COST-BENEFIT ANALYSIS MODEL
FOR GREAT LAKES BULK CARRIERS
OPERATING DURING AN EXTENDED
SEASON

Harry Benford
Horst Nowacki
Movses Kaldjian
Kwangse Kim

Department of Naval Architecture
and Marine Engineering
College of Engineering
The University of Michigan

Report to Department of Commerce,
Maritime Administration
**Contract No. 1-35487**

September 30, 1971

THE UNIVERSITY OF MICHIGAN
ENGINEERING LIBRARY
FOREWORD

Winter navigation on the Great Lakes has been a reality since before the turn of the century when icebreaking carferries were placed into regular year-round service across Lake Michigan and in the Straits of Mackinac (1). * Nevertheless, the most important units of the Great Lakes fleet -- the bulk carriers -- were customarily laid up during November, and frequently confined their operating season to as little as seven months (1). Today, however, ships in one of the major iron ore fleets are operating on what is essentially a ten-month basis (April through January) and there is widespread interest in further extension of the season, even perhaps to essentially the year around.

The trend that we see so strongly today had its beginnings with Admiral E. H. Thiele's proposal for season extensions dating back to 1959 (2). In 1962 the authors of reference 3 presented evidence that there were probably important economic benefits in Admiral Thiele's proposal. Other researchers, such as Prof. John Hazard, subsequently documented the resulting potential gains for commerce and industry in the entire Midwest (4).

In 1969 the U. S. Corps of Engineers completed an initial study for the Congress (5) and is now engaged in an ambitious multi-million dollar follow-up study of the costs and benefits of an extended season on the Lakes and through the Seaway. The U. S. Coast Guard and the Maritime Administration, among other federal agencies, have also joined in a massive cooperative

*Numbers in parenthesis indicate references in the Bibliography.
FOREWORD

effort to assist private industry in this new development.

As an integral part of the overall program, the Maritime Administration last April placed the present study contract with The University of Michigan. The intent was to provide a method for predicting costs and benefits accruing to any Great Lakes shipowner who might engage in extended season operations. This was to be presented in the form of a computerized model of general applicability. The study was to complement others concurrently underway (sponsored by several federal agencies) encompassing costs to government and overall costs and benefits to private industry and the public. In addition, the model was to be constructed in a manner that would allow easy modification as new facts are gathered from continuing research and development.

The present report meets the foregoing specification, we believe, to the maximum extent possible under the existing constraints of time, budget, and available information. The value of the report lies in the analytical technique, or model, presented. The model clearly indicates the more critical areas for further research, and provides a sound framework for continuing investigation. As more experience is gained in actual winter operations and as more research reports become available the model can quickly be refined to a degree that will allow fast, reliable economic projections. These, in turn, can be used to optimize the design of ships -- or taken as inputs to broader analyses aimed at optimizing the entire transport system.
ACKNOWLEDGMENTS

This report is the product of many minds both internal and external to The University of Michigan.

Among the external sources, two design firms gave us every possible cooperation: R. A. Stearn, Inc. of Sturgeon Bay, Wisconsin; and Marine Consultants and Designers of Cleveland, Ohio. Although both are occasionally quoted in the report, there are many other instances where their factual information was incorporated along with our own and no attribution given. Much of the data on ship weights, building costs, and operating costs benefited from their guidance. Mr. Ernest Marshall, glaciologist, contributed expert advice on ice conditions on the Great Lakes.

Several graduate students devoted much time and thought to the project. Among these was Mr. M. Walaa Anwar, who assisted with the structural analysis and Mr. Peter Swift, who helped develop the cost and weight estimating methods.

Drawing on the experience of our friends in Northern Europe, we received much helpful advice from the following individuals:

Professor Jansson of the Technical University of Helsinki
Mr. Brenner of ABS (Helsinki)
Captain Aalto of the Finnish Board of Navigation
Mr. Grunér of the Finnish Steamship Company
Mr. Sundström of Finnlines
Mr. Wihuri of Suomen Tankkilaiva Oy, Helsinki
Dr. Palosuo of the Finnish Institute of Marine Research
ACKNOWLEDGMENTS

Mr. Pehrsson of Kamewa, Kristinehamn/Karlstadt
Dr. Waas of the Hamburg Ship Model Basin
Mr. Lauritzen of J. Lauritzen Lines, Copenhagen
Professor Prohaska of the Hydro and Aerodynamic Laboratories, Denmark
Dr. Røren of Det norske Veritas

Closer to home, we were fortunate enough to receive close cooperation from several ship operating companies, the U. S. Army Corps of Engineers, and the U. S. Coast Guard. Individually, we want to offer particular thanks to:

Mr. C. F. Beukema of U. S. Steel Corporation Great Lakes Fleet
Mr. Richard Tesreau of U. S. Steel Corporation Great Lakes Fleet
Captain John Rankin of U. S. Steel Corporation Great Lakes Fleet
Mr. W. R. Ransom of U. S. Steel Corporation Great Lakes Fleet
Mr. Clare Snider of Ford Motor Company Marine Division
Captain Dwight King of Cleveland Tankers
Mr. John Horton of Cleveland Cliffs Iron Co.
Mr. James Moon of Mobil Oil Company

Mr. M. E. Parr of the Maritime Administration supplied useful information on the new tax law as it affects Great Lakes Ships. Mr. Frank Kesterman, also of the Maritime Administration, provided effective liaison between ourselves and the Office of
Research and Development. Mr. John Couch of Litton Ship Systems Division assisted with advice on machinery capital costs.

While we are anxious to express our sincere thanks to all of the aforementioned individuals and organizations, we must also state that we bear full responsibility for any shortcomings contained herein.

Joan Barnowe and Dawn Mulder merit special thanks for their exceptional patience and efficient operation in typing this report.

Harry Benford
Horst Nowacki
Movses Kaldjian
Kwangse Kim
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>uniform annual returns before tax</td>
</tr>
<tr>
<td>B</td>
<td>beam</td>
</tr>
<tr>
<td>BHP</td>
<td>brake horsepower</td>
</tr>
<tr>
<td>C</td>
<td>annual transport capacity</td>
</tr>
<tr>
<td>$C_B$</td>
<td>block coefficient</td>
</tr>
<tr>
<td>CN</td>
<td>cubic number $= \frac{LBD}{100}$</td>
</tr>
<tr>
<td>CP</td>
<td>controllable pitch</td>
</tr>
<tr>
<td>CR</td>
<td>capital recovery factor</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>displacement at summer loadline, long tons, fresh water</td>
</tr>
<tr>
<td>D</td>
<td>depth</td>
</tr>
<tr>
<td>DW</td>
<td>deadweight</td>
</tr>
<tr>
<td>K</td>
<td>number in crew</td>
</tr>
<tr>
<td>L</td>
<td>length between perpendiculars</td>
</tr>
<tr>
<td>LS</td>
<td>lightship weight</td>
</tr>
<tr>
<td>M</td>
<td>operating months per year</td>
</tr>
<tr>
<td>N</td>
<td>economic life of a ship, or years remaining in case of an existing ship</td>
</tr>
<tr>
<td>NPV</td>
<td>net present value</td>
</tr>
</tbody>
</table>
SYMBOLS AND ABBREVIATIONS

NPVI  net present value index
P     initial investment
r     freight rate, $ per long ton
RFR   required freight rate, $ per long ton
S     percentage ice cover
SHP   shaft horsepower
T     summer loadline draft
W_C   weight of conveyor system (exclusive of A-frame and hoppers)
W_M   weight of propulsion plant, wet
W_O   weight of outfitting and hull engineering
W_S   weight of structure
Y     uniform annual operating costs

Notes

1. Other symbols and abbreviations are explained wherever used.

2. All weights are in long tons and all dimensions in feet except as noted.

3. All costs are in 1971 dollars.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOREWORD</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>v</td>
</tr>
<tr>
<td>SYMBOLS &amp; ABBREVIATIONS</td>
<td>ix</td>
</tr>
<tr>
<td><strong>I. SUMMARY OF THE PROBLEM &amp; PROPOSED SOLUTION</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>II. DETAILED ANALYTICAL METHODS</strong></td>
<td>7</td>
</tr>
<tr>
<td>A. Design</td>
<td>7</td>
</tr>
<tr>
<td>B. Weights</td>
<td>11</td>
</tr>
<tr>
<td>C. Investments</td>
<td>16</td>
</tr>
<tr>
<td>D. Operating Environment (Ice Conditions)</td>
<td>23</td>
</tr>
<tr>
<td>E. Speed &amp; Power in Open Water &amp; in Ice</td>
<td>30</td>
</tr>
<tr>
<td>F. Annual Transport Capability</td>
<td>45</td>
</tr>
<tr>
<td>G. Operating Costs</td>
<td>56</td>
</tr>
<tr>
<td>H. Measures of Merit</td>
<td>65</td>
</tr>
<tr>
<td>I. Synthesis</td>
<td>71</td>
</tr>
<tr>
<td><strong>III. COMPUTER PROGRAM</strong></td>
<td>75</td>
</tr>
<tr>
<td>A. Inputs</td>
<td>76</td>
</tr>
<tr>
<td>B. Implicit Assumptions</td>
<td>81</td>
</tr>
<tr>
<td>C. Output</td>
<td>83</td>
</tr>
<tr>
<td>D. Sample Study</td>
<td>83</td>
</tr>
<tr>
<td><strong>IV. PRELIMINARY CONCLUSIONS</strong></td>
<td>102</td>
</tr>
<tr>
<td><strong>APPENDICES</strong></td>
<td></td>
</tr>
<tr>
<td>I. THE NEW TAX LAW AND ITS EFFECT ON THE ANNUAL COSTS OF CAPITAL RECOVERY</td>
<td>103</td>
</tr>
<tr>
<td>II. SPEED AND POWER IN ICE</td>
<td>119</td>
</tr>
<tr>
<td>III. ICE STRENGTHENING AND STEEL WEIGHTS</td>
<td>137</td>
</tr>
<tr>
<td>IV. FLOW CHART</td>
<td>141</td>
</tr>
<tr>
<td><strong>BIBLIOGRAPHY</strong></td>
<td></td>
</tr>
<tr>
<td>A. References Cited in Report</td>
<td>154</td>
</tr>
<tr>
<td>B. Other References</td>
<td>157</td>
</tr>
</tbody>
</table>
I. SUMMARY OF THE PROBLEM AND PROPOSED SOLUTION

The object of this study is to establish a widely-applicable procedure for estimating the economic benefits (to shipowners) from extensions of the Great Lakes operating season. An important secondary object is to help ship designers optimize the design of ships intended for ice operations.

The study attempts no firm conclusions or recommendations as to the best length of operating season or ship design. It weighs the economic costs and benefits to the shipowner and specifically ignores public costs for icebreaker assistance, etc. The study omits all reference to the benefits of lessened stockpiling requirements and miscellaneous problems relating to possible shore damage, etc.

In its present form, the proposed analytical procedure is, we believe, sound in principle. There are inevitably several gaps in quantitative factors -- both major and minor. Among the major gaps are the changing characteristics of the ice itself, average speeds obtainable through ice, and costs of hull reinforcement. Thus, while this report provides what we believe is a valid foundation, its usefulness will be limited until further knowledge is gained from ongoing research, including of course full scale experimental operations and methodical ice surveys.

