1, 5 and 10 and ship life of 20, 25 and 30 years.

The procurement costs for aluminum and steel vessels with lives in excess of 20 years were increased from the baseline figures in Tables 24 and 25 as follows:

(1) The aluminum hull structure was assumed to be satisfactory for a 30 year life without modification.

(2) The steel hull structure was assumed to be satisfactory for a life of 25 years without plate renewal, based upon discussions with American Bureau of Shipping. Two methods are therefore open to extend the hull life to 30 years: provide greater plate thickness initially so that the net plate thickness at 30 years is marginally satisfactory, or renew excessively corroded plate at 25 years. The first approach was chosen, and one-sixteenth inch was added to the immersed shell plating throughout, which would extend the shell life 5 years, based on an average corrosion rate of .01 inches per year. This increases the light ship weight 90 tons, with a corresponding increase in cost and reduction in

## TABLE 24 Price of Steel Bulk Carrier

| | | |
|---|---|---|
| | Material Cost | |
| (1) | Steel | $ 1,629,000 |
| (2) | Outfit | 2,805,000 |
| (3) | Mach | 1,865,000 |
| (4) | Total | $ 6,299,000 |
| | Direct Labor Cost | |
| (5) | Steel | $ 1,302,000 |
| (6) | Outfit | 1,110,000 |
| (7) | Mach | 423,000 |
| (8) | Total | $ 2,840,000 |
| (9) | Indirect & Engr. Material Cost | $ 250,500 |
| (10) | Indirect & Engr. Labor Cost | $ 1,210,000 |
| (11) | Total Direct & Indirect Labor Cost | $ 4,050,000 |
| (12) | Overhead | $ 2,430,000 |
| (13) | Profit | $ 1,302,900 |
| (14) | Total Construction Price - 1 Ship | $14,332,400 Note (a) |

Steel salvage value = 5943 x .025 x 2240 = $332,500 (For hull material when vessel is scrapped) + 5943 x .025 x .12 x 2240 = $40,000 (Waste produced during construction)
Total Salvage Value = $372,500 Note (b)

Notes for Table 24
(a) Unit costs, labor rates, etc. based upon Reference (69)
(b) Scrap value of steel = 2-1/2 cents per pound

## TABLE 25 Price of Aluminum Bulk Carrier

| | | | | Notes |
|---|---|---|---|---|
| | Material Cost | | | |
| (1) | Alum. | (3426 L.T.) ($1230/L.T.) (1.05) = | $ 4,425,000 | (a) |
| (2) | Outfit | 2,805,000 + 210,000 | 3,015,000 | (b) |
| (3) | Mach. | | 1,865,000 | |
| (4) | Total | | $ 9,305,000 | |
| | Direct Labor Cost | | | |
| (5) | Alum. | (1.25)(1,302,000) = | $ 1,630,000 | (c) |
| (6) | Outfit | | 1,110,000 | (d) |
| (7) | Mach. | 423,000 + 100,000 = | 523,000 | (e) |
| (8) | Total | | $ 3,263,000 | |
| (9) | Indirect & Engr. Material Cost | | $ 382,000 | |
| (10) | Indirect & Engr. Labor Cost | | $ 1,535,000 | |
| (11) | Total Direct & Indirect Labor Cost | | $ 4,798,000 | |
| (12) | Overhead | | $ 2,710,000 | |
| (13) | Profit | | $ 1,719,500 | |
| (14) | Total Construction Price - 1 Ship | | $18,914,500 | |

Aluminum Salvage Value = 3426 x .18 x 2240 = $1,390,000 (for hull material when vessel is scrapped)
+ 3426 x .18 x 2240 x .05 = $72,000 (waste produced during construction)

Total Salvage Value = $1,462,000 (f)

Notes for Table 25
(a) Aluminum alloy price = 55 cents per pound - $1230 per long ton. (plate, extrusions and weld wire). Wastage allowance = 5%
(b) Additional outfitting costs for aluminum ship:
$220,000 for additional fire protection insulation and deck covering
$110,000 for aluminum hatch covers
$150,000 for hull attachments (doors, hatches, spars, ladders)
$ 30,000 for ventilation
$ 10,000 for installation of deck machinery
$ 80,000 for piping systems outside machinery spaces
$ 50,000 for miscellaneous equipment and outfit
$ 20,000 for impressed current cathodic protection system
$ 40,000 for improved fire extinguishing equipment
Reduced outfitting cost of $500,000 for reduced initial painting of hull
Net additional outfitting cost = $210,000
(c) Total labor for hull structure of aluminum ship assumed to be 25% greater than that for steel ship
(d) Increases in labor included in total addition to outfit material cost, Note (b)
(e) Added $100,000 for increased piping cost and isolation of machinery and equipment
(f) Scrap value of aluminum = 18 cents per pound

## TABLE 26 Operating and Maintenance Cost Assumptions

1. All costs for U. S. flag operation.

2. Steel ship price based upon dry bulk carrier model 1968 prices (Reference (69)) escalated by 20 per cent to suit 1970 costs.

3. Crew size = 34 men. Wage rates estimated by escalating 1969 Atlantic rates. Wage rates for both ships = $740,391 per year including vacation, overtime, pension and welfare, social security, training, etc.

4. Subsistence cost = $30,600 per year. Overhead = $50,000 per year.

5. Hull and Machinery Insurance. Used Benford's formula (Reference (71)) for both ships. IHM = 10,000 + (.007)×(total construction cost). $110,327 per year for steel ship. $142,402 per year for aluminum ship. (For single ship procurement)

6. Protection and indemnity insurance = $43,367 per year for both ships. War reserve insurance = (.001)×(construction cost).

7. Fuel cost = $30.00 per ton for marine diesel fuel for diesel generator and $16.00 per ton for Bunker C for diesel propulsion unit.

8. Drydock cost based upon an average of $.30 per gross ton per haul day or lay day. (Reference (69)) Downtimes assumed equivalent for steel and aluminum hulls, though the aluminum hull might require more special surveys.

9. Renewal of 12,000 square feet (total area under hatches) tank top and bulkhead every 7 years expressed as average cost added directly to annual maintenance cost. Salvage values accounted for. Weight of structure renewed = 120 tons and 220 tons for aluminum and steel hulls respectively. This area suffers cumulative damage from abrasion and impact during cargo loading and unloading and requires periodic renewal.

10. Painting cost - Added $9500 per year for cost of steel ship ($30,332) over that of aluminum ship ($20,832) per discussion with Maritime Administration officials. This is based on the assumption that bottom painting requirements for steel and aluminum ships are identical but the aluminum ship's topside and interior are unpainted and require only occasional washdown and scrubbing. The ship's crew is assumed to perform sandblasting and painting on the steel ship's topsides.

11. Maintenance and Repairs (other than hull) - Steel ship = $156,257 per year. Aluminum ship = $179,787 per year. This assumes that maintenance costs for machinery and equipment are identical for steel and aluminum ships but uninsured repair costs of aluminum ships are higher. In addition $200,000 has been allocated for a major overhaul of main and auxiliary diesel engines and hull for ships with a life in excess of 20 years. Miscellaneous costs = $20,000; stores and supplies = $38,224. (Reference (69))

12. Financial assumptions - Owner's investment of 25 per cent of initial ship cost; remainder borrowed from bank at 7 per cent interest rate; after tax return to Owner of 10 per cent on total investment; 50 per cent tax rate; accelerated method of depreciation; loan period equal to ship life; no investment tax credit; inflation not considered.

13. Voyage assumptions as follows:

   - No limiting drafts
   - Fuel carried based upon (1.10) (leg distance)
   - Cargo greater than ship capacity is always available
   - No canal costs or canal delays
   - No cargo handling costs. Freight rate for transportation cost only
   - Other voyage data as follows:

| Voyage Length, Nautical Miles | 4000 | 8400 | 12000 | 14300 | | 25310 | |
|---|---|---|---|---|---|---|---|
| | | | | Leg 1 | Leg 3 | Leg 1 | Leg 3 |
| Cargo Loading Rate - Ton per Hr. | 6000 | 6000 | 6000 | 1700 | 3000 | 2000 | 6000 |
| Cargo Unloading Rate - Ton per Hr. | 1600 | 1600 | 1600 | 500 | 1500 | 500 | 1600 |
| Port Delay Loading - Days | .25 | .25 | .25 | 1 | 1 | 5 | .25 |
| Port Delay Unloading - Days | .25 | .25 | .25 | 1 | 1 | 5 | .25 |
| Port Costs Loading - $ | 2000 | 2000 | 2000 | 2000 | 8000 | 8000 | 2000 |
| Port Costs Unloading - $ | 2500 | 2500 | 2500 | 5000 | 2000 | 8000 | 2500 |
| Other Costs - $ | 0 | 0 | 0 | 2000 | 0 | 2000 | 0 |

TABLE 27 Comparison of Steel and Aluminum Bulk Carriers ( *Challenger* Clas

| Case Number | Ship Life (Years) | No. of Ships Purchased | Structure Material | Round Voyage Distance | Annual Cargo Carried-L.T. |
|---|---|---|---|---|---|
| 1) | 20 | 1 | Steel | 14,300 | 514,101 |
| 2) | 20 | 5 | Steel | 14,300 | 514,101 |
| 3) | 20 | 10 | Steel | 14,300 | 514,101 |
| 4) | 20 | 1 | Steel | 25,310 | 309,646 |
| 5) | 20 | 5 | Steel | 25,310 | 309,646 |
| 6) | 20 | 10 | Steel | 25,310 | 309,646 |
| 7) | 25 | 1 | Steel | 14,300 | 512,816 |
| 8) | 25 | 5 | Steel | 14,300 | 512,816 |
| 9) | 25 | 10 | Steel | 14,300 | 512,816 |
| 10) | 25 | 1 | Steel | 25,310 | 308,872 |
| 11) | 25 | 5 | Steel | 25,310 | 308,872 |
| 12) | 25 | 10 | Steel | 25,310 | 308,872 |
| 13) | 30 | 1 | Steel | 14,300 | 512,816 |
| 14) | 30 | 5 | Steel | 14,300 | 512,816 |
| 15) | 30 | 10 | Steel | 14,300 | 512,816 |
| 16) | 30 | 1 | Steel | 25,310 | 308,872 |
| 17) | 30 | 5 | Steel | 25,310 | 308,872 |
| 18) | 30 | 10 | Steel | 25,310 | 308,872 |
| 19) | 20 | 1 | Aluminum | 14,300 | 533,759 |
| 20) | 20 | 5 | Aluminum | 14,300 | 533,759 |
| 21) | 20 | 10 | Aluminum | 14,300 | 533,759 |
| 22) | 20 | 1 | Aluminum | 25,310 | 325,688 |
| 23) | 20 | 5 | Aluminum | 25,310 | 325,688 |
| 24) | 20 | 10 | Aluminum | 25,310 | 325,688 |
| 25) | 25 | 1 | Aluminum | 14,300 | 533,759 |
| 26) | 25 | 5 | Aluminum | 14,300 | 533,759 |
| 27) | 25 | 10 | Aluminum | 14,300 | 533,759 |
| 28) | 25 | 1 | Aluminum | 25,310 | 325,688 |
| 29) | 25 | 5 | Aluminum | 25,310 | 325,688 |
| 30) | 25 | 10 | Aluminum | 25,310 | 325,688 |
| 31) | 30 | 1 | Aluminum | 14,300 | 533,759 |
| 32) | 30 | 5 | Aluminum | 14,300 | 533,759 |
| 33) | 30 | 10 | Aluminum | 14,300 | 533,759 |
| 34) | 30 | 1 | Aluminum | 25,310 | 325,688 |
| 35) | 30 | 5 | Aluminum | 25,310 | 325,688 |
| 36) | 30 | 10 | Aluminum | 25,310 | 325,688 |

* Ship Price + Owner's Invest. Costs - Salvage Value

available deadweight for weight critical cargoes. It is assumed that the use of inorganic zincs or equal in conjunction with a reasonable maintenance program will prevent excessive corrosion of the topside plating.

(3) Procurement costs for machinery and outfit were assumed identiaal for 20, 25 and 30 year lives, since they do not directly affect the qualitative results of the study. In reality however, it is obvious, that the cost of equipment with a 30 year life will be higher than for a 20 year life, in most cases.

The first voyage of 14,300 miles consisted of the following legs:

| From | To | Distance | Cargo |
|---|---|---|---|
| Seattle | Yokohama | 4,280 | Wheat |
| Yokohama | Gladstone, Australia | 3,600 | Ballast |
| Gladstone | Tacoma | 6,400 | Alumina |
| Tacoma | Seattle | 20 | Ballast |

The second voyage of 25,310 miles included these legs:

| From | To | Distance | Cargo |
|---|---|---|---|
| New Orleans | Bombay | 11,890 | Wheat |
| Bombay | Port Buchanan, Liberia | 7,520 | Ballast |
| Port Buchanan | Baltimore | 4,200 | Iron Ore |
| Baltimore | New Orleans | 1,700 | Ballast |

An additional eighteen cases were computed on the basis of three different two-leg voyages of 4,000, 8,400 and 12,000 miles round trip. These cases represent better opportunities than do the four-leg voyages for the aluminum bulk carrier to benefit from its greater deadweight capacity over that of the steel ship. These voyages contained one leg with a dense cargo, iron ore, as the cargo while the other leg was in ballast. Computations were made for single ship procurement with ship life varied at 20, 25 and 30 years. Results of the two-leg voyages appear on Table 28.

Many of the operating and maintenace cost assumptions were based upon data which appears in the working papers on the dry bulk carrier evaluation model, Reference (69).

## RESULTS

Four graphs were plotted to illustrate the results of the computations. Figure 19 compares RFR versus round voyage distance for the steel and aluminum ships on both the two-leg and four-leg voyages. This figure clearly shows that the two-leg voyages provide the better competitive opportunity for the aluminum ship because on these voyages with dense cargo, the full weight savings advantage of the aluminum ship is reflected. However, even with a 30-year life, the aluminum ship requires a higher RFR than the steel ship for the voyages examined. Figure 20 is a plot of RFR versus ship investment cost for the 14,300 mile, four-leg voyage. It is possible to estimate the reduced price which would be required for the aluminum ship, to provide an RFR equal to the steel ship, by projecting

TABLE 28 Comparison of Steel and Aluminum Bulk Carriers (*Challenger* Class) Two-Leg Voyages

| Case Number | Ship Life (Years) | No. of Ships Purchased | Structure Material | Round Voyage Distance | Annual Cargo Carried-L.T. | Required Freight Rate | *Ship Net Investment |
|---|---|---|---|---|---|---|---|
| 37) | 20 | 1 | Steel | 4,000 | 1,006,361 | $ 3.51 per ton | $14,520,406 |
| 38) | 20 | 1 | Steel | 8,400 | 511,838 | 6.83 | $14,520,406 |
| 39) | 20 | 1 | Steel | 12,000 | 363,610 | 9.56 | $14,520,406 |
| 40) | 25 | 1 | Steel | 4,000 | 1,003,845 | 3.42 | $14,745,466 |
| 41) | 25 | 1 | Steel | 8,400 | 510,558 | 6.66 | $14,745,466 |
| 42) | 25 | 1 | Steel | 12,000 | 362,700 | 9.32 | $14,745,466 |
| 43) | 30 | 1 | Steel | 4,000 | 1,003,845 | 3.32 | $14,745,466 |
| 44) | 30 | 1 | Steel | 8,400 | 510,558 | 6.46 | $14,745,466 |
| 45) | 30 | 1 | Steel | 12,000 | 362,700 | 9.04 | $14,745,466 |
| 46) | 20 | 1 | Aluminum | 4,000 | 1,071,989 | 3.81 | $18,064,288 |
| 47) | 20 | 1 | Aluminum | 8,400 | 547,313 | 7.38 | $18,064,288 |
| 48) | 20 | 1 | Aluminum | 12,000 | 389,366 | 10.34 | $18,064,288 |
| 49) | 25 | 1 | Aluminum | 4,000 | 1,071,989 | 3.74 | $18,264,288 |
| 50) | 25 | 1 | Aluminum | 8,400 | 547,313 | 7.25 | $18,264,288 |
| 51) | 25 | 1 | Aluminum | 12,000 | 389,366 | 10.15 | $18,264,288 |
| 52) | 30 | 1 | Aluminum | 4,000 | 1,071,989 | 3.71 | $18,264,288 |
| 53) | 30 | 1 | Aluminum | 8,400 | 547,313 | 7.18 | $18,264,288 |
| 54) | 30 | 1 | Aluminum | 12,000 | 389,366 | 10.06 | $18,264,288 |

* Ship Price + Owner's Invest. Costs - Salvage Value

horizontally to the right from the RFR of the steel ship. Aluminum ships, procured in single quantities, would require the following reduced prices at lives of 20, 25 and 30 years to compete with the 20-year life steel ship:

| Aluminum Ship Life (Years) | Required Investment to Match Steel Ship RFR |
|---|---|
| 20 | $14,850,000 |
| 25 | 15,500,000 |
| 30 | 15,700,000 |

These required investment costs for the aluminum ship are significantly less than the estimated single ship investment cost of $18,064,000. (Net investment for 20 year life - see Table 28).

The effect of ship life on RFR is plotted on Figure 21. The 4,000 and 12,000 mile, two-leg voyages are shown. It is apparent that on the shorter voyage the aluminum ship RFR comes closest to that of the steel ship. However, even beyond a 35-year life the aluminum ship can not match the steel ship RFR.

Annual transport capability of the aluminum and steel ships is plotted on Figure 22 for the two leg voyages. The transport capability of the aluminum ship is about 6.5 per cent greater at 4,000 miles and slightly more than 7 per cent in excess of the steel ship at 12,000 miles.