The final outcome of our analysis is an economic measure of merit indicating the net benefit to the shipowner from various lengths of the operating season. As one
I: SUMMARY OF THE PROBLEM

may infer, of course, benefits to shipowners should eventually become benefits to the public in the form of lower prices for consumer products.

Because of variations from year to year in the severity of weather and ice conditions, a ship with any given degree of ice strengthening would logically be operated for differing periods in the various winter seasons. Our analytical method recognizes this, treating weather and ice statistically. We use the term "ice strengthening" throughout this report in its broadest sense, including not only hull reinforcement but increased horsepower and other modifications intended to make the ship operable in ice. We do not, however, include any changes in hull form.

There are, of course, manifold variations in real-life scenarios in which different shipowners find themselves. Some are interested in extending the season with ships as yet unbuilt, others want to modify existing ships. The degree of federal assistance remains unknown. Each trade route has its own ice conditions and potential intensity of traffic. Each commodity has its own handling problems in cold weather. We have treated such factors parametrically, keeping to a minimum the arbitrary assumptions built into the analysis. The following outline summarizes the major factors and the variations considered in the present study:

A. Commodity and Trade Route

The study is presently applied to the pelletized ore
trade from the Upper Lakes to Lake Michigan (specifically, Two Harbors to South Chicago). Other important trades, such as the ore movement between Lake Superior and Lake Erie ports, and the movement of grain, limestone, coal, and petroleum, merit further study. (We assume throughout this report that cargo will always be available at the loading port and receivable at the unloading port without undue delays.)

B. Ship Type

1. Bulkers (a term designating an ordinary bulk carrier without self-unloading gear)
2. Self-Unloaders
   a. With A-frame and boom
   b. Simple shuttle type (relying on matching shore based conveyors to carry the cargo over the ship's side and ashore)

C. Degree of Ice Strengthening

1. Class 2 (unmodified)
2. Class IC
3. Class IB
4. Class IA
5. Class IA Super

See reference 6 for detailed requirements of the various ice classes.
I: SUMMARY OF THE PROBLEM

D. Overall Weather and Ice Conditions

1. Mild
2. Normal
3. Severe

E. Ship Status

1. Existing ships
2. Ships in planning stage

F. Ship Characteristics

1. Length
2. Beam
3. Depth
4. Draft
5. Block coefficient
6. Shaft horsepower
7. Crew complement
   etc.

G. Power Plant (all single-screw)

1. Steam turbine
2. Twin intermediate-speed geared diesels

H. Propeller

1. Fixed blades
2. Controllable pitch
I. Miscellaneous Design Factors

1. With or without bow thruster
2. Cruiser or transom stern
3. Self-unloading rates
4. Dock loading and unloading rates

J. Length of Operating Season

1. Standard (8 months)
2. 9 months
3. 10 months
4. 11 months
5. 11.5 months
   (or any intermediate value)

Our analytical procedure and the computer program that is its offspring are presented in a way to allow them to be easily modified to accommodate other variations or assumed inputs.

Taking any desired combination of the above variables, the user can apply our methodical procedure to determine, in sequence:

A. Design Characteristics

B. Weights

C. Investments

D. Operating Environment (ice conditions)

E. Speed and Power in Open Water and in Ice
I: SUMMARY OF THE PROBLEM

F. Annual Transport Capability

G. Operating Costs

(Chapter II, DETAILED ANALYTICAL PROCEDURE, follows the format of the outline above and adds sections on measures of merit and final synthesis.)

In short, the user can start with any reasonable combination of design and voyage variables and follow our analytical procedure to predict the resulting economic benefit of various lengths of operating season. Repeated with varying design variables, the results can be used to find the optimal ship. One must keep in mind, of course, that the optimal ship does not necessarily result in the optimal transport system. This entire study should, indeed, be looked upon as only one component of a complete transport analysis now being undertaken by various federal agencies, ship owners, and other interested parties.

It should be noted here that the economic analysis is based on the costs and benefits of the entire operating season, not just the extension. The added computational work is necessary because ice strengthening involves changes in weight and transport capacity affecting summer as well as winter operations.
II. DETAILED ANALYTICAL METHODS

A. Design

There is no intent here to design a ship, but only to analyze a proposed design (whether for a new or modified ship) in order to predict its economic merit. Our approach requires certain minimum initial inputs, notably length between perpendiculatrs (L), beam (B), depth (D), summer loadline draft (T), block coefficient (C_B), shaft horsepower (SHP), and ice class. Other important design parameters can then be derived -- or used as inputs if already known. The sequence of the analysis follows:

1. Prismatic Coefficient

\[ C_p = \frac{C_B}{C_M} \]  \[1\]

where

\[ C_M = \text{midship coefficient} \]

In Great Lakes ore carriers \( C_M \) varies between 0.990 and 0.999. We will use an average value, 0.993, at this stage.

2. Length Overall

\[ L_{OA} = fL \]  \[2\]
II: DETAILED ANALYTICAL METHODS

where

\[ f = \begin{cases} 1.0115 & \text{for transom stern ships} \\ 1.026 & \text{for cruiser stern ships} \end{cases} \]

3. Displacement

The summer load line displacement (\( \Delta \)) is based on the length between perpendiculaires and long tons of fresh water:

\[ \Delta = C B^{0.55} \]

[3]

The corresponding number of metric tons is 1.6% greater.

4. Minimum Horsepower

The specified horsepower should be checked against the minimum requirements of the ice class and adjusted upwards to that minimum if found deficient. Regulation 3 of the ice rules (6) applies the following formula:

\[ \text{min. SHP} = (1.016q\Delta + X) \text{ or } Y, \text{ whichever is less, and where } q, X, \text{ and } Y \text{ have the values shown in the following table:} \]

<table>
<thead>
<tr>
<th>Ice Class</th>
<th>q</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA Super</td>
<td>0.40</td>
<td>1500</td>
<td>25,000</td>
</tr>
<tr>
<td>IA</td>
<td>0.35</td>
<td>1000</td>
<td>22,000</td>
</tr>
<tr>
<td>IB</td>
<td>0.30</td>
<td>500</td>
<td>18,500</td>
</tr>
<tr>
<td>IC</td>
<td>0.25</td>
<td>0</td>
<td>15,000</td>
</tr>
</tbody>
</table>
The rules stipulate further that SHP should in no case be less than 1000 for any ice class and not less than 3500 for class IA Super. The minimum required power and the lower limits may be reduced by 10% "if the ship is fitted with a controllable pitch propeller and reversible main machinery." The astern power in steam turbine ships must be at least 70% of the ahead SHP.

5. Cubic Number

The cubic number (CN) is defined in the usual way:

\[ CN = \frac{LBD}{100} \]  \hspace{1cm} [4]

6. Freeboard, Draft, and Displacement

Given the summer freeboard and corresponding draft, T, the drafts at other loadlines will be as follows:

\[ T_{MS} = \text{mid-summer draft} = 1.025T \]  \hspace{1cm} [5]

When L exceeds 550 ft, the intermediate draft, \( T_I \), and winter draft, \( T_W \), will be:

\[ T_I = 0.9625T \]  \hspace{1cm} [6]

and

\[ T_W = 0.9177T \]  \hspace{1cm} [7]
II: DETAILED ANALYTICAL METHODS

At drafts, $T_X$, close to the summer loadline condition, the block coefficient, $C_{B-X}$, can be approximated as follows:

$$C_{B-X} = C_B + 0.002(T_X - T)$$  \[8\]

Given these modifications to draft and block coefficient, we can easily derive the displacements at the mid-summer, intermediate, and winter freeboards. The mid-summer displacement, for example, would be:

$$\Delta_{MS} = C_{B-MS} \frac{L_B^{BS}}{35.9}$$  \[9\]

where

$C_{B-MS} =$ block coefficient at mid-summer freeboard draft, $T_{MS}$
B. Weights

For estimating both weights and costs we divide the ship into the three traditional categories:

- Structural hull (including erections)
- Outfitting (including hull engineering)
- Machinery (complete propulsion system including liquids)

Extra features, notably self-unloading capability, are treated as appended weights and costs.

1. Structural Hull Weight

The basic (i.e. unreinforced) structural hull weight can be estimated using a modified version of Krappinger's formula (7):

\[ W_s = 668 \left( \frac{CN}{1000} \right)^{0.75} \left( \frac{L}{D+2} \right)^{0.565} + \frac{C_B}{2} \]  

The added weight of steel for ice strengthening (either new construction or modification) can be estimated from Figure 1. The curves are from (8) and carry the caution that there are bound to be large individual departures. Moreover, the curves are still tentative in nature and should be checked and refined in future studies. Despite these shortcomings, we believe the curves reflect the trends with a degree of accuracy suitable for this stage of development.
If the ship is a self-unloader with A-frame and boom, the structural weight will be increased by about 2%. For a simple shuttle conveyor without A-frame, the increase would be about 1%.

2. **Outfitting Weight**

The weight of outfitting (including hull engineering) will be but little affected by the ice class or intended length of operating season. One estimate (9) indicates an addition of only 10 tons for a class IA Super design. For our purposes, we can ignore such small increments.

The outfitting weight can be estimated as follows:

\[ W_o = 233 \left( \frac{CN}{1000} \right)^{0.3} \]  \hspace{1cm} [11]

The weight of conveyor systems may be estimated as follows:

\[ W_c = a \left( \frac{CN}{1000} \right)^b \]  \hspace{1cm} [12]

where

\[ W_c \] is the weight of the complete conveyor system (exclusive of A-frame and hoppers) in long tons,

and where

a and b have the values shown below:
II: DETAILED ANALYTICAL METHODS

<table>
<thead>
<tr>
<th>Capacity in 1000 tons per hour</th>
<th>Shuttle Conveyor</th>
<th>Boom Conveyor</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>40</td>
<td>104</td>
</tr>
<tr>
<td>6</td>
<td>53</td>
<td>147</td>
</tr>
<tr>
<td>8</td>
<td>65</td>
<td>202</td>
</tr>
<tr>
<td>10</td>
<td>77</td>
<td>252</td>
</tr>
<tr>
<td>20</td>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>

The added weight and lost buoyancy of bow thrusters are treated under section 5, which follows.

3. Machinery Weight

The wet weight of single screw machinery plants can be estimated as follows:

\[ W_M = a \left( \frac{SHP}{1000} \right)^{0.5} \]  \hspace{1cm} [13]

where

\( a = 200 \) for geared steam turbine installations

\( a = 180 \) for twin, medium speed geared diesels

The ice rules dictate minimum requirements for propeller blade thickness, shaft diameters, reduction gears, etc. In addition, special appurtenances are needed to ensure a flow of cooling water to the condenser. The resulting increase in weight is minor and is therefore
ignored in this analysis.

4. **Light Ship**

The light ship weight is simply the sum of the three component weights discussed above plus any added weights for self-unloaders. No margin need be added in studies of this kind.

5. **Deadweight**

The basic deadweight is that corresponding to the freshwater displacement at the summer loadline draft:

\[ DW = \Delta - LS \]  

[14]

where

\[ LS = \text{light ship weight} \]

Subtract 70 tons for a typical bow thruster installation. This comprises both added weight of hardware and loss of displacement.