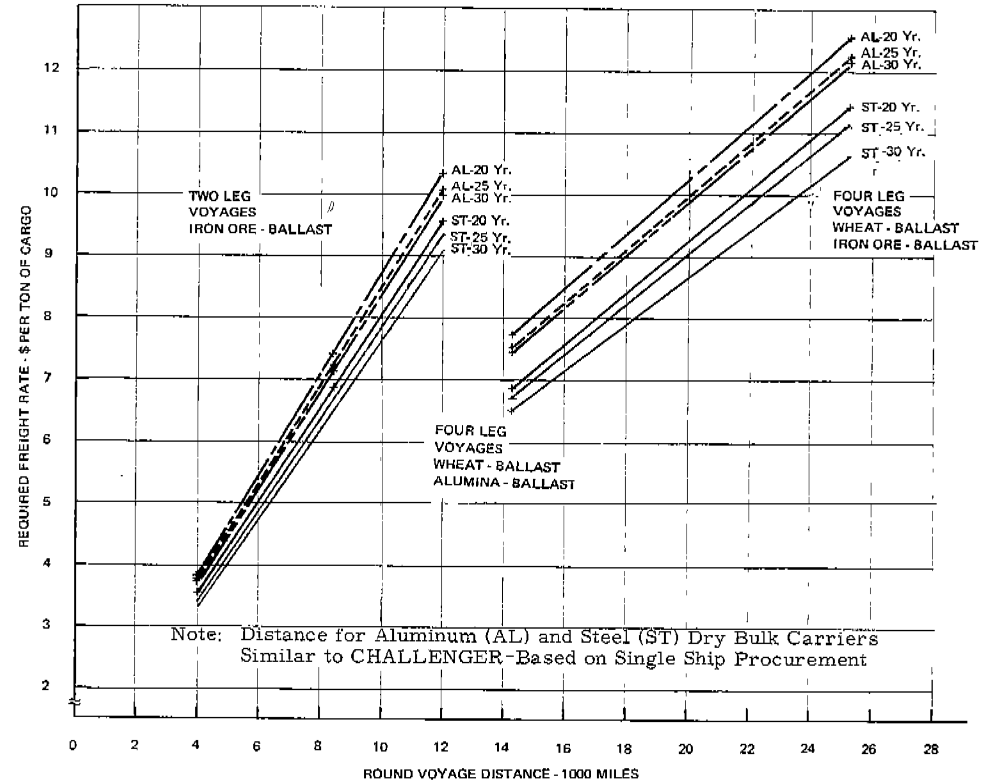



FIG. 19 Required Freight Rate Versus Round Voyage

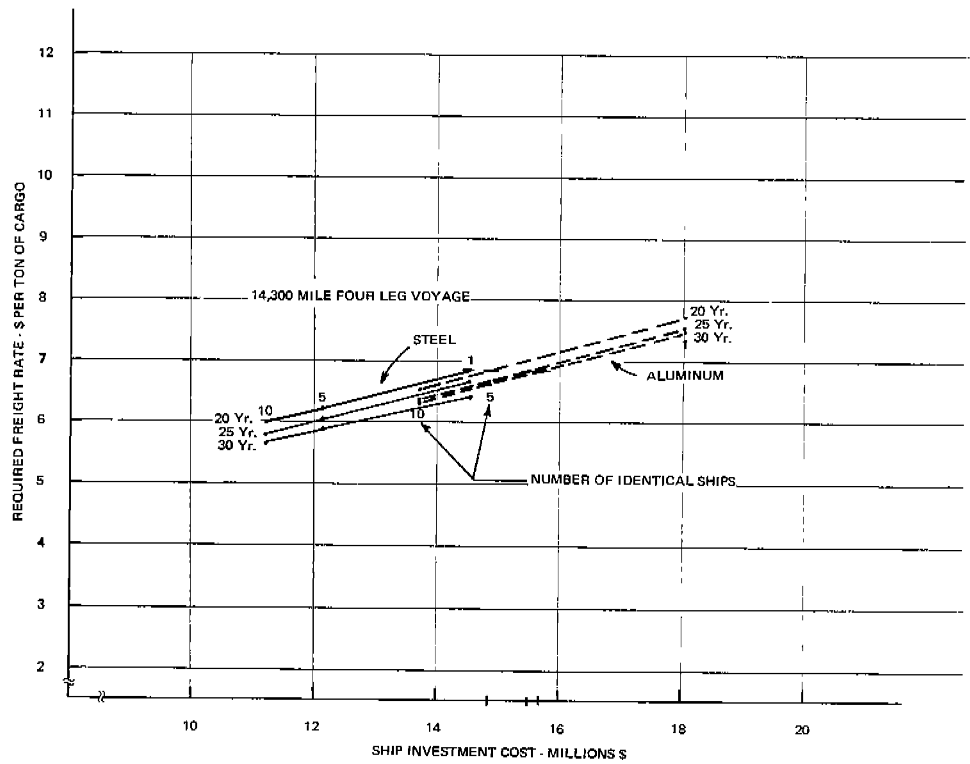



FIG. 20 Required Freight Rate Versus Ship Investment Cost

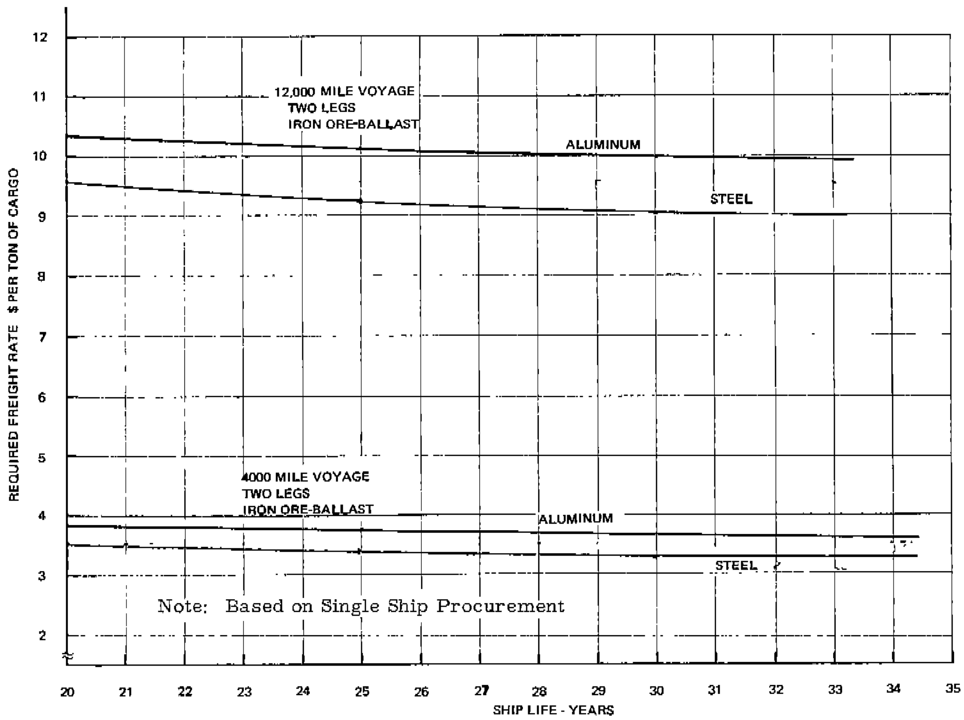



FIG. 21 Required Freight Rate Versus Ship Life

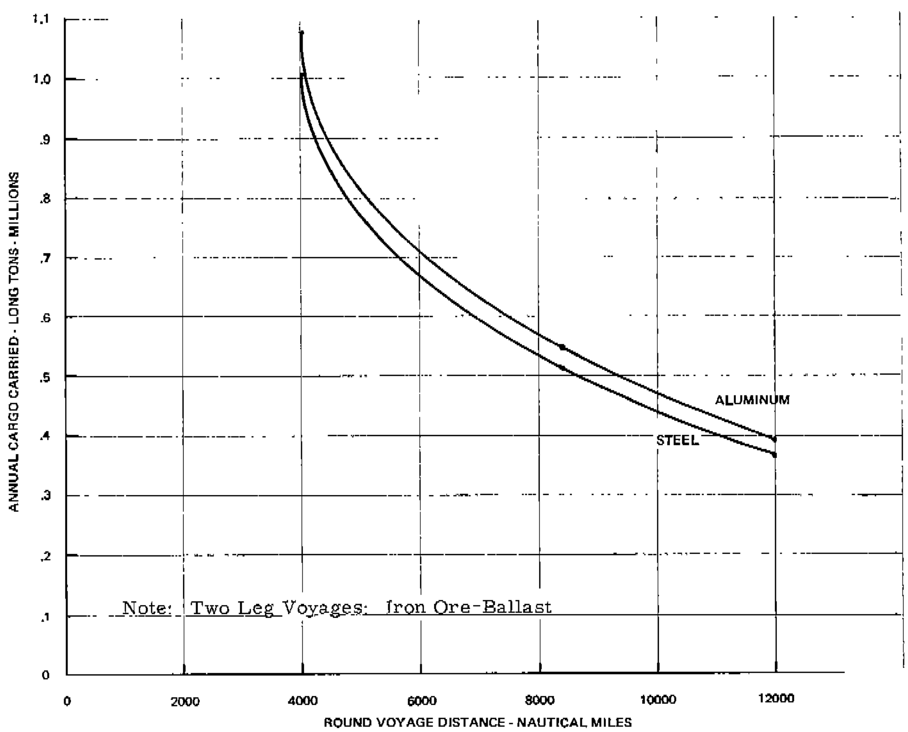



FIG. 22 Annual Transport Capability vs. Round Voyage Distance

SENSITIVITY STUDIES

The basic economic studies recently completed were based upon a fixed set of criteria, both in terms of ship cost and operational considerations. It is of interest to investigate the possible effects on life cycle economics of varying these factors, to determine which has the greatest effect on profitability and thus deserves greatest attention in future studies of this nature.

1. Direct Labor Cost - Aluminum Hull - If it is assumed that the 25 per cent differential in labor between aluminum and steel can be eliminated, the potential reduction in direct labor, overhead and profit would be approximately $580,000 for single ship procurement, with correspondingly lower reductions for larger procurements. This is about 3 per cent of procurement cost.

2. Profit - Aluminum Hull - If it is assumed that the shipbuilder will accept the same profit for building an aluminum or steel ship, the potential savings is about $400,000. However, this is unlikely, since the builder would desire to show at least an identical return on his investment and might even prefer a higher return on the aluminum hull due to the greater risks involved.

3. Hull Girder Fatigue Allowance - If the 435 ton increase in hull girder weight for fatigue could be completely eliminated, the first cost of the aluminum bulk carrier would be reduced by about $1,160,000 or 6 per cent and the available deadweight would be increased accordingly. However, there is presently no technical justification for such a reduction, though further study might lead to the conclusion that a portion of this allowance could be eliminated.

4. Tank Top Abrasion/Impact Allowance - If the 0.80 inch allowance for impact and abrasion on the aluminum ship's tank top and wing bulkheads could be reduced to 0.25 inches (the American Bureau of Shipping required 0.20 inches for steel times the factor for relative yield and ultimate strength differences), the potential weight savings would be about 100 tons or a cost savings of $270,000, with a corresponding increase in deadweight capacity.

5. Fire Protection - The additional cost associated with fire protection of the aluminum bulk carrier, including insulation and sheathing is about $260,000 greater than that of the steel ship, based upon full compliance with the intent of the present U.S. Coast Guard fire protection rules. About $160,000 of this is associated with deckhouse protection. If the requirements for deckhouse protection were waived except in stair towers, uptakes and higher fire risk areas (the galley for example), it would be possible to reduce the ship's first cost by about $150,000 and its weight by about 40 tons. Although this involves greater risk to the crew, it would not have a major effect on hull girder strength, since a fire in the deckhouse could be isolated from the main hull by proper deck covering. Such a proposal would, of course, require intensive investigation and approval by the U. S. Coast Guard.

6. Voyages - The voyages investigated for this study are considered generally representative of the spectrum of tramp operations during the next 20 years, and result in a number of ballast or volume-sensitive legs which do not afford any advantage to the aluminum bulk carrier. If such a ship were to be engaged in a trade with weight-sensitive cargoes,

such as iron ore, on two of the three legs, the spread between the RFR of the steel and aluminum ships would be reduced.

In an effort to evaluate these factors, an optimistic aluminum ship model has been established incorporating the following changes:

(a) The 25 per cent labor differential has been eliminated.

(b) One-half of the 435 ton fatigue allowance has been eliminated.

(c) The 100 ton abrasion allowance on the tank top and wing bulkheads has been eliminated.

(d) Fire protection for the deckhouse has been modified per Item 5 previously discussed.

(e) A three leg voyage with weight-sensitive cargoes carried on two legs over distances of 4000, 8400 and 12,000 miles have been assumed, with ship life of 20, 25 and 30 years, to be consistent with previous studies (Table 28).

The reduction in first cost of the ship is $1,600,000 for single ship procurement, and the available deadweight has been increased by 360 tons. Thus the 7-1/2 per cent increase in available deadweight of the baseline ship increases to about 8-1/2 per cent.

The three-leg voyages were considered with the following assumptions:

- Round voyage distances, ship life and number of ships purchased are identical to the figures of Table 28.

- Average Annual Costs for all items which do not vary with acquisition cost are identical to the two-leg voyage. This may not be entirely accurate with regard to such items as fuel costs but it is felt that this discrepancy will not materially affect the final results.

- Since cargo is carried on two of three legs instead of one of two legs, annual cargo carried will increase by 33 per cent over the values listed in Table 28.

- An additional increase of 1 per cent for cargo carried over the two leg voyage as listed in Table 28 was assigned to the aluminum vessel because of increased cargo deadweight due to the reductions in lightship.

- Salvage value of the aluminum vessel was reduced directly in proportion to changes in material weight of the vessel as originally conceived.

- Owners Investment costs, i.e., non-depreciable costs incurred during construction, were assumed independent of acquisition costs.

As indicated in Table 29 and Figure 23, the steel bulk carrier has lower RFR's than the aluminum ship for equal life spans, even for this highly optimistic case.

TABLE 29 Comparison of Steel and Aluminum Bulk Carriers ( *Challenger* Class) Three-Leg Voyages

| Case Number | Ship Life (Years) | No. of Ships Purchased | Structure Material | Round Voyage Distance | Annual Cargo Carried-L.T. | Required Freight Rate | *Ship Net Investment |
|---|---|---|---|---|---|---|---|
| 55) | 20 | 1 | Steel | 4,000 | 1,338,460 | $ 2.63 per ton | $14,520,406 |
| 56) | 20 | 1 | Steel | 8,400 | 690,981 | 5.12 | $14,520,406 |
| 57) | 20 | 1 | Steel | 12,000 | 483,601 | 7.17 | $14,520,406 |
| 58) | 25 | 1 | Steel | 4,000 | 1,254,806 | 2.43 | $14,745,466 |
| 59) | 25 | 1 | Steel | 8,400 | 679,042 | 4.74 | $14,745,466 |
| 60) | 25 | 1 | Steel | 12,000 | 482,391 | 6.64 | $14,745,466 |
| 61) | 30 | 1 | Steel | 4,000 | 1,254,806 | 2.31 | $14,745,466 |
| 62) | 30 | 1 | Steel | 8,400 | 679,042 | 4.48 | $14,745,466 |
| 63) | 30 | 1 | Steel | 12,000 | 482,391 | 6.27 | $14,745,466 |
| 64) | 20 | 1 | Aluminum | 4,000 | 1,447,185 | 2.68 | $16,467,612 |
| 65) | 20 | 1 | Aluminum | 8,400 | 738,873 | 5.18 | $16,467,612 |
| 66) | 20 | 1 | Aluminum | 12,000 | 525,644 | 7.26 | $16,467,612 |
| 67) | 25 | 1 | Aluminum | 4,000 | 1,447,185 | 2.63 | $16,667,612 |
| 68) | 25 | 1 | Aluminum | 8,400 | 738,873 | 5.10 | $16,667,612 |
| 69) | 25 | 1 | Aluminum | 12,000 | 525,644 | 7.14 | $16,667,612 |
| 70) | 30 | 1 | Aluminum | 4,000 | 1,447,185 | 2.62 | $16,667,612 |
| 71) | 30 | 1 | Aluminum | 8,400 | 738,873 | 5.06 | $16,667,612 |
| 72) | 30 | 1 | Aluminum | 12,000 | 525,644 | 7.10 | $16,667,612 |