6. **Variable Weights**

Weights of fuel, fresh water, etc. are dealt with under section F, Annual Transport Capability.
II: DETAILED ANALYTICAL METHODS

C. Investments

In a parametric study such as this, cost estimates must be made as a step in helping to choose between alternatives. Our principal aim, then, is to establish a procedure that illuminates cost trends as influenced by the major design and operating variables.

Nevertheless, because the outcome of the present report is intended for use in broad studies of the overall transport system, the cost estimates must be as accurate as possible in absolute as well as relative terms. This does not mean, however, that our cost estimates are intended as being suitable for bidding purposes. They should be continually scrutinized and modified before further application.

All cost figures shown are based on 1971 conditions and dollar values.

1. New Construction

Table 1 summarizes the cost estimating relationships that we propose for structure, outfit, and machinery. The figures apply to non-self-unloading ships (bulkers) with single screw and fixed propeller blades. The costs of such miscellaneous items as engineering, planning, staging, temporary lights, cleaning, and trials are recognized in the cost coefficients shown in table 1. We use the
### C. INVESTMENTS

**TABLE I**

**COST ESTIMATING RELATIONSHIPS**

<table>
<thead>
<tr>
<th>Ship Component</th>
<th>Cost Component</th>
<th>Material ($)</th>
<th>Labor (man-hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>$236 \ W_S</td>
<td></td>
<td>$130,000 \left(\frac{W_S}{1000}\right)^{0.85}$</td>
</tr>
<tr>
<td>Outfit</td>
<td>$2400 \ W_O</td>
<td></td>
<td>$280 \ W_O</td>
</tr>
<tr>
<td>Machinery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam Turbine</td>
<td>Material, labor, overhead</td>
<td>$900,000 \left(\frac{SHP}{1000}\right)^{0.60}$</td>
<td>add 3% if 70% backing power is specified</td>
</tr>
<tr>
<td>Intermediate Diesel</td>
<td></td>
<td>$550,000 \left(\frac{BHP}{1000}\right)^{0.70}$</td>
<td></td>
</tr>
</tbody>
</table>
following additional assumptions in estimating the total cost:

Overhead: 75% of labor cost
Average hourly rate: $4.10
Profit: 5% mark-up on total cost to shipyard

The cost of the hull (structure and outfitting) can be taken as the sum of the two material costs plus $7.175 per total man-hour of labor. Adding the cost of machinery gives the total cost to the shipyard. The invested cost is found by increasing that figure by the assumed profit mark-up, or 5%.

2. Ice Strengthening, New Construction

In the case of new construction, there are no appended costs for structure or machinery because of ice strengthening. Those costs are already recognized in the weight and horsepower estimates -- which automatically affect the cost estimates. In the outfitting category, however, there will be modest increases for strengthened rudder and steering gear. We propose the following:

\[ C = a \frac{LB}{100} \]  \[15\]

where

\( C \) = added cost to the owner for winter outfitting
a = 0 for class II or IC

= $15 for class IB

= $30 for class IA

= $45 for class IA Super

3. **Extra Features**

The investment cost figures cited above should be increased for special features such as self-unloading gear, bow thrusters, or controllable pitch propellers. These extras are discussed next.

Self-unloading systems will add to the cost approximately as follows:

\[ C = a \left( \frac{CN}{1000} \right)^b \]  \[ [16] \]

where

\( C \) = Cost of conveyor system (including shipyard profit) in dollars

and

a and b have the values shown below:
II: DETAILED ANALYTICAL METHODS

<table>
<thead>
<tr>
<th>Capacity in 1000 tons per hour</th>
<th>Shuttle Conveyor</th>
<th>Boom Conveyor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1000 a</td>
<td>$1000 b</td>
</tr>
<tr>
<td>4</td>
<td>224 0.31</td>
<td>442 0.23</td>
</tr>
<tr>
<td>6</td>
<td>280 0.31</td>
<td>597 0.22</td>
</tr>
<tr>
<td>8</td>
<td>337 0.30</td>
<td>794 0.19</td>
</tr>
<tr>
<td>10</td>
<td>395 0.30</td>
<td>922 0.19</td>
</tr>
<tr>
<td>20</td>
<td>800 0.30</td>
<td></td>
</tr>
</tbody>
</table>

The foregoing figures exclude extra costs of hull structure, which are already recognized in the added weight (hence cost) of the structure.

The complete installed cost of a typical 800 BHP diesel driven bow (or stern) thruster is about $150,000. This would include shipyard profit.

Controllable pitch propellers imply a redesign of many features of the propulsion plant. Estimating the added cost is therefore difficult. In meeting ice class requirements, fitting a CP propeller may allow a reduction in required horsepower. That saving, however, is already factored into the design and cost estimates. What we need here is an estimate of the added cost for any given horsepower. We make the following tentative proposal:

\[ C = a \left( \frac{SHP}{1000} \right)^{0.60} \]  

[17]

where

- 20 -
C: INVESTMENTS

\[ C = \text{added cost for a CP propeller installation, including shipyard profit} \]

and

\[ a = \$20,000 \text{ for steam turbine plants} \]
\[ = \$13,500 \text{ for geared diesel plants} \]

We have not taken up two other complications: the cost savings from multi-ship contracts and the owner's added first costs for legal fees, design agent's fees, and owner's furnished equipment. For purposes of this study we shall specifically ignore both of those countervailing factors.

4. **Conversions**

There are several variations that can be tried in ice-reinforcing the structure of typical Great Lakes ships. The more successful approaches will, we believe, tend to cost about the same.

Figure 2, from reference 8, indicates approximate costs for structural conversions. The cost of modifying the outfitting for winter operations can be estimated by increasing by 25% the "a" values previously shown for equation 15.

Where horsepowers must be increased to meet ice rules, we assume the existing plant will be replaced. The scrap value should be close to the cost of removal, so we can infer that the total machinery cost would be about the same as for new construction.
Fig. 2: Cost of Structural Strengthening Con of Existing Ships
D. Operating Environment (Ice Conditions)

This section attempts to establish a convenient summary of the probable ice conditions that will be met in winter navigation. Ice survey statistics are still largely unavailable, few quantitative measurements having yet been made. This step in the overall procedure is one that will remain crude until extensive, methodical ice surveys are made over a period of years. As an interim step, intended only to illustrate the idea, we have asked Mr. Ernest Marshall to estimate the average ice conditions at various times of year on each of the major legs of the voyage between Two Harbors and South Chicago. His estimates are summarized in tables 2 to 6. The values are based on data derived from aerial photographs and ice thickness measurements, the latter taken at shore stations rather than in way of the ship channels. This is only a rough stab, but is the best that can be done at this time. Mr. Marshall's estimates apply to ice conditions during a winter of normal severity, which would occur in about 50% of the years during the life of a ship. Milder conditions and more severe conditions can be assumed to obtain with equal probability during the remaining 50% of the years. Means for assessing these variations are explained in section F (Annual Transport Capability).

We must assume that ice conditions will present impassable barriers at various points and at different times following break-up of the ice
cover in the spring. This condition will set physical upper limits on the length of the operating season that will vary with the overall weather conditions, the level of federal assistance, and the particular trade route. In general, however, the blockage time will seldom exceed the minimum two-week period required for annual overhaul and repair of ships, locks, and shoreside equipment.

Other environmental factors that must be considered in assessing schedules and risks include:

Pressure ridges
Winds
Long nights
Aids to navigation
Drifting ice (and risk of grounding any trapped ship)
Harbor ice and docking problems
Locks
Freezing spray
Density of traffic

These factors are not overlooked in the scheduling estimates presented in section F: Annual Transport Capability.
<table>
<thead>
<tr>
<th>Leg (see Frontispiece)</th>
<th>Total Distance (st. miles)</th>
<th>Class I (&lt;70% ice cover)</th>
<th>Class II (70%-90% ice cover)</th>
<th>Class III (&gt;90% ice cover)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distance (st. miles)</td>
<td>Thickness (inches)</td>
</tr>
<tr>
<td>1. W. end</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Superior</td>
<td>47</td>
<td>41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. W. basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Central basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Whitefish Bay</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Upper St. Mary's</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Lower St. Mary's</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Upper L. Huron</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Straits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Upper L. Mich.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Island area</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. N. basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Michigan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. S. basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Michigan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>811</strong></td>
<td><strong>684</strong></td>
<td><strong>16</strong></td>
<td></td>
</tr>
</tbody>
</table>

Notes: See table 6
### TABLE 3

**FEBRUARY 15 ICE CONDITIONS**

**BETWEEN TWO HARBORS AND SOUTH CHICAGO**

<table>
<thead>
<tr>
<th>Leg (see Frontispiece)</th>
<th>Total Distance (&lt;70% ice cover)</th>
<th>Class I</th>
<th>Class II (70%–90% ice cover)</th>
<th>Class III (&gt;90% ice cover)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(st. miles)</td>
<td></td>
<td>Distance (st. miles)</td>
<td>Thickness (inches)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. W. end</td>
<td>47</td>
<td>3</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>L. Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. W. basin</td>
<td>137</td>
<td>116</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>L. Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Central basin</td>
<td>150</td>
<td>150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Whitefish Bay</td>
<td>22</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Upper St. Mary's</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Lower St. Mary's</td>
<td>49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Upper L. Huron</td>
<td>33</td>
<td>25</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>8. Straits</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Island area</td>
<td>49</td>
<td>44</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>11. N. basin L. Michigan</td>
<td>90</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. S. basin L. Michigan</td>
<td>146</td>
<td>136</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>811</strong></td>
<td><strong>543</strong></td>
<td><strong>80</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** See Table 6
<table>
<thead>
<tr>
<th>Leg (see Frontispiece)</th>
<th>Total Distance (&lt;70% ice cover)</th>
<th>Class I Distance (st. miles)</th>
<th>Class I Thickness (inches)</th>
<th>Class I Type</th>
<th>Temp (F)</th>
<th>Notes</th>
<th>Class II (70%-90% ice cover)</th>
<th>Class III (&gt;90% ice cover)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. W. end L. Superior</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18 sheet 32</td>
<td>47</td>
<td>18</td>
</tr>
<tr>
<td>2. W. basin L. Superior</td>
<td>137</td>
<td>137</td>
<td>18</td>
<td>sheet</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Central basin L. Superior</td>
<td>150</td>
<td>106</td>
<td>44</td>
<td>15</td>
<td>sheet</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Whitefish Bay</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>5. Upper St. Mary's</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>6. Lower St. Mary's</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>7. Upper L. Huron</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>8. Straits</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>9. Upper L. Mich.</td>
<td>51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>51</td>
<td>15</td>
</tr>
<tr>
<td>10. Island area</td>
<td>49</td>
<td></td>
<td>25</td>
<td>12</td>
<td>sheet</td>
<td>30 12</td>
<td></td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>11. N. basin L. Michigan</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. S. basin L. Michigan</td>
<td>146</td>
<td>132</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>811</strong></td>
<td><strong>348</strong></td>
<td><strong>206</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>257</strong></td>
<td></td>
</tr>
</tbody>
</table>

Notes: See table 6
### TABLE 5
APRIL 1 ICE CONDITIONS
BETWEEN TWO HARBORS AND SOUTH CHICAGO

<table>
<thead>
<tr>
<th>Leg (see Frontispiece)</th>
<th>Total Distance (st. miles)</th>
<th>Class I (&lt;70% ice cover)</th>
<th>Class II (70%-90% ice cover)</th>
<th>Class III (&gt;90% ice cover)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. W. end</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Superior</td>
<td>47</td>
<td>39</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>2. W. basin</td>
<td>137</td>
<td>98</td>
<td>39</td>
<td>14</td>
</tr>
<tr>
<td>L. Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Central basin</td>
<td>150</td>
<td>150</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>L. Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Whitefish Bay</td>
<td>22</td>
<td>15</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>5. Upper St. Mary's</td>
<td>17</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Lower St. Mary's</td>
<td>49</td>
<td>5</td>
<td>44</td>
<td>12</td>
</tr>
<tr>
<td>7. Upper L. Huron</td>
<td>33</td>
<td>33</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>8. Straits</td>
<td>20</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Upper L. Mich.</td>
<td>51</td>
<td>10</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>10. Island area</td>
<td>49</td>
<td>49</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>11. N. basin</td>
<td>90</td>
<td>90</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>L. Michigan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. S. basin</td>
<td>146</td>
<td>140</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>L. Michigan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>811</td>
<td>640</td>
<td>62</td>
<td>109</td>
</tr>
</tbody>
</table>

Notes: See table 6
TABLE 6
NOTES FOR TABLES 2-5

1. Windrowed sheet ice plus 10 inches snow cover.

2. Snow cover 3 inches.

3. Snow cover 17 inches, snow ice 3 inches, lake ice 15 inches.

4. Refrozen brash and windrowed sheet ice; possible ridges.

5. Snow cover 7 inches, snow ice 6 inches, lake ice 11 inches.

6. Snow cover 10 inches, snow ice 8 inches, lake ice 9 inches.

7. Snow cover 3 inches.

8. Snow cover 6 inches, snow ice 6 inches, lake ice 12 inches.

9. Snow cover 6 inches, snow ice 6 inches, lake ice 12 inches.

10. Basic ice cover 17 inches with 7 inches of snow on 6 inches snow ice, and 11 inches lake ice. There will also be loose ice beneath. Pressure ridge may extend 20-30 feet downward. Windrows over about half the area.

11. No snow on ice.

12. Snow ice 5 inches, lake ice 7 inches.

13. 1 inch of snow.

14. Snow ice 6 inches, lake ice 9 inches.

15. Snow ice 5 inches, lake ice 10 inches. Windrows over about half the area.

16. Snow ice 5 inches, lake ice 7 inches.

17. Loose brash.

18. Possibly some delays due to brash close to shore and to packing.
II: DETAILED ANALYTICAL METHODS

E. Speed and Power in Open Water and In Ice

The solution of our overall problem requires reasonably facile computational procedures for estimating the speed and power of Great Lakes bulk carriers in open-water and in ice. The procedures must analyze ships that are in various conditions of loading and operating in various conditions of ice.

1. Open Water

R. A. Stearn, Inc. is supporting a long-term research project at The University of Michigan aimed at providing a rigorous and accurate procedure for estimating speed and power of Great Lakes bulk carriers in open water. That study is now nearly complete and should be published within a year. In the meantime, Krappinger's relatively simple approach (7) will be found generally suitable for the task at hand.

2. Speed and Power Constraints

In some instances speeds are limited in restricted channels. In other instances a ship with a high ice classification may have a machinery installation whose upper range of power would be wasted in open-water conditions. In the latter case, we need to estimate reasonable levels of power and corresponding speed in open water. As a temporary expedient, we can set an arbitrary upper limit on power utilization at that level corresponding to an operating speed of $0.55(L)^{0.5}$ in the loaded
condition, and \(0.60(L)^{0.5}\) in ballast. This detail merits future study.

3. **Speed in Ice: Introduction**

Estimating the powering requirements for Great Lakes bulk carriers operating in ice is a difficult task owing to the almost complete lack of full scale observation, model measurements, and theoretical foundations.

A semi-empirical method of power estimation has been developed for the present study. Observations in the Baltic fleets and the voyage records taken from a few Great Lakes ships during the 1970-71 extended season are considered. However, since these data are crude and meager, and limited to just a few ship types and ice conditions, we must rely for now on theory for representing the parametric influences of hull shape, power plant and propulsion system, as well as ice condition.

Such a theory can be deduced by suitable adaptation of methods originally developed for different ships and conditions. When full-scale test results for Great Lakes ships become available, they can be used to check and improve the proposed estimating method.

Different powering estimates are derived for ships continuously breaking ice and for operation in broken ice in the track of an icebreaker or another ship, or in open pack ice.
II: DETAILED ANALYTICAL METHODS

4. Breaking Ice

In deriving a tentative method for estimating speed and power in solid ice, we have drawn on early theoretical work of Shimanshkij (10), Kashteljan, et al (11), and later derivations of U. S. Coast Guard researchers such as Melberg, Lewis, and Edwards (12, 13). Although in the physical reasoning we are largely in agreement with Lewis and Edwards' assumptions, we cannot use their equations for our powering estimates because suitable values for several of their coefficients are not known for bulk carriers. Moreover, the influence of hull form is not shown in their expressions. We have therefore developed a compromise approach, relying on Lewis and Edwards for systematic tendencies and on Kasteljan for certain relative magnitudes. The details and theoretical background of this development are found in the appendix. In outline, we propose the following:

a) We start with Kashteljan's equation for the total resistance of a ship moving through solid sheet ice (all in metric tons):

\[ R_{\text{ice}} = R_1 + R_2 + R_3 + R_4 \]  \[ \text{[18]} \]

where:

\( R_1 \) = icebreaking resistance, corresponding to work done in breaking the ice.

\( R_2 \) = resistance due to submergence of
broken ice, turning the broken ice, and other effects proportional to the weight of the broken ice.

\[ R_3 = \text{resistance due to cleaning broken ice out of the channel laterally by accelerative forces.} \]

\[ R_4 = \text{water resistance, friction and wave-making, computed as if ice were not present.} \]

Further, according to Kashteljan

\[ R_1 = k_1 B \rho_s \eta h \]  \hspace{1cm} [19]  
\[ R_2 = k_2 B \rho_s \eta^2 h^2 \]  \hspace{1cm} [20]  

and

\[ R_3 = k_3 B \frac{k_4 \eta V}{e_2} \]  \hspace{1cm} [21]  

where the \( k \) coefficients have the values shown below (derived from model and full-scale tests on the Russian icebreaker *Ermak*):

\[ k_1 = 0.004 \]
\[ k_2 = 3.6 \]
\[ k_3 = 0.25 \]
\[ k_4 = 1.65 \]

and where
II: DETAILED ANALYTICAL METHODS

\[ B = \text{ship's beam in meters} \]

\[ m_0 = \text{Kashteljan's vertical ice force coefficient (a function of bow shape). See comments below.} \]

\[ s = \text{ice strength in metric tons per square meter} \]

\[ h = \text{ice thickness in meters} \]

\[ g_i = \text{specific weight of ice in metric tons per cubic meter} \]

\[ V = \text{ship's speed in meters per second} \]

\[ e_2 = \text{Shimanshkij's lateral ice pressure coefficient. See table 7.} \]

Kashteljan's vertical ice force coefficient, \( m_0 \), is intended as a measure of hull form efficiency in generating vertical forces. His definition of \( m_0 \) is not altogether suited to our particular needs. (See more on this in the appendix.) Nevertheless, since all his \( k \) values were derived from the Ermak tests, with \( m_0 \) appearing in the first two terms (i.e. \( R_1 \) and \( R_2 \)), we must stick to all of Kashteljan's definitions in the context of his equation.

b) Turning next to the work of Lewis and Edwards, we find these formulations for the same three components of total ice resistance:
### TABLE 7
**FORCE COEFFICIENTS**

<table>
<thead>
<tr>
<th>Ship</th>
<th>$e_1$</th>
<th>$e_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>24,000 HP icebreaker</td>
<td>1.9</td>
<td>3.13</td>
</tr>
<tr>
<td>12,000 HP icebreaker</td>
<td>2.17</td>
<td>3.40</td>
</tr>
<tr>
<td>J. Stalin</td>
<td>2.03</td>
<td>3.25</td>
</tr>
<tr>
<td>Ermak</td>
<td>2.41</td>
<td>3.52</td>
</tr>
<tr>
<td>Timber freighter</td>
<td>0.33</td>
<td>1.83</td>
</tr>
<tr>
<td>Timber freighter</td>
<td>0.54</td>
<td>2.28</td>
</tr>
<tr>
<td>Timber freighter</td>
<td>0.80</td>
<td>2.71</td>
</tr>
<tr>
<td>Far East cargo ship</td>
<td>0.41</td>
<td>2.34</td>
</tr>
<tr>
<td>Typical Great Lakes ore carrier</td>
<td>0.21</td>
<td>1.55</td>
</tr>
</tbody>
</table>

**Note:** Last line is derived from University of Michigan study; all others are from Shimanskij (10).
II: DETAILED ANALYTICAL METHODS

\[ R_1 = C_0 \sin h^2 \]  \hspace{1cm} [22]

\[ R_2 = C_1 g_1 Bh^2 \]  \hspace{1cm} [23]

\[ R_3 = C_2 r_1 Bhv^2 \]  \hspace{1cm} [24]

where

\( C_0, C_1, \) and \( C_2 \) are coefficients of as yet undefined quantitative values for Great Lakes ore carrier hull forms

\( r_1 = \) mass density of ice

and all other terms are as previously defined.

Our problem now is to combine the relative magnitudes found by Kashteljan with the systematic tendencies expressed by Lewis and Edwards.

c) Experience shows that ore carriers of the type operated last January could not break sheet ice more than about 2 ft thick. Thus, when \( h = 2 \) ft (0.61 m), speed becomes zero hence the components \( R_3 \) and \( R_4 \) also become zero. We can of course calculate the thrust delivered by the propeller of our typical ore carrier at zero speed, so we know the numerical value of \( R_1 + R_2 \). As already shown, this is:

\[ R_1 + R_2 = k_1 B m_0 \sin h + k_2 B m_0 g_1 h^2 \]

\[ = B m_0 (k_1 \sin h + k_2 g_1 h^2) \]  \hspace{1cm} [25]

\[ - 36 - \]
d) Kashteljan's vertical ice force coefficient, \(m_0\), does not seem altogether suited to our particular purpose. Therefore, we propose a modified version derived from Shimanshikij's vertical ice force coefficient \(e_1\) -- the numerical value of which we have calculated for our typical ore carrier. We call our new vertical ice force coefficient \(m\):

\[
m = \frac{A}{e_1} \tag{26}
\]

where

\(A = \) empirically derived number that varies with ice conditions.

e) If we substitute our \(\frac{A}{e_1}\) for \(m_0\) in equation 25, we have

\[
R_1 + R_2 = B \frac{A}{e_1} (k_1 s h + k_2 g_1 h^2) \tag{27}
\]

And so, at zero speed we know all numerical values except \(A\), which can thus be derived and then used to find the value of ship speed in sheet ice of less than the limiting thickness.

f) In summary, we propose these expressions for the components of total resistance of a ship moving through solid sheet ice:

\[
R_1 = k_1 s B h m = 0.004 s B h m \tag{28}
\]

\[
R_2 = k_2 g_1 B h^2 m = 3.6 g_1 B h^2 m \tag{29}
\]
II: DETAILED ANALYTICAL METHODS

\[ R_3 = k_3 B^{k_4} \frac{hv}{e_2} = 0.25B^{1.65} \frac{hv}{1.55} \quad [30] \]

\[ R_4 = \text{open water resistance} \]

g) Discussion:

The expression for the zero speed ice resistance derived in steps c through e is somewhat provisional. It presumes that bulk carriers will have the same percentage ratio of \( R_4 \) and \( R_2 \) as did the icebreaker Ermak from which Kashteljan's coefficients were derived.