* Ship Price + Owner's Invest. Costs - Salvage Value

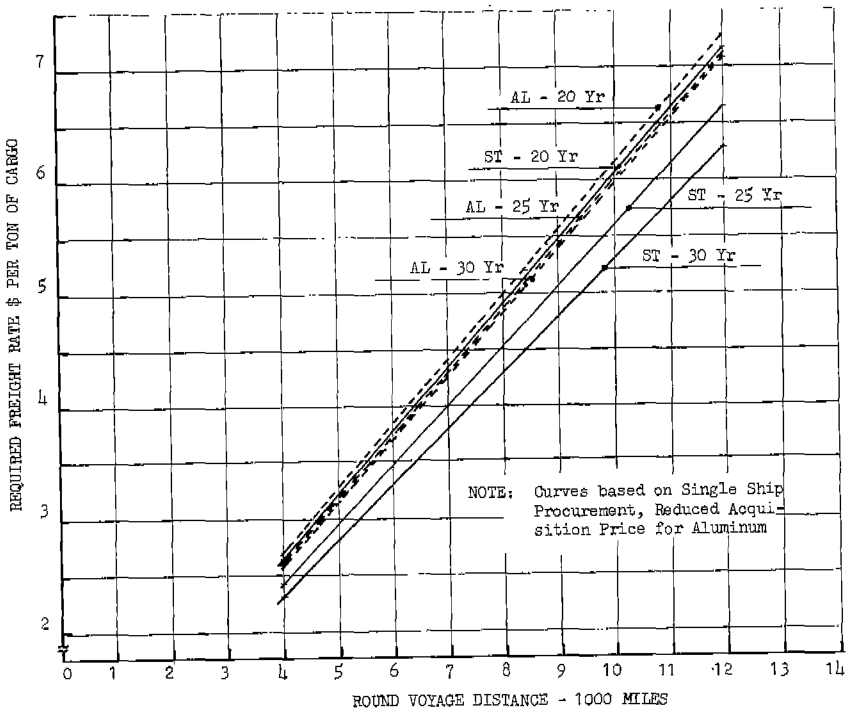



FIG. 23 Required Freight Rate Versus Round Voyage - 3 Legs Weight Sensitive Cargo

## CONCLUSIONS

The following conclusions may be drawn from this study:

- For the realistic cases examined, an aluminum dry bulk carrier similar to CHALLENGER always produced a higher RFR than that of a steel ship with the same life.

This unfavorable economic potential of the aluminum ship resulted even though factors favorable to the higher priceddaluminum ship were considered including:

- Aluminum ship cargo deadweight capacity was increased because of reduced structure weight
- Aluminum ship life was extended from 20 to 30 years with no increase in scantlings
- Aluminum ship salvage value was $1,089,500 more than that of the steel ship
- After tax return on investment of 10 per cent and 7 per cent interest on borrowed capital, both relatively low at present, were assumed.

The foregoing sensitivity studies indicate that there are several areas in which the acquisition cost of an aluminum bulk carrier might be reduced. However, these studies also clearly indicate that at this time even with these reductions, it is unlikely that an aluminum bulk carrier will be directly competitive with an equivalent steel vessel on the basis of Required Freight Rate.

## V. RECOMMENDED AREAS FOR FURTHER STUDY

One of the results of a limited feasibility study such as this, is that numerous questions are raised which can not be satisfactorily answered within the time or cost allocated to the study. The aluminum bulk carrier study is no exception, and in the following paragraphs, the major areas requiring further study are delineated. These areas are listed approximately in order of priority, based upon their relative importance in establishing feasibility of using aluminum for the hull structure of large ships.

### CONSTRUCTION COSTS

The cost of fabricating large aluminum ship structures must be more fully defined to permit more accurate construction cost estimates and trade-offs of alternative construction techniques. At present, it is necessary to use approximate over-all manhours-per-pound values to estimate labor costs and associated overhead, which do not permit the type of relatively sophisticated trade-offs required to optimize structural design. For example, it is difficult to choose between various potential methods of providing required deck area, such as thick plates, thinner plates with doublers or double wall cellular construction. Several qualified shipyards should be authorized to evaluate the construction costs of large aluminum hulls in greater detail.

### MAINTENANCE COSTS

Reduced hull maintenance costs are a key selling point of aluminum, and data is required to more accurately evaluate the life cycle hull maintenance cost of an aluminum hull for comparison to the equivalent steel hull. This is particularly important as the ships get older, since the costs of steel hull repairs begin to increase rapidly as plate replacement becomes necessary. The best potential source of long-term hull maintenance data on large aluminum hulls would be Navy records on the hull maintenance of the PGM gunboat. This data should be closely monitored and periodically evaluated by the Ship Structures Committee and applicable Navy activities.

### WELDING

The technology of welding thick aluminum plates to form subassemblies under shipyard conditions as well as the erection of subassemblies requires considerable investigation. Areas of particular concern are weld sequence, heat input, edge preparation, speed of welding, required level of cleanliness and environment control and quality control required to affect sound welds with minimum cracking, porosity, inclusions, residual stresses and distortion. An area of major concern is the possible need to accomplish welding in a protected environment to maintain adequate control on moisture and cleanliness.

### FIRE RESISTANCE

The analysis of the fire problem which was conducted for this study was of necessity somewhat limited, and should be extended to include the results of the SNAME fire test program. Additional economic trade-offs are required to optimize the protection of aluminum structures as well as means of detecting, extinguishing and preventing fires. Proposed areas to be investigated in further detail are as follows:

(a) Inerting system for cargo holds and other unmanned spaces as required, including type of gas, dispersion of gas throughout the cargo, methods of gas-freeing the spaces and extent to which gas-freeing is required for human safety.

(b) Optimum insulation system(s) for vertical and horizontal surfaces in the Engine Room, accommodations and other working or living space.

(c) Composition of deck covering to limit surface temperature to the required 400 degrees F.

(d) Discussions with U. S. Coast Guard to determine the extent of fire protection required in the deckhouse. The present study is based upon full compliance with the intent of current U. S. Coast Guard requirements. However, a lesser degree of protection has been accepted in previous aluminum deckhouses, though these were installed on steel hulls.

## DESIGN CRITERIA

Several factors entering into the establishment of design criteria require further clarification, including the following:

(a) The question of design stresses for welded structures is not fully clarified. At present, a "welded" yield based upon the 0.2 per cent offset in a 10 inch gage length is proposed, rather than the prime or O-temper values. However, this average design stress may not adequately account for the structural response in way of the heat-affected zone, which is the weak link in the structural system, since the use of a 10 inch gage length in lieu of a 2 inch gage length tends to diminish the apparent effects of this degradation.

(b) The relative importance of yield and ultimate strengths in converting from steel to aluminum requires further consideration. In specific cases, the equal ranking used in this study may not be optimum.

(c) The question of safety factors should be considered when the variability in structural performance due to the human element in fabrication is better understood. The use of identical safety factors for aluminum and steel designs implies that the conversion of raw materials into a fabricated product produces identical stress concentration and residual stress effects which may not be true. The entire question of residual stress levels must be investigated.

## DEFLECTIONS

These studies indicate that hull deflection should not be a limiting factor in itself as long as the hull length/depth ratio conforms to present standards, and stresses are kept reasonably low. However, the question of allowable hull girder deflections deserves further study, in view of the extensive body of opinion among Regulatory Agencies that such limitations should be established.

FATIGUE STRENGTH

As noted earlier in this report, there are a number of factors relating to alloy fatigue strengths which require further clarification and testing. Foremost among these is the question of fatigue strength in the presence of salt spray. This requires an extensive test program, incorporating the following variables: intensity of salt spray, effect of fillet and butt welds, alloys (plate and extrusion temper) bead-on versus bead-off. Additional testing of extrusion tempers would also be advisable, in both the welded and unwelded condition.

FRACTURE TOUGHNESS

Further testing is required to determine the relative quantitative fracture toughness of aluminum and steel for comparison with anticipated stress levels. These tests should evaluate the following variables: directionality (transverse versus longitudinal), welding and other fabrication procedures, environment (sea water versus salt spray), effects of repeated loads, and alloys (plate and extrusion tempers).

CORROSION AND ABRASION

The exfoliation resistance of 5083 alloy should be tested to determine if an H117 temper is required. Further testing on the relative abrasion resistance of aluminum and mild steel is also required.

DESIGN DETAILS

A study should be initiated to standardize design details for aluminum ship structures, both to facilitate fabrication and to prevent excessive residual stress build-up and subsequent cracking. This is a vital step which must be taken before a large aluminum hull can be built, if structural failures are to be avoided. Specific areas to be detailed would include end connections of intercostal stiffeners, connections of continuous stiffeners to web frames or other supports, stanchion endings, proportions of stiffeners, relief of hard spots and other stress raisers, required clearances for proper welding. The required size and continuity of fillet welds requires further study, as there is presently a significant difference between Navy and commercial requirements.

## VI. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The conclusions to be derived from this Feasibility Study for an Aluminum Bulk Carrier are summarized below:

1. General - The construction of a bulk carrier utilizing aluminum alloy for the hull structure is technically feasible within the present state-of-the-art in shipbuilding, but is not economically justified in direct competition with a steel vessel of equivalent capabilities.

2. Review of Aluminum Alloys - The present 5000 series aluminum alloys being considered (5052, 5083, 5086, 5154, 5454 and 5456) have sufficiently high welded mechanical and physical properties for the proposed application, though additional research is required in the area of

fatigue, particularly in the presence of salt spray, as well as fracture toughness and abrasion resistance relative to mild steel. Limited test data indicates a significant reduction in the endurance limit of aluminum alloys when subjected to salt spray.

3. The area under the S-N fatigue curve of welded higher strength 5000 series alloys (5083 or 5456) is about 0.48 times that of mild steel, while the corresponding value for lower strength 5086 alloy is about 0.38. This is indicative of the relative required section moduli of the hull girders of an aluminum and steel bulk carrier for equivalent fatigue life.

4. The notch and fracture toughness of aluminum alloys appear acceptable for hull structural applications. However, stress levels, including effects of stress concentrations, should be kept below the yield stress.

5. The corrosion resistance of 5000 series aluminum alloys is acceptable for a marine environment if proper precautions are taken. The recent introduction of the H116 and H117 temper has apparently solved the exfoliation problem, and suitable gasketing and isolation procedures are available to minimize problems with dissimilar metals. Higher magnesium alloys are somewhat susceptible to stress corrosion problems which must be considered in selection of tempers and operating temperatures. Loss of strength and thickness of aluminum alloys in a salt water environment over a 20 year vessel life will not be significant.

6. The corrosion resistance of 5000 series alloys is acceptable for the range of bulk cargoes and liquids which might be carried, with the exception of copper, tin or mercury ores, potassium hydroxide and carbonate and trisodium phosphate. Precautions are required for a limited number of other potential cargoes.

7. The abrasion resistance of aluminum when subjected to the loading and unloading of bulk cargoes will be significantly less than that of steel, necessitating additional margins in tank top and lower bulkhead thicknesses.

8. The weldability and workability of 5000 series aluminum alloys are very good, and the state-of-the-art in welding technology is presently adequate for the thicknesses of material being considered. Potential problem areas such as control of shrinkage, weld sequence, structural details, residual stresses and environmental protection require further study.

9. The cost of the 5000 series alloys being considered is relatively independent of alloy and temper, and has little effect upon the selection of alloys.

10. Alloy 5083 was selected for all material in the primary hull structure of the bulk carrier, based upon its high strength and good workability. Alloy 5086 may be substituted for 5083 for secondary structures, and alloy 5454 is to be used in areas of high temperature. The relative over-all ranking of the 5000 series alloys considered was very close, so that alternative selections can be justified.

11. <u>Operations with Existing Aluminum Ships</u> - Experience to date with large aluminum ships is limited, but considerable data is available on the performance of aluminum deckhouses, patrol craft, crew boats and pleasure craft. This data indicates that the performance of recently-built aluminum

vessels and marine structures has been good, though problems have been experienced in the areas of corrosion (particularly at bi-metallic joints), exfoliation, abrasion and localized cracking of structures, particularly at improperly designed or fabricated structural connections. Field repairs have been somewhat difficult due to lack of trained personnel.

12. The problems encountered to date in the operation of aluminum ships either have been or can be solved, and should not affect the feasibility of building and operating an aluminum bulk carrier.

13. General maintenance of aluminum hulls has been excellent, and painting is not considered necessary above the waterline.

14. Design Criteria for Hull Structure - A review of design requirements of various regulatory bodies and the Navy relative to large aluminum hulls indicates no consistent body of opinion. These existing criteria require improvement for application to the design of an aluminum bulk carrier.

15. Rational, justifiable design criteria can be established for the strength requirements of the hull girder and local structures of an aluminum bulk carrier. In general these criteria are based upon modification of proven steel scantlings to aluminum, on the basis of relative yield and ultimate strength ratios, as well as relative fatigue strengths of the two materials. Relative corrosion rates must also be considered.

16. Restrictions on hull girder deflection are unnecessary for large hulls, since strength considerations lead to the selection of scantlings with sufficient rigidity.

17. Thermal stresses are not a constraint in the design of an aluminum bulk carrier.

18. Fabrication of Large Aluminum Hulls - Discussions with shipyard personnel indicate that the fabrication of a large aluminum hull, such as a bulk carrier, is entirely feasible.

19. State-of-the-art welding, cutting and materials handling concepts are considered adaptable to the construction of an aluminum bulk carrier.

20. Major areas requiring more detailed study include welding techniques and sequence qualification of welders, environmental control.

21. Fire Protection. A satisfactory level of fire protection, i.e. detection, extinguishing and protective shielding, can be achieved for large aluminum ships.

22. Living, working and stores spaces should be protected by conventional deck covering, insulation and sheathing. Surfaces in machinery spaces should be similarly protected, and steel should be utilized for local structures such as machinery flats and small tanks. Extinguishing equipment within these spaces should conform to present U. S. Coast Guard standards.

23. Protection of aluminum surfaces in the cargo hold is considered impractical. As an alternative, a $CO_2$ and $N_2$ inerting system is recommended, in conjunction with improved detection and extinguishing equipment.

24. Installation of Systems and Equipment. Selection of materials for propeller, shafting, rudder, piping systems, sea valves, etc. which are compatible with aluminum construction is feasible, though isolation and protection with anodes or waster pieces is required in many cases.

25. The faying surfaces between steel equipment and aluminum foundations must be properly gasketed. The use of cast epoxy at the interface or butyl rubber coating is recommended. Access to inspect this interface is very important.

26. An impressed current cathodic protection system is recommended for hull corrosion control.

27. Operational Characteristics of an Aluminum Bulk Carrier - Maintenance costs for the hull of an aluminum bulk carrier will be somewhat lower than those of an equivalent steel vessel, since the topsides require no paint. However, drydocking cycles will be essentially similar to the steel vessel for renewal of bottom paint and maintenance of equipment.

28. Repairs to the aluminum hull will be more expensive than for a steel hull due to higher material cost and lack of trained welders in many areas of the world.

29. Special surveys are recommended of the hull structure of a large aluminum bulk carrier to check structural connections, corrosion, welds, etc.

30. Comparative Ship Design and Evaluation - The principal dimensions of the aluminum bulk carrier selected for this study are essentially similar to the baseline steel ship, although a deeper double bottom and greater hull girder depth might be desirable for an independent design to increase stiffness.

31. The weight per foot amidships for the 5083 aluminum alloy bulk carrier will be about .62 times that of the mild steel ship, while the stiffness will be about 0.66 times that of the steel. The use of fatigue strength rather than static strength in designing the hull girder adds about 435 tons or 15 per cent to the hull structural weight. For a typical bulkhead, the weight reduction factor is 0.55.

32. The total weight of hull structure was reduced from 5920 to 3375 long tons, a savings of 43 per cent. The corresponding reduction in machinery and outfit weight was 4 and 14 per cent respectively.

33. Greater ballast capacity is required for an aluminum bulk carrier to provide suitable propeller and bow immersion in the ballast condition. The stability of the aluminum and steel designs are essentially identical.

34. Cost Studies. An aluminum bulk carrier similar to the MV CHALLENGER produces a higher required freight rate (RFR) than an equivalent steel ship, regardless of the level of procurement, voyage type or length, potential hull life or the higher salvage value of an aluminum ship. Thus the greater earning capability of the aluminum hull is not sufficient to offset its higher capital cost.

35. The aluminum ship's RFR is lowest for high-density cargoes where the full weight savings can be considered (i.e. not volume limited). The transport capability of the aluminum ship is about 7 per cent greater than that of the steel ship.

36. Recommended Areas for Further Study. Further research is required in the areas of construction and maintenance costs, welding, fire resistance, design criteria, deflections, fatigue strength and fracture toughness, corrosion, abrasion and design details.

## RECOMMENDATIONS

On the basis of the foregoing conclusions, the following recommendations are offered:

1. Further efforts toward the development of an aluminum bulk carrier should be terminated.

2. Since aluminum construction for large hulls appears technically feasible, similar studies should be made of the use of aluminum construction in a design where weight-savings in hull structure are of greater importance. High-speed destroyers, small containerships, trailerships and shallow draft landing craft are examples of such vessels. In view of aluminum's excellent cryogenic properties, future studies should also be directed toward LNG carriers.

3. Research into the areas previously delineated for further study should be initiated, sponsored jointly by the Government and the aluminum industry.

4. Existing large aluminum ships such as the SACAL BORINCANO, SEA PROBE and the Navy's PGM gunboats should be carefully monitored to fully document their performance.

5. The future development of a prototype large aluminum hull should be encouraged.

## LIST OF REFERENCES


(1) Aluminum Standards and Data. The Aluminum Association, April 1968.

(2) Report of Aluminum Weld Test Program. SNAME. Technical and Research Bulletin No. 2-13, January 1965.

(3) Fatigue Resistance of Aluminum and Its Products, by G.A. Butz and G.E. Nordmark. Society of Automotive Engineers, National Farm, Construction and Industrial Machinery Meeting, Milwaukee, Wisconsin, September 1964.

(4) Alcoa Aluminum - Magnesium Alloys, by K.F. Thornton, Alcoa, November 1957.

(5) Fatigue Properties of 5000 Series Alloys at Room and Elevated Temperatures, by J.O. Lyst. Alcoa Research Laboratories Report No. 9-64-13, April 1964.

(6) Fatigue Properties of Aluminum Welds - A Review of the Literature and Compilation of Data on 5056, 5083, 5086, 5456 and 6061 Alloys, by G.C. Wolfer and N.L. Person. Kaiser Aluminum Interim Project Report No. MS PR 66-20, March 1966.

LIST OF REFERENCES (Cont'd)

(7) Fatigue Properties of 5083, 5086 and 5456 Aluminum-Alloy Sheet and Plate, by H. Mindlin and C.E. Jaske. Reynolds Metals Co., October 1968.

(8) Axial-Stress Fatigue Strengths of As-Welded Aluminum Alloy Butt Joints, by I.D. Eaton. Alcoa Research Laboratories, Engineering Design Division Report 12-62-11, March 1962.

(9) Axial-Stress Fatigue Test Results for Transverse Butt Welds in Aluminum-Magnesium Alloys, by G.E. Nordmark. Alcoa Research Laboratories, Engineering Design Division Report 12-60-17, May 1960.

(10) Fatigue Properties of 5083 and 5086 Sheet and Plate Products by F.W. DeMoney. Kaiser Aluminum Interim Project Report No. MS PR 58-48, June 1958.

(11) Axial-Stress Fatigue Properties of Aluminum Alloy Plate Butt Welds, by N.L. Person. Kaiser Aluminum Project Report No. MS PR 67-110, November 1967.

(12) Axial-Stress Fatigue Properties of Plain and Welded 5454, 5086, 5083 and 5456 Plate at Room Temperature and -320 degrees F, by J.G. Kaufman and F.G. Nelson. Alcoa Research Laboratories Report No. 9-60-24, June 1960.

(13) Summary of Notch Toughness and Fatigue Data for Al-Mg Alloys by B.D. McLaughlan. Alcan Research and Development Limited Report KS-78-69-15-4, April 1969.

(14) The Corrosion Fatigue Behavior of Al-Mg Alloys, by C. Panseri, L. Mori and P. Dettin. British Corrosion Journal, July 1966.

(15) Aluminum in Shipbuilding, by A. Brinck. A/S Nordic Aluminum Industry, Oslo, Norway, Translated July 1947

(16) Rotating-Beam Fatigue Properties of 5183 MIG Butt Welds in 5083-0 and 5086-H112 Plate, by N.L. Person. Kaiser Aluminum Interim Project Report No. MS PR 64-86, November 1964.

(17) Summary of Cryogenic Data on Aluminum Alloys 5083 and 5086. Kaiser Aluminum and Chemical Corp., June 1960.

(18) Residual Welding Stresses in Aluminum Alloys, by H.N. Hill. Alcoa Research Laboratories, Engineering Design Division Report 12-60-43, 1960.

(19) Shipbuilding Guide to Aluminum Construction, by C.H. Holtyn. Reynolds Metals Co., October 1963.

(20) Alcoa News Release, February 1969.

(21) High Toughness Al-Mg Alloys for Marine Applications, by J.G. Kaufman. Alcoa Research Laboratories Report No. 9-69-4, March 1969.

LIST OF REFERENCES (Cont'd)


(22) Welding Alcoa Aluminum, Aluminum Co. of America.

(23) Corrosion-Fatigue, by P.T. Gilbert. Metallurgical Reviews, 1956.

(24) Fabrication, Welding and Inspection of Ship Hulls. Department of the Navy, NAVSHIPS 0900-000-1000, October 1968.

(25) Radiographic Standards for Production and Repair Welds. Department of the Navy, NAVSHIPS 0900-003-9000, March 1967.

(26) The Effect of Weld Defects with Special Reference to BWRA Research, by F.M. Burdekin, J.D. Harrison and J.G. Young. Conference on the Significance of Defects in Welds, Institute of Welding, London, February 1967.

(27) A Proposed Acceptance Standard for Welded Defects Based Upon Suitability for Service by J.D. Harrison, F.M. Burdekin and J.G. Young. Conference on the Significance of Defects in Welds, Institute of Welding, London, May 1968.

(28) Influence of Weld Defects on Performance, by D.V. Lindh and G.M. Peshak. Welding Journal, February 1969.

(29) Fatigue Strength of Butt Welds in Structural Steels, by L.A. Harris, G.E. Nordmark and N.M. Newmark. Welding Research Council Research Reports, February 1955.

(30) Fatigue Strength of Welds in Low-Alloy Structural Steels, by J.E. Stallmeyer, etc. Welding Research Council Research Reports, June 1956.

(31) Fatigue of Welded Steel Structures, by W.H. Munse. Welding Research Council, 1964.

(32) Control of Steel Construction to Avoid Brittle Failure, Edited by M.E. Shank. Welding Research Council, 1957.

(33) The Fatigue of Metals and Structures, by H. Grover, S.A. Gordon and L.R. Jackson. Department of the Navy, NAVWEPS 00-25-534, 1954 (Revised 1960).

(34) Cumulative Fatigue Damage, by H.T. Corten and T.J. Dolan. International Conference on Fatigue of Metals, September 1956 (2277-S).

(35) Fatigue of Metals Under Combinations of Stresses, by W.N. Findley. ASME Transactions, August 1957.

(36) Effects of Complex Stress-Time Cycles on the Fatigue Properties of Metals, by W.L. Starkey and S.M. Marco. ASME Transactions, August 1957.

(37) Fracture Behavior of Aluminum Alloys, by R.E. Zinkham and J.H. Dedrick. Chapter 6, Fracture. Academic Press, 1969.