Further, it implies to a degree that the mechanism of breaking ice by the bulk carrier is still essentially vertical bending as in the icebreaker. In reality this is doubtful because with the blunt bulk carrier bow shear, cleavage and buckling failure of the ice sheet may play a greater part, particularly when the ship is in the loaded condition. Further efforts should be undertaken to determine the actual failure mechanisms for ice being broken by blunt bows.

Moreover, the use of our final expression above does not necessarily imply the same type of ice sheet failure Kashteljan envisioned, since the coefficient \( m \) was introduced to reach agreement with actual bulk carrier ice cutting performance. All we assume by using the above equation is that the dependence on \( B, h, \) and \( s \) has the same functional character as deduced by
earlier investigators.

Part of the ice resistance depends on ship speed because in cleaning the broken ice out of the ship's channel the ice floes have to be moved faster as ship speed increases and the kinetic energy imparted to them in their lateral and rotational motion is also raised. To represent this resistance component, we have followed Kashteljan:

\[
R_3 = 0.25B^{1.65} \frac{hV}{e_2}
\]  \[30\]

Although we share the physical reservations of Lewis and Edwards, we have no other quantitative relation which contains the hull shape influence \((e_2)\). At low speeds this term is obviously dominated by the other components of ice resistance, and at high speeds the entire ice resistance becomes small relative to the water resistance, which relaxes the accuracy requirements on this term.

In summary, we have deduced a parametric equation for the zero-speed ice resistance based on the physical assumptions by Kashteljan and Lewis and Edward. This equation is adapted to direct observation and bulk carrier operating practice by means of input information on only three elements:

* The limiting ice thickness the ship can break.
II: DETAILED ANALYTICAL METHODS

*The ratio of ice-cutting to ice submergence resistance.

*The dependence of ice strength on temperature and seasonal condition.

5. **Resistance in Broken Ice**

The complex physical process of a ship moving through broken ice in the track of an icebreaker or another vessel or through open pack ice has been studied by numerous authors (11, 14-19).

Bronnikov's (18) approach to estimating the resistance of cargo ships going through pack ice appears to be best suited for the present purpose. Bronnikov proposes an equation expressing the pure ice resistance in terms of the parametric influences of ice condition and principal ship characteristics:

\[
R_{ip} = (R_{ip})_0 \left( \frac{D}{D_0} \right)^{S h} \left( \frac{m}{S_0} \right)^{n t_o} \left( \frac{L/B}{L/B_0} \right)^q \\
\left( \frac{C_{B0}}{C_B} \right)^r \left( \frac{(B_1/B)_o}{B_1/B} \right)^k
\]

[31]

where the subscript zero denotes a standard arctic cargo ship that was tested by Bronnikov, and the quantities without subscript are for the actual ship in question.

All quantities are in metric units and are
defined as follows:

\[ R_{ip} = \text{pure ice resistance, metric tons} \]
\[ D = \text{displacement, metric tons} \]
\[ h = \text{ice thickness, meters} \]
\[ S = \text{ice state, surface coverage in percent} \]
\[ T = \text{draft of vessel, meters} \]
\[ L, B = \text{length, beam of vessel} \]
\[ C_B = \text{block coefficient} \]
\[ B_1 = \text{width of channel or lead in pack ice} \]

The pure ice resistance of the standard reference vessel, \((R_{ip})_o\), is given in Table 5 of Bronnikov's article (18) for Froude numbers, \(F_n\), from 0.075 to 0.275, and may be approximated by

\[ (R_{ip})_o = 977 F_n^{1.42} \]

Since \(F_n = \frac{V}{\sqrt{gL}}\)

we have

\[ F_n = 0.298 \frac{V_k}{\sqrt{L}} \] \[\text{[32]}\]

The following data belong to this standard case:
II: DETAILED ANALYTICAL METHODS

\[ D_0 = 10920 \text{ tons} \]
\[ h_0 = 0.8 \text{ meter} \]
\[ S_0 = \text{state } 8 = 0.8 \]
\[ T_0 = 7.3 \text{ meter} \]
\[ (L/B)_0 = 6.6 \]
\[ C_{B0} = 0.65 \]
\[ (B_1/B)_0 = 15 \]

Bronnikov found the values of the exponents for his ice resistance equation from model tests as,

\[ s = 0.753 F_n^{0.278} \quad [33] \]
\[ m = 0.308 F_n^{-0.61} \quad [34] \]
\[ n = 0.79 F_n^{-0.49} \quad [35] \]
\[ p = 1.759 F_n^{0.75} + 0.35 \quad [36] \]
\[ q = 2.5 F_n^{0.455} - 0.60 \quad [37] \]
\[ r = 38.36 F_n^{2.356} + 1.25 \quad [38] \]
\[ k = 0.039 F_n^{-1.24} \quad [39] \]

The values of \( D, h, t, L/B \) will be derived from the actual ice conditions and bulk carrier characteristics. The surface coverage and width
of channel ratio in the track of an icebreaker
or other bulk carrier may be reasonably
estimated as

\[ S = 0.8 \]

\[ B_1/B = 1.5 \]

This summarizes the relationships for the
estimation of broken ice resistance, which
should next be checked for consistency with
other available reference data.

6. **Practical Considerations**

To this point we have proposed rational methods
for estimating the speed of Great Lakes bulk
carriers in sheet ice and in channels cut
through the ice. Our methods are derived from
work done principally in connection with Baltic
operations. Baltic ice is relatively stable,
being generally anchored by the many islands
of that region. On the Great Lakes, however,
there are few islands and the ice is therefore
less well behaved. It is likely to drift,
giving alternately the advantages of open water
and the disadvantages of jams in constricted
areas. Under those conditions available
theoretically derived methods are anything but
satisfactory. Pending later development of some
more rational approach to this problem, we
propose to divide the sailing distance, D,
through partial ice-covered waters into two
components, thus:
II: DETAILED ANALYTICAL METHODS

\[ D = D_i + D_w \]

in which

\[ D_i = \text{distance through equivalent sheet ice} \]

and

\[ D_w = \text{distance in open water} \]

We reason that the proportional distance that the ship must move through ice will be less than the fraction of ice coverage. Often the wind will carry the ice altogether clear of the ship's course, or the course can be modified to take advantage of open passages. Further, smaller blocks of ice, while adding to the fraction of ice cover, are easily broken or simply pushed aside and so do not contribute their theoretical share to the total resistance. In recognition of these considerations, we propose to estimate the equivalent distance through sheet ice as follows:

\[ D_i = DS^3 \]

where

\[ S = \text{fractional ice coverage in the region under consideration} \]

Furthermore, in recognition of course modifications, as well as time lost in building up speed in open water, we propose an arbitrary increase of 10% in the open water distance.
F. Annual Transport Capability

1. Key Factors

In estimating the annual transport capability of any proposed Great Lakes ship, we must recognize variations in three important factors. The first is the time required per round trip -- which will be essentially uniform on any given route until ice begins to form, and will then progressively increase. Second is the changing cargo capacity per trip as a function of the freeboard requirements. The third factor, of course, is the length of the operating season. Variations due to fluctuating Lake levels will be specifically ignored because they will have no real impact on the matter under study. We assume, too, that the designer has recognized channel depths in selecting his design drafts. (That is, the operator will always be free to load his ship to the load line appropriate to the season.)

2. Freeboard Seasons

The statutory freeboard seasons are as follows:

- April 16-30: Intermediate (I)
- May 1-September 15: Midsummer (MS)
- September 16-30: Summer (S)
- October 1-31: Intermediate (I)
- November 1-April 15: Winter (W) or (I)
Recent research has led to a tentative relaxation of the freeboard rules, permitting application of the intermediate loadline during the winter months. Nevertheless, to be conservative, we shall assume the use of the winter draft from November 1 to April 15. The analytical procedure will be kept flexible, however, permitting either choice.

3. Combined Influence of Schedule and Trip Capacity

Figure 3 shows how the annual transport capacity is affected by the three previously mentioned factors.

As a matter of convenience, we have arbitrarily set the start of the navigating season at April 16 throughout this study. We assume, too, that extensions of the operating season will apply to delayed lay-up rather than early starts. This is logical because the worst ice conditions usually obtain in early Spring. There is nothing in our analytical procedure, however, that would prevent the use of other assumptions.

We have stopped our analysis one-half month shy of year-round navigation. Ships, locks and shore cargo gear all need periodic overhauls. We assume the majority of that work would be done just before the start of the new operating season, that is, at the end of March or early in April.
Fig. 3: Influence of Cargo Capacity and Round Trip Time on Annual Transport Capacity
II: DETAILED ANALYTICAL METHODS

4. Proforma Ice-Free Round-Trip Time

The time required for a normal (ice-free) round trip can best be found by estimating the time needed for each of several discrete segments of the voyage. These are:

a. Time at full speed, loaded
b. Time at full speed, ballast
c. Time in speed-restricted waters
d. Loading time
e. Unloading time
f. Docking and undocking time
g. Time in lock passage
h. Waiting (queuing) time at locks and docks
i. Weather delays

The following assumptions can be made:

a. The open-water ballast speed will be 6% greater than the loaded speed at full power

b. The ship will average 10 mph in all speed-restricted waters

c. The loading and unloading rates will vary considerably between different ships and different ports, and will therefore be treated as input variables. Rates used should be adjusted in recognition of time lost during shifting, adjusting gear, etc. The average rate will be only about 85% of the maximum continuous rate.
d. Docking and undocking time in hours per round trip will equal $0.5 \left( \frac{L}{100} \right)^{0.5}$

e. Locking through the Soo will require 3 hours per round trip.

f. Queuing delays will average 5 hours per round trip if passage through the Soo is required, otherwise 4 hours.

Alternative assumptions can of course be made to suit specific circumstances.

While estimating the voyage time requirements, we can also find the fuel consumption per round trip and the required weight of fuel on board at the loading port. This information will be needed at a later step in the analysis.

5. Proforma Winter Schedule

Looking next at winter schedules, we must recognize that the time per round trip will increase steadily once the ice becomes a factor (usually about December 15). In real life the owners would treat each successive voyage individually and in sequence. We can, however, arrive at essentially the same outcome with less analytical work if we estimate the time requirements at each of several key dates (January 15, February 15, March 15, and April 1) and then interpolate, if required, for intermediate dates. In doing this, we take the ice conditions predicted for any given date and assume them to remain constant during that one round trip.
II: DETAILED ANALYTICAL METHODS

Finding the time required for a round trip through ice follows the same procedure as that just outlined for normal operations. There will of course be time losses at locks and docks as well as slower operating speeds in ice. These time losses can be categorized as follows:

a. Slower speed at full power, loaded
b. Slower speed at full power, ballast
c. Possible slower speed in restricted waters
d. Slower loading rates
e. Slower unloading rates
f. More time docking and undocking
g. More time in lock passage
h. More frequent weather delays
i. Time lost stopped in ice awaiting ice-breaker assistance
j. Convoy delays, one-way traffic delays, etc.