LIST OF REFERENCES (Cont'd)


(38) Fracture Toughness Characterization Procedures and Interpretations to Fracture-Safe Design for Structural Aluminum Alloys by R.W. Judy Jr., R.J. Goode and C.N. Freed. Naval Research Laboratory, NRL Report 6871, March 1969.

(39) Aluminum - The Age of Ships, by C. Hoylton. Transactions of the Society of Naval Architects and Marine Engineers, 1966.

(40) Deterioration of Metals in An Ocean Environment, by F. LaQue. Ocean Engineering Vol. 1 No. 3, February 1969.

(41) Small Craft Design-Structures, by K.B. Spaulding, Jr. Lecture Notes for Small Boat Design Course Presented at the University of Michigan, 1967.

(42) Aluminum in Shipbuiling, by A. Brinck. A/S Nordic Aluminum Industry, Oslo, Norway, 1957.

(43) Alcoa Aluminum-Magnesium Alloys Suitable for Structural Welding Applications, by K.F. Thornton, November 1, 1957.

(44) The Aluminum Association Tentative Exfoliation Test for Al-Mg Alloys for Boat and Ship Hull Construction by D. Sprowls, et al.

(45) Comparative Engineering Data on Alloys 5083 and 5086. Kaiser Technical Bulletin DC-62-1.

(46) Aluminum with Food and Chemicals, 2nd Edition, The Aluminum Association, February 1969.

(47) Railroad Compatibility Study, Kaiser Technical Bulletin R-64-2.

(48) The Economics of Operating Aluminum Hopper Wagons by W.F. Campbell. Railway Gazette, September 13, 1963.

(49) Counteracting Abrasion of Aluminum Rock Bodies, Alcan Report dated January 1965.

(50) A Technical Report on Off-Highway Rock Bodies, by W.C. Weltman. Alcoa Report dated April 1959.

(51) Aluminum Dump Truck and Trailer Design and Construction. Alcoa, August 1966.

(52) Aluminum Alloy Construction. Lloyds Register of Shipping (Yachting Section), Supplement No. 9 dated 3 September 1964.

(53) The Effects of Ship Stiffness Upon the Structural Response of a Cargo Ship to an Impulsive Load by M. St. Denis, S. Fersht. SSC Report No. 186 dated September 1968.

(54) Fire Tests on the Steamship NANTASKET - Vol. 45, 1937 Transactions of the Society of Naval Architects and Marine Engineers.

(55) Fire Protection Handbook, National Fire Protection Association

LIST OF REFERENCES (Cont'd)

(56) Handbook of Industrial Loss Prevention, Factory Mutual System.

(57) Fire Resistance of Steel Deck Floor Assemblies, U.S. Department of Commerce, National Bureau of Standards

(58) Stateroom Fire Test, Vol. 58, 1950 Transactions of the Society of Naval Architects and Marine Engineers.

(59) Fire Protection in Passenger Ships, with Particular Reference to Aluminum Structures, 1952 Institution of Naval Architects.

(60) Typical Class A-60, A-39, A-15 and A-0 Steel Bulkheads and Decks, Navigation and Vessel Inspection Circular No. 10-63, April 1, 1963, Treasury Department, U. S. Coast Guard.

(61) Standard Materials, American Society for Testing of Materials - ASTM-E-119-67.

(62) Standard Methods of Fire Tests of Door Assemblies - American Society for Testing of Materials - ASTM-E-152-66.

(63) Standard Method of Test for Surface Burning Characteristics of Building Materials - American Society for Testing of Materials - ASTM-E-84-67.

(64) Tentative Method of Test for Surface Flammability of Building Materials Using an 8 Foot Tunnel Furnace - American Society for Testing of Materials - ASTM-E-286-65T

(65) Fire Control for Passenger Vessels, Vol. 45, 1937 Transactions of the Society of Naval Architects and Marine Engineers.

(66) Circulating Water Wall Construction for Fire Protection - Progressive Architecture, October 1969.

(67) Report of Fire Endurance Test of Insulated Aluminum Marine Bulkhead, SNAME Technical and Research Report, dated July 1967.

(68) IMCO Listing of Fire Casualties FP1X/7.1.

(69) Working Papers on Ship Evaluation Model for Competitive Merchant Ship Project. Prepared for U.S. Department of Commerce, Maritime Administration, Washington, D.C. by Booz, Allen Applied Research, Inc., April 1969.

(70) Trading Opportunities for U.S. Flag Dry Bulk Carriers. Prepared for U.S. Department of Commerce, Maritime Administration, Washington, D.C. by Booz, Allen Applied Research, Inc. August 1969.

(71) Analysis and Statistics of Large Tankers. The University of Michigan, College of Engineering, Department of Naval Architecture and Marine Engineering, October 1968.

## ADDITIONAL SOURCES OF INFORMATION

Alcoa Structural Handbook, Aluminum Company of America

Alcoa Aluminum Handbook, Aluminum Company of America

Welding Alcoa Aluminum, Aluminum Company of America

Structural Aluminum Design, Reynolds Aluminum Company

Aluminum Construction Manual - Specifications for Aluminum Structures, The Aluminum Association

# APPENDIX A

## DETERMINATION OF LONG-TERM BENDING MOMENTS FOR ALUMINUM BULK CARRIER

References:

(A1) Lewis, E.V. "Predicting Long Term Distribution of Wave-Induced Bending Moments on Ships Hulls", SNAME, 1967

(A2) "Analysis and Interpretation of Full Scale Data on Midship Bending Stresses of Dry Cargo Ships" Ship Structure Committee Report SSC-196, June 1969

1. The stresses occurring in a critical portion of the ships hull girder, such as the deck edge, are function of the basic still water bending moment and randomly varying wave-induced vertical and horizontal bending moments and similarly varying inclinations of the ship's principal axes. The still water bending moment is easily established. Statistical analysis methods can be used to predict long term distribution trends of random variables, yielding expected stress or bending moment levels versus number of encounters at such levels during a ship's lifetime. This is a lengthy process when considering a single variable, and would be prohibitive and without proven precedent for phase-combined effects of several random variables. Accordingly, since vertical bending moments account for the major portions of actual stresses, and have been the most thoroughly researched, the bulk carrier design will be based upon expected still water bending moments and predicted long-term distribution of wave-induced vertical bending moments and resulting stresses.

2. The dimensions of the bulk carrier CHALLENGER fit well with those for a Series 60 tanker for which long-term probability data is reported in Reference (A1). Figure 17 of Reference (A1) gives $X_j$ vs Q log 10 $(X > X_j)$ plots of bending moment coefficients in head seas of various significant heights for a 600 foot ship with L/B = 7.0, L/d = 17.5 $C_B = .8$ and $V/\sqrt{L} = .34$. Probabilities of occurrence of such seas in the design's intended service may be combined with Figure 17 values to produce a single curve of expected bending moment coefficient for the anticipated distribution of weather according to

$$Q(X > X_j) \quad \sum_{i=1}^{N} \quad P_i Q_i (X > X_j)$$

Minor adjustment of this curve to account for a $V/\sqrt{L}$ of the design, higher than 0.34, may be based upon proportioning the ordinates according to variations in bending moment with ship speed for the 600 feet, $C_B = .80$ ship shown in Figure 12 of Reference (A1). The $X_j$ vs Q log 10 $(X > X_j)$ (and corresponding $X_j$ vs N) plot will indicate the steepness of static trochoidal waves which would produce bending moments equivalent to the levels of dynamic bending moments expected to be induced by perturbation from the static condition. These moments are superimposed on the still water bending moment.

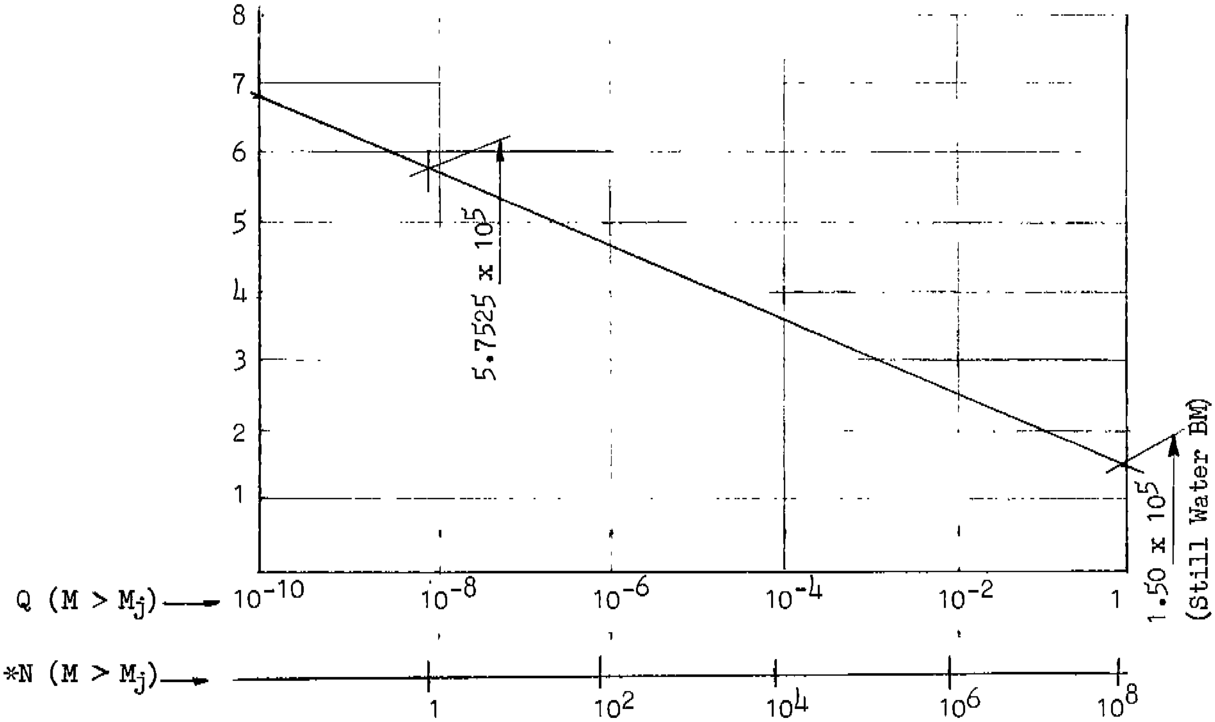
3. A standard bending moment calculation for a wave of a given height combines the bending moment due to the differing weight and buoyancy distribution at the still waterline with the moment due to

redistribution of the still water buoyancy to reflect the wave. Therefore, such a calculation may be used to evaluate the levels of total bending moments (static plus dynamic) to be expected. Accordingly, standard bending moment calculations for several wave heights and for still water may be made to produce an $M_j$ vs Q log $(M > M_j)$ plot by plotting the obtained bending moments at the probabilities corresponding to the $X\left(\frac{h_e}{L}\right)$ values at which the bending moments have been calculated. The sense (hog or sag) of this curve of expected moments will be the same as that of the still water bending moment. By subtracting 2 times the still water bending from its ordinates a curve of expected moments of the opposite sense may be obtained. The foregoing procedure should be based upon the load condition of the design yielding the highest still water bending moment, since the effect of load distribution is more significant to the calculated wave bending moment than is the draft at which it occurs. Finally, if the base scale of probability is multiplied by the expected number of oscillations in the intended life of the ship, the resultant log 10 base scale will indicate the numbers of oscillations during the life of the ship in which it should be expected the $M_j$ levels of bending moments are reached.