Table 8 summarizes tentative delay times arising from the several causes outlined above. These values are little more than intuitive predictions. They merit study and modification as experience is gained in winter navigation. In them, we imply a substantial level of federal assistance:
### TABLE 8

**ADDED DELAY TIMES IN NORMAL WINTER WEATHER**

(Times shown are in hours per round trip)

<table>
<thead>
<tr>
<th>Cause of Delay</th>
<th>Date</th>
<th>Dec 15</th>
<th>Jan 15</th>
<th>Feb 15</th>
<th>Mar 15</th>
<th>April 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ice Class</td>
<td>2</td>
<td>1C</td>
<td>1B</td>
<td>1A</td>
<td>1A S</td>
</tr>
<tr>
<td>Loading Time*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unloading Time*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Locks</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Docking &amp; Undocking</td>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Weather</td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Waiting for Ice-breaker, Slow Convoys, etc.</td>
<td></td>
<td>0</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>20 16 12 8 4 30 23 18 13 8 40 30 24 18 12</td>
</tr>
<tr>
<td>Total Hours</td>
<td></td>
<td>4</td>
<td>14</td>
<td>12</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>

For mild winters: reduce total delay time by 33%
For severe winters: increase total delay time by 50%

*Cargo handling delays in cold weather are a function of the commodity. We are considering pelletized ore here, which would be unaffected.
II: DETAILED ANALYTICAL METHODS

a. Aids to navigation allowing operation at night

b. Powerful new icebreakers with beams of 105-110 ft operating in Whitefish Bay, St. Mary's River, Straits of Mackinac, and Detroit

c. Ice-deflector dikes and artificial islands to anchor ice

d. Continuing support of ice-related research and development

6. Trip Capacity

Turning next to the cargo capacity per trip, we start with the summer loadline condition and modify that value to suit other freeboard and fuel weight requirements.

The cargo capacity at the summer loadline, $C_s$, is found in the usual way:

$$C_s = DW - Q \quad [40]$$

where

$DW = \text{deadweight at summer loadline}$

(see section B)

and

$Q = \text{miscellaneous deadweight items, largely fuel}$

Note: All weights are in long tons.
For purposes of this analysis, the weight of the miscellaneous deadweight items is taken as the weight of fuel required for a one-way trip, plus a margin of 50% before December 15 and 100% after that date. All other variable weights (i.e., fresh water, stores, supplies, and fuel for miscellaneous services and self-unloading) will add another 150 long tons. (In the case of diesel machinery, the weight of lubricating oil is taken as part of the light ship.)

The weight of bunkers required for a one-way trip and the fuel consumed per round trip are both based on the SHP-hr figures derived from the scheduling analysis outlined in the preceding paragraphs. For new steam plants with 1450G - 950F reheat cycles, the daily fuel consumption, in long tons, at full power will be close to $4 \left( \frac{\text{SHP}}{1000} \right) + 8$. The corresponding figure for intermediate speed geared diesels burning blended oil will be $3.8 \left( \frac{\text{BHP}}{1000} \right) + 4$. When operating at reduced powers (as when in speed-restricted areas), the specific fuel consumption will increase according to these ratios:

<table>
<thead>
<tr>
<th>Percent of Maximum Power</th>
<th>Relative Fuel Consumption per SHP - hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steam</td>
</tr>
<tr>
<td>100</td>
<td>1.000</td>
</tr>
<tr>
<td>90</td>
<td>1.007</td>
</tr>
<tr>
<td>80</td>
<td>1.025</td>
</tr>
<tr>
<td>70</td>
<td>1.051</td>
</tr>
<tr>
<td>60</td>
<td>1.089</td>
</tr>
<tr>
<td>50</td>
<td>1.143</td>
</tr>
</tbody>
</table>
II. DETAILED ANALYTICAL METHODS

All of the above figures apply to the main propulsion unit alone. Incremental consumption for auxiliaries, hotel services, etc. are discussed in section G, Operating Costs.

7. Seasonal Variations

As discussed in section C, we must recognize that winter weather conditions will be unusually mild or unusually severe during some years. We have assumed that such extremes will each occur during about 25% of the years over the life of the ship. We shall further assume, pending development of data, that the ice cover and ice thickness during mild seasons will be only two-thirds of the figures applicable to normal seasons. Similarly, during severe seasons, the ice cover and thickness will be 50% greater than normal. Of course the ice cover percentage in any given area will never exceed 100%.

8. Recapitulation

In summary, the estimate of annual transport capability requires:

a. A proforma voyage analysis representing a typical voyage during the ice-free season. This will determine time requirements, bunker weight, and fuel consumption.

b. Individual proforma voyage analyses appropriate to each of several key dates during the winter season.
c. Calculation of cargo capacities per trip as a function of changing freeboard seasons and bunker requirements.

d. Summary calculations leading to the annual transport capability attainable during various lengths of operating season.
II: DETAILED ANALYTICAL METHODS

G. Operating Costs

Operating cost estimates are based on 1971 conditions and dollar values. We have specifically ignored inflation. If all prices rise together, a recognition of inflation will have no appreciable effect on design decisions (20). If some elements of cost are expected to rise faster than others, the relative gain of that particular element may deserve recognition. For this particular investigation, however, we feel there is little to gain from such complexities.

1. Fuel

Current average cost levels on the Lakes are about $30 per long ton for No. 6 fuel oil (bunker C) suitable for steam propulsion and $33.50 per long ton for No. 4 oil (blended) suitable for medium-speed diesels.

Section F outlines a procedure for estimating propulsion plant fuel requirements per voyage and per year. These should be increased by about 2% for steam plants and 1% for diesels for fuel burned during idle status. Further additions for the hotel and miscellaneous services can be estimated as follows:

<table>
<thead>
<tr>
<th>Service</th>
<th>Pounds Fuel per Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>85</td>
</tr>
<tr>
<td>Heating or cooling</td>
<td>85</td>
</tr>
<tr>
<td>Auxiliary machinery</td>
<td>80</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>250</strong></td>
</tr>
</tbody>
</table>
With self-unloaders, add 0.12 pound of fuel per ton of cargo handled during the year.

2. **Wages and Benefits**

During the normal 8-month operating season, the daily cost for crew wages including benefits, can be taken as $380 + $46 per crew member. For 8 months, the total becomes:

$$C_W = 92,500 + 11,200 K$$  \[41\]

where

$$K = \text{number in crew}$$

As ships are operated into the winter season, daily crew costs may well tend to increase. This could result from bonus wages, from crew rotation plans, or from combinations thereof. For purposes of this study, we tentatively assume a 15% increase in daily crew costs after December 15. (This is not to be interpreted as a recommended wage policy, but only as a guess about the future.) The costs would then be:

$$\text{per day} = 440 + 53K$$  \[42\]

$$\text{per month} = 13,400 + 1630K$$  \[43\]

3. **Subsistence**

Average subsistence costs can be taken as $2.70 per man-day, or $82.50 per man-month.
II. DETAILED ANALYTICAL METHODS

4. P & I Insurance

Protection and indemnity insurance rates will be influenced by these factors: crew size, ship size, and length of season. During the regular season, we can estimate the monthly P & I cost as:

\[ P \& I \text{ per month} = 11K + 8.4 \frac{CN}{1000} \]  \[ \text{[44]} \]

where

\[ K = \text{number in crew} \]

\[ CN = \text{cubic number} \]

During the winter months, we shall tentatively assign a 25% increase in the cost of P & I insurance.

5. H & M Insurance

Hull and machinery insurance is a critical factor in evaluating the economics of winter operation. To begin with, we can estimate the normal season costs as follows:

\[ H \& M \text{ per month} = 1000 + \frac{P}{1000} \]  \[ \text{[45]} \]

where

\[ P = \text{initial investment in the case of a new design or the resale value in the case of an existing ship} \]
G. OPERATING COSTS

In general studies such as this, resale values will be unknown. That is not serious, however, because our measure of merit will be based on differences in cost. (See section II-I, Synthesis.) This means that we can apply an arbitrary value to an unmodified ship, say $5,000,000, and then add to that figure the estimated costs of ice-strengthening. This procedure is based on the supposition that any dollars spent in reinforcing the ship will directly affect its resale value.

Based on experience gained to date in winter operations on the Lakes, plus knowledge of insurance costs for Baltic winter operations, we propose using the foregoing relationship, equation 44, for operations between April 16 and January 16. After January 16 we propose

\[
\text{Annual cost of H & M} = M(1000 + \frac{P}{1000})^{\frac{M-9}{M}} \quad (a)
\]

where

\[M = \text{months of operation per year}\]

and

\[a = 1.234 \text{ for ice class 2} \]
\[1.184 \text{ for ice class IC} \]
\[1.129 \text{ for ice class IB} \]
\[1.068 \text{ for ice class IA} \]
\[1.039 \text{ for ice class IA super} \]
II: DETAILED ANALYTICAL METHODS

Let us illustrate with an example. Assume a class IB ship with a first cost of $12 million operating for 11 months. If there were no winter weather problems, the annual cost of H & M insurance would be:

\[ 11(\$1000 + \$12,000) = \$143,000 \]

Recognizing added winter risks, however, the annual cost becomes:

\[ 11(\$1000 + 12000)1.129^{11-9} \]
\[ = (\$143,000)1.129^2 \]
\[ = (\$143,000)1.276 = \$182,000 \]

6. Maintenance & Repair

The total cost of maintenance and repair during the normal season can be taken as:

\[ M \& R = 5000 \left( \frac{CN}{1000} \right)^{2/3} + f_1 \left( \frac{SHP}{1000} \right)^{2/3} + Z \quad [47] \]

where

CN = cubic number

\( f_1 = \$6600 \) for diesel plants
\[ = \$5000 \] for steam plants

and

\( Z = 0 \) for bulkers
\[ \$50,000 \] for self-unloaders
Experience may well prove that ice-strengthened hulls will have considerably lowered costs for maintenance and repair incurred during the normal season. For now, however, we shall ignore that potential benefit.

Until further experience is gained in winter operations, we propose that total annual M & R costs be handled according to the following:

$$M \& R = \frac{M}{8} \left\{ (a)^{M-9} \left[ \frac{5000 \left( \frac{CN}{1000} \right)^{2/3}}{f_1 \left( \frac{SHP}{1000} \right)^{2/3}} \right] + Z \right\}$$  \[48\]

where a has the same values shown under H & M insurance (equation 46)

The relative severity of the winter season will have its influence on M & R costs. The figures cited above are intended to represent average values.

7. **Towing**

During the normal season, towing costs per round trip can be estimated as follows:

$$\text{Cost per round trip} = a \frac{LB}{1000}$$  \[49\]

where

- $a = 13.5$ for ships without bow thrusters
- $= 4$ for ships with bow thrusters
During the winter months, more tug service will be required. We estimate the increases would average 50% of the figures shown above, that is:

\[ a = \$20.25 \text{ for ships without bow thrusters} = \$6 \text{ for ships with bow thrusters} \]

8. **Stores and Supplies**

The monthly cost of stores and supplies is a function of two principal factors: ship size and crew size. There will be little if any increase in monthly cost for winter operation. We propose the following relationship as being valid for any length of operating season:

\[
\text{Monthly cost of stores and supplies} = 50\left(\frac{CN}{1000}\right) + 37(K-10) \tag{50}
\]

where

\[ K = \text{number of men in crew} \]

These figures include cost of lubricating oil in the case of steam driven ships. For diesel installations, the cost of lube oil should be added. The quantity used can be taken as 0.5% of the fuel burned, by weight. The average cost is about $0.12 per pound.

9. **Winter Lay-up**

There are three main factors to consider in
estimating the cost of winter lay-up: the lay-up cost itself, the cost of wharfage and winter watch force, and the cost of fitting out in the spring. Since the total cost is relatively small, we shall simply set it at $75,000 regardless of ship size.

As winter operations approach the year-round maximum, the lay-up operation will involve mooring a live ship rather than a dead one. Wharfage costs will be less, but there will be a skeleton crew on board. We suggest the following scale of costs:

<table>
<thead>
<tr>
<th>Months of Operation</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 10</td>
<td>$75,000</td>
</tr>
<tr>
<td>11</td>
<td>$25,000</td>
</tr>
<tr>
<td>11.5</td>
<td>$10,000</td>
</tr>
</tbody>
</table>

10. Overhead & Miscellaneous

The overhead and miscellaneous category is one that is difficult to analyze. Some costs should vary with ship size, and some with length of operating season. Most, however, will remain fixed regardless of those factors. We propose the following:

Overhead cost per year = $50,000 + $2000M

+ $1250(\frac{CN}{1000}) \quad [51]

where

M = operating months per year
II: DETAILED ANALYTICAL METHODS

11. **Summary**

The ten cost categories above constitute the entire annual operating cost of the ship. (Annual costs of capital recovery are included elsewhere.) Total figures should be found for normal, mild, and severe winters. Total costs arrived at should not be interpreted as predictions of absolute costs for any given ship or owner, but only as indicators of industry-wide trends. They are intended mainly to express realistically the dependence of costs on operating schemes and design variables.
H. Measures of Merit

In selecting a measure of merit we must consider the circumstances involved as well as what use we intend to make of the number once we find it. In a typical season, as winter approaches, a shipowner will have to decide how long to keep his ship operating. If there is plenty of cargo to carry, he need only ask himself if the income from each added voyage exceeds the incremental costs of providing that added service.* As long as the answer is yes, he should keep his ship going and thereby increase his company's profits.

In this study we are faced with a more difficult circumstance than that sketched above. We are dealing with imaginary ships or imaginary modifications to existing ships. Our aim is to examine the economics of alternative investments (i.e., ships varying in degrees of ice strengthening) and to find for each the relative profitability that would result from different lengths of operating season. The big difference here is that the investment is no longer a fixed amount and capital costs must be factored into our measure of merit. Moreover, we cannot confine our analysis to the added costs and added incomes of each winter voyage. The different degrees of ice strengthening will produce changes in speed and cargo capacity that will affect cash

*If the shipowner is carrying cargo for a parent corporation, income can be taken as equal to the cost that would have been charged by an independent operator providing the same service.
II: DETAILED ANALYTICAL METHODS

flows throughout the year. Each alternative must be assessed on its total annual merits, not on any shortcut method of cost differences incurred during an extended season.

Without engaging in a discussion of their relative virtues, we propose three different measures of merit: (a) required freight rate, (b) net present value, and (c) yield. These are explained below.

1. **Required Freight Rate**

The required freight rate, RFR, is the unit cost an owner must charge his customer if the owner is to earn a reasonable interest rate of return (i.e., yield) on his investment. The alternative that promises the lowest RFR is presumably the one that is ideal for the trade.

The RFR criterion may seem out of place in a steel corporation's fleet. It is logical, nevertheless, because each subsidiary division of a corporation should justify its investments on a basis of contributing its share to the corporation's overall profits.

Where the annual transport capability is essentially constant year after year, the required freight rate takes the following form:

\[ RFR = \frac{(CR)P + Y}{C} \]  [52]

where
CR = capital recovery factor

P = initial investment

Y = annual operating costs

C = annual transport capacity

The capital recovery factor, CR, merits discussion. It is the factor by which the initial investment is multiplied in order to find the annual cost of capital recovery. The latter comprises the owner's stipulated yield (return of investment plus profit) and the corporate income tax. The numerical value is a function of those two factors and many others -- among which the new tax deferral privilege looms large. See appendix I. For our purposes, a capital recovery factor of 11% appears to be a generally suitable figure.

2. Net Present Value

The net present value, NPV, of an investment is found by discounting all future annual cash flows, both positive and negative, to "time zero," which is usually the time when cash begins to flow as a result of the decision. The discount factors are based on the timing of the cash flows and the owner's stipulated minimum acceptable interest rate. Because of the complexities of the tax laws, the cash flow pattern is also complex (even if we assume uniform annual returns before tax). These difficulties can be handled by methods developed
II: DETAILED ANALYTICAL METHODS

in appendix I. They require many assumptions as to bank loan arrangements, depreciation plans, etc. Because of these considerations, we recommend the use of a simplified NPV procedure. The final numerical outcome, while slightly inaccurate, will nevertheless give reliable indication of the relative merits of alternative proposals.

The approach we recommend makes two major simplifying assumptions: (a) the investment is made in a single amount at "time zero," (b) an interest rate of 10% applied to the uniform before-tax returns will be equivalent to a rate of 9% applied to the non-uniform after-tax returns. (Appendix I shows why this difference is so small.)

Given the above assumptions, the expression for net present value becomes

\[ NPV = (SPW-10\%-N)A - P \]  \[ 53 \]

where

\( (SPW-10\%-N) \) = series present worth factor for 10% interest and a ship life of \( N \) years

\( = 9.425 \) for a 30-year life

\( = 9.775 \) for a 40-year life

\( = 9.911 \) for a 50-year life

\( A \) = annual return before tax

\( = Cr - Y \)

where
C = annual transport capacity

r = freight rate

Y = annual operating costs

The net present value criterion can be criticized because it is fundamentally biased in favor of large projects or over-design. Since investment funds are usually limited, finding NPV per dollar invested is a logical way of overcoming that bias. This leads to the net present value index, NPVI ( = \( \frac{NPV}{I} \)). Given the assumptions of single investments and uniform returns, NPVI is exactly equivalent to the yield as a measure of merit. That is, it will rank alternatives in exactly the same order. This is explained in (20). This leads us, then, to our final measure of merit, explained below.

3. **Yield**

Yield is also called discounted cash flow rate of return, equivalent interest rate of return, internally generated interest rate, etc. It is simply the interest rate that makes the net present value equal to zero. In complex cash flows it can be found only by trial-and-error. Given the assumptions made in finding NPV, however, we can easily simplify the task. We need only find the predicted capital recovery factor, CR, and then convert that figure to its corresponding interest rate:

\[
CR = \frac{A}{P} \quad [54]
\]
II: DETAILED ANALYTICAL METHODS

All terms are as defined in the preceding paragraphs. The interest rate can be found from curves, as in (21) or from interest tables.

In the above procedure, note that we are deriving before-tax interest rates. The alternative promising highest yield before tax will also promise highest yield after tax, as long as all alternatives have equal lives. Going further, if we recognize that capital recovery factors and interest rates are near-linear in relationship, we can eliminate the final, awkward step in the calculation and use CR as a surrogate for yield. CR will, in short, put the various alternatives in the same ranking as would yield, given our usual assumptions as to uniform returns and equal lives.
I. Synthesis

A. Handling Annual Variations

The foregoing sections have explained proposed methods for systematically estimating the costs and benefits that may be expected from alternative ship designs and lengths of operating season. In each case, we come up with three numerical values for any selected measure of merit: one for normal winter weather conditions, one for mild conditions, and one for severe conditions. The intent of this section is to propose a rational method for integrating these differing results.

Our proposed method is based on the reasonable assumption that a shipowner will want to operate his ship longer in mild winters than in severe winters. We assume then that he will choose a length of operating season that would in each case correspond to the optimum value of whatever measure of merit he chooses to use. For example, suppose that the required freight rate is the criterion and the predicted values for a class IA design on a given trade route are as follows:

<table>
<thead>
<tr>
<th>Weather Condition</th>
<th>Probability</th>
<th>Dec 15</th>
<th>Jan 15</th>
<th>Feb 15</th>
<th>Mar 15</th>
<th>April 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild</td>
<td>25%</td>
<td>$2.00</td>
<td>1.95</td>
<td>1.90</td>
<td>1.85*</td>
<td>1.90</td>
</tr>
<tr>
<td>Normal</td>
<td>50%</td>
<td>$2.00</td>
<td>1.97</td>
<td>1.95*</td>
<td>1.98</td>
<td>2.05</td>
</tr>
<tr>
<td>Severe</td>
<td>25%</td>
<td>$2.00</td>
<td>1.98*</td>
<td>2.00</td>
<td>2.05</td>
<td>2.15</td>
</tr>
</tbody>
</table>

*Minimum value for assumed winter condition

Note: Values shown are arbitrary and are only for purposes of illustration.
In comparing this design with its alternatives, we would use the weighted average (expected) value of the required freight rate based on the probabilities of mild, normal, and severe winters. In this particular case, the expected value would be:

\[ RFR = 0.25\times 1.85 + 0.50\times 1.95 + 0.25\times 1.98 \]

\[ = 0.4625 + 0.975 + 0.495 = 1.9325 \]

say $1.93$

This approach accords with the general policy that an owner would naturally follow. That is, he keeps on operating his ship until the out-of-pocket costs for one more voyage equal or exceed the income to be derived from that voyage. That will lead to maximum profit for the year. Since the investment is a fixed amount for a ship already built, maximum profit then also means minimum total cost per ton carried.

B. Income

In using either net present value or yield as a criterion, we need to use current freight rates to convert annual transport capacity to annual gross revenue. Current freight rates (based on docks suitable for drafts over 23 feet and with unloading times under 24 hours) are as follows:
Head of Lakes to Lower Lakes: $2.43 per long ton
Marquette to Lower Lakes: $2.18 per long ton
Escanaba to Lake Erie or Detroit: $1.83 per long ton
Escanaba to Lake Michigan: $1.46 per long ton

The rates shown above are exclusive of cargo off-loading. Current dock charges are $0.76 per long ton for unloading into a rail car or $1.02 per long ton for unloading into a stockpile. We suggest that the former figure be used for self-unloaders with shuttle conveyors and the latter for self-unloaders with boom conveyors.

C. Existing Ships

In analyzing the economics of existing ships, whether ice-strengthened or not, we face the difficulty of assessing the true invested cost: namely, the net disposal value at the time of analysis. That is, the owner who continues to operate an existing ship must justify his decision to forego the opportunity of selling it on the open market. This sort of estimate can of course be made in any real-life situation and used as the "invested cost" applied to any of the forementioned measures of merit.

In a general study, such as this, however, the task becomes impractical. The best general solution is to treat continued operation of the existing, unstrengthened ship as one of the
II: DETAILED ANALYTICAL METHODS

alternatives. The merits of any other alternative can then be weighed by asking whether the added income is enough to justify the added investment. Either net present value or yield would be suitable criteria in this approach.