4. In applying the foregoing procedures to the subject design it was considered that probabilities based on average North Atlantic weather would be realistic yet not overly conservative, in view of contemplated tramp operations in the various seas of the world. Accordingly, the values given by Figure 18 of Reference (A1) for a 600 foot ship are considered valid for this application, subject to minor correction for Froude number. Based on Figure 12 of Reference (A1), increasing the Froud number from 0.1 to about 0.2 would increase the $\frac{h_e}{L}$ value at $Q = 10^{-10}$ from about .0485 shown on Figure 18 of Reference (A1) to .05.

5. Bending moment estimates for the various loadings of the MV CHALLENGER were reviewed. Noting that the subject design will have a deeper load line than the loadings reviewed, and further that light ship weight is expected to be about 2900 tons less than that used in the estimates, Mandelli methods were used to correct for the effects of these. Accordingly, the design bending moment was estimated to vary from 150,000 foot tons (sagging) in still water to 675,000 foot tons for an $\frac{h_e}{L} = .05$ wave. The resulting $M_j$ vs Q log 10 $(M > M_j)$ plot is shown on Figure A1. Based upon an expectancy of $1.26 \times 10^8$ cycles in as computed thereon for the design's lifetime, it may be expected that once in its lifetime the bending moment will exceed 575,250 foot tons. Also in its lifetime, there is a 99 per cent probability that the bending moment will not exceed 680,250 foot tons. This is obtained by a statistical method given in Appendix A of Reference (A2) and is recommended as the bending moment to be used in yield stress considerations. However, for fatigue considerations the values in the probability range from 1 to $1.26 \times 10^{-8}$ are considered appropriate.

FIG. 1A Long Term Distribution of Vertical Bending Moment (For Preliminary Design)




*N ($M > M_j$) is probable number of times $M_j$ will be exceeded by ships bending moment in its lifetime of n cycles.

(n = 20 Yrs x 200 Sea Days/Yr x 86400 Sec/Day x .3666** CPS = 1.26 x $10^8$ Cyc.)

** Average North Atlantic

Note: Fatigue Factor R Value $\geq \dfrac{(2\, M_{St.Wat.} - M_j)}{M_j}$

# APPENDIX B

## EXCERPTS FROM RULES AND REGULATIONS FOR CARGO AND MISCELLANEOUS VESSELS

Subchapter I

CG-257

## PART 92 - CONSTRUCTION AND ARRANGEMENT

### 92.07 STRUCTURAL FIRE PROTECTION

#### 92.07-1 Application

(a) The provisions of this subpart, with the exception of Section 92.07-90, shall apply to all vessels of 4,000 gross tons and over contracted for on or after January 1, 1962. Such vessels contracted for prior to January 1, 1962, shall meet the requirements of Section 92.07-90(a).

(b) The provisions of this subpart, with the exception of Section 92.07-09, shall apply to all industrial vessels of 300 gross tons and over but less than 4,000 gross tons, contracted for on or after July 1, 1968, which carry in excess of 12 industrial personnel. Such vessels contracted for prior to July 1, 1968, shall meet the requirements of Section 92.07-90(b).

#### 92-07-5 Definitions

92.07-5(a) Standard fire test. A "standard fire test" is one which develops in the test furnace a series of time temperature relationships as follows:

5 minutes - 1,000 degrees F
10 minutes - 1,300 degrees F
30 minutes - 1,550 degrees F
60 minutes - 1,700 degrees F

92.07-5(b) "A" Class divisions. Bulkheads or decks of the "A" Class shall be composed of steel or equivalent metal construction, suitably stiffened and made intact with the main structure of the vessel, such as shell, structural bulkheads, and decks. They shall be so constructed, that if subjected to the standard fire test, they would be capable of preventing the passage of flame and smoke for one hour.

92.07-5(c) "B" Class bulkheads. Bulkheads of the "B" Class shall be constructed with approved incombustible materials and made intact from deck to deck and to shell or other boundaries. They shall be so constructed that, if subjected to the standard fire test, they would be capable of preventing the passage of flame and smoke for one-half hour.

92.07-5(d) "C" Class divisions. Bulkheads or decks of the "C" Class shall be constructed of approved incombustible materials, but need meet no requirements relative to the passage of flame.

92.07-5(e) Steel or other equivalent metal. Where the term "steel or other equivalent metal" is used in this subpart, it is intended to require a material which, by itself or due to insulation provided, has structural and integrity qualities equivalent to steel at the end of the applicable fire exposure.

92.07-5(f) Approved material. Where in this subpart approved materials are required, they refer to materials approved under the applicable subparts of Subchapter Q (Specifications) of this chapter, as follows:

| | |
|---|---|
| Deck Coverings | 164.006 |
| Structural Insulations | 164.007 |
| Bulkhead Panels | 164.008 |
| Incombustible Materials | 164.009 |
| Interior Finishes | 164.012 |

92.07-5(g) Stairtower. A stairtower is a stairway which penetrates more than a single deck within the same enclosure.

92.07-10 Construction

92.07-10(a) The hull, superstructure, structural bulkheads, decks, and deckhouses shall be constructed of steel. Alternately, the Commandant may permit the use of other suitable material in special cases, having in mind the risk of fire.

92.07-10(b) Bulkheads of galleys, paint and lamp lockers, and emergency generator rooms shall be of "A" Class construction.

92.07-10(c) The boundary bulkheads and decks separating the accommodations and control stations from cargo and machinery spaces, galleys, main pantries and storerooms, other than small service lockers, shall be of "A" Class construction.

92.07-10(d) Within the accommodation and service areas the following conditions shall apply:

92.07-10(d)(1) Corridor bulkheads in accommodation spaces shall be of the "A" or "B" Class intact from deck to deck. Stateroom doors in such bulkheads may have a louver in the lower half.

92.07-10(d)(2) Stairtowers, elevator, dumbwaiter and other trunks shall be of "A" Class construction.

92.07-10(d)(3) Bulkheads not already specified to be of "A" or "B" Class construction may be of "A", "B", or "C" Class construction.

92.07-10(d)(4) The integrity of any deck in way of a stairway opening, other than a stairtower, shall be maintained by means of "A" or "B" Class bulkheads and doors at one level. The integrity of a stairtower shall be maintained by "A" Class doors at every level. The doors shall be of self-closing type. Holdback hooks, or other means of permanently holding the door open will not be permitted. However, magnetic holdbacks operated from the bridge or from other suitable remote control positions are acceptable.

92.07-10(d)(5) Interior stairs, including stringers and treads, shall be of steel.

92.07-10(d)(6) Except for washrooms and toilet spaces, deck coverings within accommodation spaces shall be of an approved type. However, overlays for leveling or finishing purposes which do not meet the requirements for an approved deck covering may be used in thicknesses not exceeding 3/8 of an inch.

92.07-10(d)(7) Ceilings, linings, and insulation, including pipe and duct laggings, shall be of approved incombustible materials.

92.07-10(d)(8) Any sheathing, furring or holding pieces incidental to the securing of any bulkhead, ceiling, lining, or insulation shall be of approved incombustible materials.

92.07-10(d)(9) Bulkheads, linings, and ceilings may have a combustible veneer within a room not to exceed 2/28 of an inch in thickness. However, combustible veneers, trim, decorations, etc., shall not be used in corridors or hidden spaces. This is not intended to preclude the use of an approved interior finish or a reasonable number of coats of paint.

92.07-10(e) Wood hatch covers may be used between cargo spaces or between stores spaces. Hatch covers in other locations shall be of steel or equivalent metal construction. Tonnage openings shall be closed by means of steel plates.

92.07-10(f) Nitrocellulose or other highly flammable or noxious fume-producing paints or lacquers shall not be used.

92.07-90 Vessels contracted for prior to July 1, 1968.

(a) For all vessels of 4,000 gross tons and over contracted for prior to January 1, 1962, existing structure arrangements and materials previously approved will be considered satisfactory so long as they are maintained in good condition to the satisfaction of the Officer in Charge, Marine Inspection. Minor repairs and alterations may be made to the same standard as the original construction. Major alterations and conversions shall be in compliance with the provisions of this subpart to the satisfaction of the Officer in Charge, Marine Inspection.

(b) For industrial vessels of 300 gross tons and over but less than 4,000 gross tons, contracted for prior to July 1, 1968, which carry in excess of 12 industrial personnel, existing structure arrangements and materials previously approved will be considered satisfactory so long as they are maintained in good condition to the satisfaction of the Officer in Charge, Marine Inspection. Minor repairs and alterations may be made to the same standard as the original construction. Major alterations and conversions shall be in compliance with this subpart to the satisfaction of the Officer in Charge, Marine Inspection.

# APPENDIX C

## FIRE TEST METHODS

References:

| | |
|---|---|
| (C1) | "Standard Materials" - ASTM-E-119-67 |
| (C2) | "Fire Tests on Steamship NANTASKET" Vol. 45, 1937 Transactions of SNAME |
| (C3) | Typical Class A-60, A-39, A-15 and A-0 Steel Bulkheads and Decks, Navigation and Vessel Inspection Circular No. 10-63, April 1, 1963, Treasury Department, U. S. Coast Guard |
| (C4) | Stateroom Fire Test, Vol. 58, 1950 Transactions of the Society of Naval Architects and Marine Engineers |
| (C5) | Fire Protection in Passenger Ships, with Particular Reference to Aluminum Structures, 1952 Institution of Naval Architects |

1. Test methods have been developed to determine, insofar as practicable, the various effects of fires of controlled intensity on such components as columns, decks, bulkheads and other members, (Reference (C1)). The results of such tests are recorded as the period of fire resistance expressed in minutes or hours. They signify that the component tested resists, to the required degree, the effects of the controlled fire under specific conditions of restraint or load, or both restraint and load, for the period and are reported to the nearest integral minute. The ratings so developed are the accepted criteria of the fire resistance of the various materials and types of construction.

2. The control for the intensity of the fire for tests of components is based on the Standard Time-Temperature Curve (Figure C-1). This curve was prepared in 1918 through conferences among representatives of eleven technical societies or organizations called jointly by the ASTM Committee on fireproofing and the NFPA Committee on Fire-Resistive Construction.

3. The test exposure to be evaluated is plotted on the time-temperature graph together with the standard curve. The area under the test curve and above a baseline taken as the maximum temperature to which the exposed materials under consideration may be subjected without damage, expressed in "degree-hours", is an approximation of the severity and duration of a fire involving ordinary combustibles. Any fire test data can be compared to the Standard Time-Temperature Curve by the approximation that comparative measures of fire severity can be obtained by assuming that the area under the test curve, expressed in "degree-hours", gives the equivalent severity to an equal area under the Standard Time-Temperature Curve.

4. This method for recording the fire resistance of shipbuilding materials and constructions was first utilized during the SS NANTASKET ship-

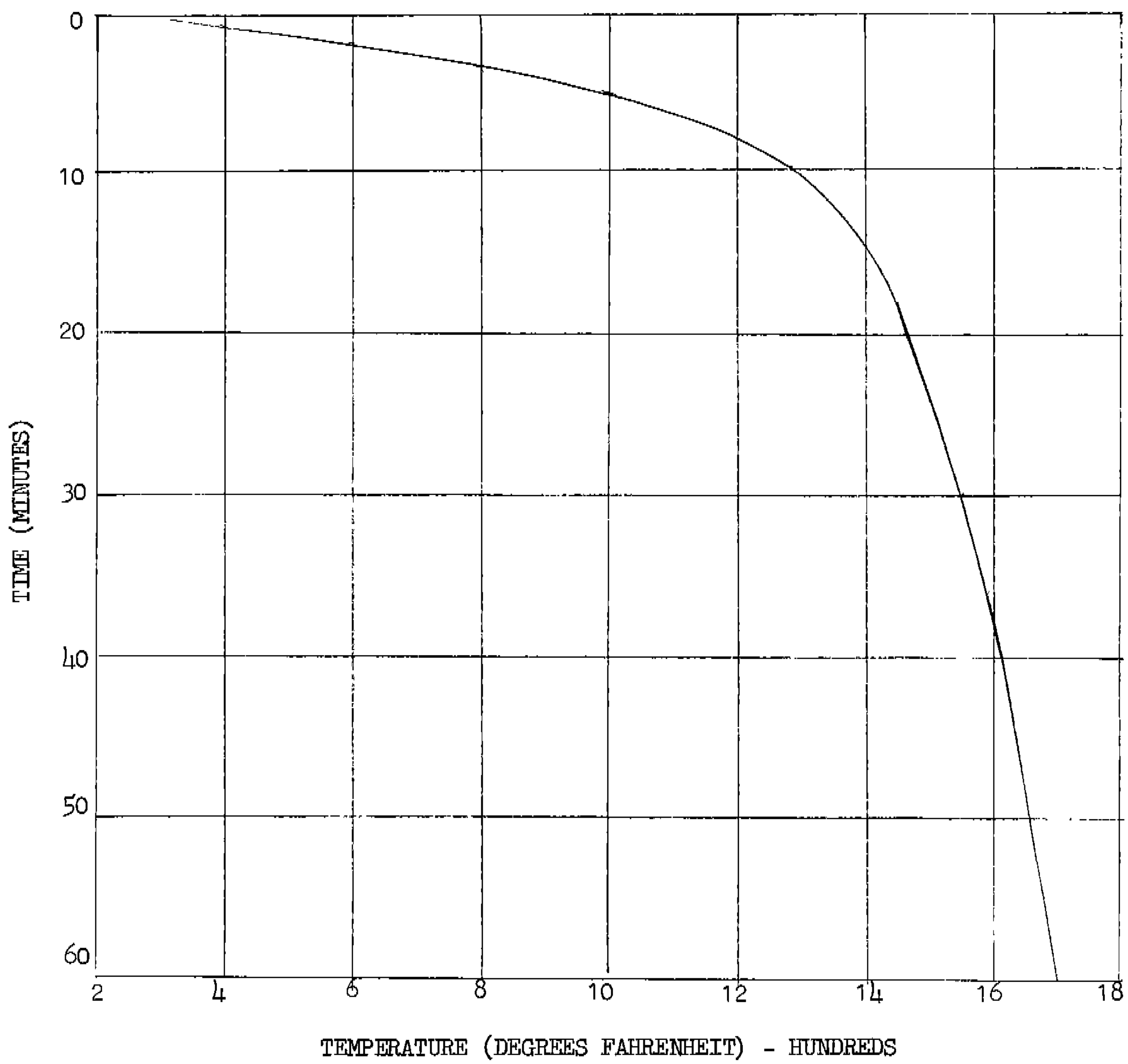



FIG. C-1 Standard Time - Temperature Curve for Fire Tests

board tests in 1936 (Reference (C2)). A stateroom was loaded with 5 pounds of combustibles per square foot of area. The resulting fire was found to be of a severity equal to that represented by the standard curve. All the later tests conducted at this time were compared to the standard curve and the comparative value of the exposure approximated. Thus, the comparative fire resistance of the various materials and constructions were evaluated.

5. By this method the U. S. Coast Guard, in conjunction with the National Bureau of Standards have developed constructions utilizing approved materials for steel ships based on a time-temperature rating, Reference (C3). Some subsequent tests for aluminum have been conducted, again using this method of evaluation, (References (C4) and (C5)). This is also the basis of the tests being conducted under the auspices of the Society of Naval Architects and Marine Engineers and the U. S. Coast Guard.

UNCLASSIFIED
Security Classification

## DOCUMENT CONTROL DATA - R & D

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY *(Corporate author)*<br>Gibbs & Cox, Inc.<br>New York, New York | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP |

3. REPORT TITLE
Design Considerations for Aluminum Hull Structures - Study of Aluminum Bulk Carrier

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Technical Report -- SSC-218

5. AUTHOR(S) *(First name, middle initial, last name)*
Charles J. Altenburg, and Robert J. Scott

| 6. REPORT DATE | 7a. TOTAL NO OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| November 1970 | 128 | 71 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO.<br>N00024-70-C-5138 | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>16671/1-598 |
| b. PROJECT NO.<br>SF354-22-306<br>c. Task 2022, SR-190<br>d. | 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* |

10. DISTRIBUTION STATEMENT

Distribution of this Document, SSC-218, is unlimited.

| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY |
|---|---|
| | Naval Ship Engineering Center |

13. ABSTRACT


This study was undertaken to evaluate the benefits and constraints that will develop when ship design as well as fabrication procedures are modified to employ aluminum alloys instead of steel for hull structure of a large deadweight carrier.

The fabrication of a large aluminum hull with state of the art materials and construction techniques is shown to be technically feasible. Present 5000 series alloys have adequate properties, though additional research is required, particularly into fatigue characteristics. Experience to date with existing aluminum ships has been good, though instances of cracking at welds and corrosion have been noted. Criteria for the design of the aluminum hull structure are presented and justified. Methods of fire protection and system/equipment installation are evaluated, and operational characteristics of an aluminum bulk carrier are reviewed.

The designs of a large aluminum bulk carrier and an equivalent steel ship are presented and compared. The aluminum ship's structure weighs 43 per cent less than the steel ship, and its hull is about 50 per cent more flexible. Cargo deadweight is increased 7-1/2 per cent.

Cost studies indicate that for the same return on investment the required freight rate of the aluminum bulk carrier is higher than the equivalent steel ship, for all levels of procurement, assumed hull life, or voyage length considered.

UNCLASSIFIED
Security Classification

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Final Technical Report | | | | | | |
| Aluminum | | | | | | |
| Bulk Carriers | | | | | | |
| Study - Aluminum Bulk Carriers | | | | | | |
| Material Studies - Aluminum Bulk Carriers | | | | | | |
| Fabrication - Aluminum Bulk Carriers | | | | | | |
| Design Studies - Aluminum Bulk Carriers | | | | | | |
| Ship Design - Aluminum Bulk Carriers | | | | | | |
| Cost Studies - Aluminum Bulk Carriers | | | | | | |

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

GPO 915-616

UNCLASSIFIED
Security Classification

## SHIP RESEARCH COMMITTEE
Maritime Transportation Research Board
National Academy of Sciences-National Research Council

The Ship Research Committee has technical cognizance of the inter-agency Ship Structure Committee's research program:

PROF. R. A. YAGLE, CHAIRMAN, *Prof. of Naval Architecture, University of Michigan*

DR. H. N. ABRAMSON, *Director Department of Mechanical Sciences, Southwest Research Inst.*

MR. W. H. BUCKLEY, *Chief Structural Criteria and Loads, Bell Aerosystems Co.*

DR. D. P. CLAUSING, *Senior Scientist, U.S. Steel Corporation*

MR. A. E. COX, *Senior Program Manager, Newport News Shipbuilding & Dry Dock Co.*

MR. J. F. DALZELL, *Senior Research Engineer, Stevens Institute of Technology*

DR. W. D. DOTY, *Senior Research Consultant, U.S. Steel Corporation*

MR. F. D. DUFFEY, *Manager of Welding & Methods, Maryland Shipbuilding & Dry Dock Co.*

MR. D. FAULKNER, *Research Associate, Massachusetts Institute of Technology*

PROF. W. J. HALL, *Prof. of Civil Engineering, University of Illinois*

MR. J. E. HERZ, *Chief Structural Design Engineer, Sun Shipbuilding & Dry Dock Co.*

MR. G. E. KAMPSCHAEFER, JR, *Manager, Application Engineering, ARMCO Steel Corporation*

PROF. B. R. NOTON, *Prof of Aerospace & Civil Engineering, Washington University*

MR. W. W. OFFNER, *President, X-ray Engineering International*

CDR R. M. WHITE, USCG, *Chief Applied Engineering Section, U.S. Coast Guard Academy*

MR. R. W. RUMKE, *Executive Secretary, Ship Research Committee*

Advisory Group II, "Ship Structural Design" prepared the project prospectus and evaluated the proposals for this project.

MR. J. E. HERZ, Chairman, *Chief Structural Design Engineer, Sun Shipbuilding & Dry Dock Co.*

MR. A. E. COX, *Senior Program Manager, Newport News Shipbuilding & Dry Dock Co.*

MR. D. FAULKNER, *Research Associate, Massachusetts Institute of Technology*

PROF. J. E. GOLDBERG, *Prof. of Civil Engineering, Purdue University*

PROF. B. R. NOTON, *Prof. of Aerospace & Civil Engineering, Washington University*

PROF. J. R. PAULLING, JR., *Prof. & Chairman of Department of Naval Architecture, University of California*

MR. D. P. ROSEMAN, *Naval Architecture, Hydronautics, Inc.*

CDR R. M. WHITE, USCG, *Chief, Applied Engineering Section, U.S. Coast Guard Academy*

The SR-190 Project Advisory Committee provided the liaison technical guidance, and reviewed the project reports with the investigator.

PROF. B. R. NOTON, Chairman, *Prof. of Aerospace & Civil Engineering, Washington University*

MR. C. R. CUSHING, *President, Cushing & Nordstrom, Inc.*

MR. D. P. COURTSAL, *Chief Marine Engineer, Dravo Corporation*

## SHIP STRUCTURE COMMITTEE PUBLICATIONS

*These documents are distributed by the National Technical Information Service, Springfield, Va. 22151. These documents have been announced in the National Technical Information Service Journal U.S. Government Research & Development Reports (USGRDR) under the indicated AD numbers.*

SSC-206, *Permissible Stresses and their Limitations* by J. J. Nibbering. 1970. AD 710520.

SSC-207, *Effect of Flame and Mechanical Straightening on Material Properties of Weldments* by H. E. Pattee, R. M. Evans, and R. E. Monroe. 1970. AD 710521.

SSC-208, *Slamming of Ships: A Critical Review of the Current State of Knowledge* by J. R. Henry and F. C. Bailey. 1970. AD 711267.

SSC-209, *Results from Full-Scale Measurements of Midship Bending Stresses on Three Dry Cargo Ships* by I. J. Walters and F. C. Bailey. 1970. AD 712183.

SSC-210, *Analysis of Slamming Data from the "S. S. Wolverine State"* by J. W. Wheaton, C. H. Kano, P. T. Diamant, F. C. Bailey. 1970. AD 713196.

SSC-211, *Design & Installation of a Ship Response Instrumentation System Aboard the Container Vessel "S. S. Boston"* by R. A. Fain, J. Q. Cragin, and B. H. Schofield. (To be published).

SSC-212, *Ship Response Instrumentation Aboard the Container Vessel "S.S. Boston": Results from the 1st Operational Season in North Atlantic Service* by R. A. Fain, J. Q. Cragin, and B. H. Schofield. 1970. AD 712186.

SSC-213, *A Guide for Ultrasonic Testing and Evaluation of Weld Flaws* by R. A. Youshaw. 1970. AD 713202.

SSC-214, *Ship Response Instrumentation Aboard the Container Vessel "S. S. Boston": Results from 2 Operational Seasons in North Atlantic Service* by J. Q. Cragin. 1970. AD 712187.

SSC-215, *A Guide for the Synthesis of Ship Structures Part One - The Midship Hold of a Transversely-Framed Dry Cargo Ship* by Manley St. Denis. 1970. AD 717357

SSC-216, *To be Published.*

SSC-217, *Compressive Strength of Ship Hull Girders: Part I - Unstiffened Plates* by H. Becker, R. Goldman, and J. Pazerycki Mithras. 1970. AD 717590