A typical shipowner will have old, inefficient ships as well as newer, more economical units in his fleet. Winter operation with the newer ships will allow him to dispose of his less economical ships at an earlier date. Alternatively, he may simply put the older ships into idle status until business picks up or disposal values rise. These are complexities to which this study report can be applied to suit individual circumstances.
III. COMPUTER PROGRAM

A complete analysis of extended season economics is too cumbersome to be made manually for more than a limited number of alternative proposals. We have therefore developed a computer program derived from the analytical procedure explained in chapter II. The program is flexible and can be readily modified to suit individual requirements as to ship design, cargo, trade route, and preferred measure of merit. Such requirements are fed into the computer, along with appropriate assumptions as to delay times, freight rates, interest rates, etc. The computer does the necessary calculations and prints out the estimated value of the three measures of merit for the standard 8-month season, for 8.5 months, 9 months, 9.5 months, etc. through 11.5 months. It also indicates derived values of various key parameters such as hull form coefficients, a breakdown of weights and costs, and round trips per season.

The computer program is written in Fortran IV and a typical run costs around $1.50 on the University's IBM model 360/67 computer.

Chapter II section E mentions two alternatives to estimating speed and power in open water: Krappinger's approximation (7) and a more rigorous method recently developed by Nowacki and others under a grant from R. A. Stearn, Inc. The latter approach is used in the program.

The rest of this chapter specifies the necessary
III: COMPUTER PROGRAM

inputs, outlines the major implied assumptions and explains how to interpret the outputs.

A. Inputs

The inputs presuppose a notional or preliminary design of a ship generally suited to the intended trade route requirements. Alternatively, an existing ship may be the subject of analysis. The following specifications are required (and shown here in the sequence recorded in the print-out).

1. Trade Route

Each trade route requires its own sub-routine recognizing differences in distances through ice, ice conditions, delays in ice, ice temperature, etc. The only data prepared to date are those for the trade route between Two Harbors, Minnesota, and South Chicago. Other trade routes can be analyzed when data become available.

2. Cargo

Any kind of cargo can be assumed. Some will be more difficult to handle in the winter, however.

3. Ship Status

The program needs to be instructed as to whether it is analyzing a proposed ship or an existing one.
4. **Ice Class**

The Finnish ice class number must be given. Class 2 indicates an ordinary, unstrengthened ship.

5. **Winter Weather Conditions**

The alternative weather condition inputs are:

- Mild
- Normal
- Severe

6. **Principal Dimension**

The following dimensions must be given:

- Length between perpendiculrars
- Beam
- Depth
- Draft at summer load line
III: COMPUTER PROGRAM

7. **Block Coefficient**

The block coefficient must be given. If the midship coefficient is known it can be used as an input, otherwise a value of 0.993 is assumed.

8. **Speed and Power**

In new designs the service speed in open water at summer draft should be specified. The computer will find the required SHP. It can also work in the opposite direction but at slightly added cost. The computer further checks the SHP against the minimum requirements of the ice class, adjusts the power upward if required, and recomputes the speed.

In existing ships, both speed and SHP are presumably known. Both should be used as inputs.

9. **Machinery Type**

The type of machinery must be given. Machinery code 1 indicates a conventional single screw geared steam turbine plant. Code 2 indicates a conventional single screw twin geared diesel plant.

10. **Propeller Type**

A code 1 propeller indicates fixed blades; code 2 indicates controllable pitch.
11. **Self-Unloader**

   Code 0 indicates no self-unloading capability. Code 1 indicates a self-unloader.

12. **Conveyor Type**

   A code 1 conveyor indicates a boom installation; code 2 indicates a shuttle conveyor.

13. **Cargo Handling Speed**

   Any loading and unloading rates can be used as inputs.

   **Note:** The unloading rate used as an input should recognize that the theoretical rate will seldom be reached in practice. We suggest the nominal rate be reduced by 15%.

14. **Bow Thruster**

   The code 0 indicates no bow thruster. Code 1 indicates the installation of a thruster.
15. **Number in Crew**

The program will accept any number in the crew complement.

16. **Delays**

Queuing delays will vary from port to port and with general level of activity. As average figures, we suggest 4 hours per round trip if no canal locks are involved, or 5 hours if passage through the Soo is required. The program will accept any figure, however, and this input can be used to recognize other delays not explicitly covered elsewhere. (Note: delays in ice are covered elsewhere.)

17. **Economic Factors**

The program computes three measures of merit: net present value, capital recovery factor (as a surrogate for yield) and required freight rate. For net present value, the discount rate (before tax) should be specified, as should the freight rate and economic life in years. For capital recovery factor, the freight rate must be specified. For required freight rate, the capital recovery factor (before tax) will be needed. For existing ships, an approximate book value must be given.
B. Implicit Assumptions

In its present form, the program contains several assumptions that should be widely applicable to bulk carriers on the Great Lakes. If the user wants to modify any of them, however, that can be done with small trouble. Most of the assumptions can be inferred from reading through chapter II. Indeed, we urge that the program not be used without prior knowledge of the procedures explained in that chapter.

The key assumptions of the program are the following:

1. Ships are U. S.-built and operated.

2. Ships are conventionally arranged Great Lakes type bulk carriers with only moderate degree of automation.

3. Hulls are constructed largely of mild steel.

4. Ships are fitted with single screw propulsion systems.

5. Steam plants burn residual fuel oil; diesel plants burn blended oil.

6. The federal government will provide substantial assistance (e.g. several large ice breakers, winter navigation aids, bubbler systems, ice diversion dikes, etc.).

In addition to the above, there are many assumptions regarding building and operating costs, and ice
III: COMPUTER PROGRAM

conditions, together with speed and delays in ice, that are critically important to the projected economics. These assumptions are stated in detail in chapter II. It is particularly important to note that the assumed ice conditions, speed in ice, and delays in ice are necessarily little better than guesses at this stage. Obviously, then, no strong reliance should be placed on the numerical results until reliable data are gathered and incorporated into the program.

Appendix IV shows the flow diagram for the computer program.
C. Output

The computer program can be modified to print out any figure used in the computation. We have selected a few key items and these are clearly indicated in the typical print-out sheets reproduced for the sample study described next.

D. Sample Study

As an illustration of the use of the computer program, we have put through several analyses for an imaginary bulk carrier with five different ice classes, all assuming normal winter weather conditions. In the case of the 1B ice class ship, however, we analyzed mild and severe winter weather conditions as well. The ship specifications are as follows:

Trade route: Two Harbors, Minnesota to South Chicago
Cargo: iron ore pellets
Length between perpendiculares: 825 ft
Summer draft: 25.5 ft
Beam: 105 ft
Depth: 51.5 ft
Service speed: 14.5 knots
Block coefficient: 0.90
Power plant: twin geared diesels, single screw (code 2)
III: COMPUTER PROGRAM

Propeller: fixed blade (code 1)
Self-unloader: boom type (code 1/1)
Crew complement: 24
Bow thruster (code 1)
Cargo handling speed
  Loading: 20,000 tons per hour
  Unloading: 8,000 tons per hour
Queueing delays: 5 hours per round trip
Freight rate: $3.45 per long ton including discharging
Capital recovery factor before tax: 0.110
Interest rate for NPV: 10.5% before tax
Ship's economic life: 40 years

The next several pages are extracted from the print-out for the proposed ship with the 1B ice class variation operating under normal winter weather conditions. The hand-printed notes or references to table 9 explain the items that are not fairly obvious. As always, we ask the machine only to indicate the relative merits of various alternatives. The decision is made by a human being who can weigh the intangible factors along with the economics. We have, however, noted the best predicted values of the measures of merit and summarized them in table 10. The table also indicates the length of operating season that leads to the best attainable value of the measure of merit.
Table 11 compares the best attainable values of the measures of merit with the values associated with a normal 8-month season. All numbers are derived from the sample study. The table gives a quantitative indication of the merit of the extended season. Because of the nature of the inputs, however, it should not be used to reach conclusions as to the best degree of ice strengthening.

Table 12 compares the economic predictions for the 1B ice class ship operating into a severe winter with those for an unreinforced ship operating over a normal 8-month season.

The 6 pages following table 12 present the economic summary print-outs for the 1B ice class sample ship in mild and severe winter conditions, plus the other ice class variations in normal winter conditions.
PRINCIPAL DESIGN INPUTS

TRADE ROUTE... TWO HARB-GARY
CARGO.............. CRF PLTS
SHIP STATUS... PROPOSF
ICF CLASS........ I-B
WINTER WEATHER..... NORMAL

LENGTH B.P...... 825.0 FT      SERVICE SPEED... 14.5 KNOT
SUMMER DRAFT... 25.5 FT        BLOCK COEFF.... 0.940
BEAM............. 105.0 FT      DEPTH.............. 51.5 FT

SHAFT HORSE POWER... 1 0. - Indicates SHP not given
MACHINERY TYPE.... 2
PROPELLER TYPE.... 1

SELF UNLOADER..... 1
CONVYOR TYPE...... 1
UNLOADING SPEED (L.T./HOUR)... 8000.
LOADING SPEED (L.T./HOUR)..... 20000.

ROW THRUSTER... 1
NUMBER OF CREW.... 24.
DAYS........... 5.0 HOURS

FRUIT RATE/L.TCN...($)... 3.45
DESIRED CRF BEFORE TAX... 0.110
DISCOUNT RATE BEFORE TAX... 0.105
LIFE EXPECTANCY.... 40

(cont.)
FINAL RESULTS OF MILK CARRIER ANALYSIS

1. MAIN DIMENSIONS
   Length B.P. = 825.0 FT.
   Beam = 105.0 FT.
   Depth = 51.5 FT.
   Designed Draft = 25.5 FT.
   Displacement = 55377. TONS
   Deadweight = 41752. TONS
   Displacement Volume = 1988043. CU. FT

2. SPEED AND POWER
   Service Speed... 15.52 Knot see note 1, table 9
   Service Speeds... 17.88 MILE/HOUR
   Effective H.P.... 8603
   Maximum Cont. H.P.... 17113. note 2
   Horsepower used in Restricted Area... 3861. note 3

3. FORM COEFFICIENTS AND RATIOS
   C.B = 0.900
   C.P = 0.906
   C.M = 0.993
   L/D = 16.02
   L/B = 7.86
   R/D = 2.035
   R/T = 4.118
   T/D = 0.495
   \[ \frac{V_k}{V_L} \leq \frac{L}{\sqrt{\Delta}} \]
   V/Sqrt(L) = 0.540
   Length-Disp Ratio = 21.65
   CUBIC NUMBER... 44612.

- 87 - (cont.)
4. WEIGHT BREAKDOWN (LONG TONS)

STEEL HULL... 10755.7
OUTFITTING... 1646.1
MACHINERY... 798.1

ADDED STEEL WEIGHT FOR ICE CLASS... 435.
CONVEYOR WEIGHT = 848.
BOW THRUSTER WEIGHT = 7. note 4
TOTAL ADDITIONAL WGT = 918. note 5

TOTAL OUTFITTING WEIGHT = 1646.
TOTAL HULL STEEL WEIGHT = 11191.

LIGHT SHIP... 13625.5

VARIABLE WEIGHT... 150. note 6
FUEL WEIGHT.... 179.
VARIABLE WEIGHT INCLUDING F.O. ... 329.

DEADWEIGHT... 41752.

SUMMER PAYLOAD (L.T.).... 41423.
INTERNATIONAL PAYLOAD... 39233.
ICE SEASON PAYLOAD...... 36569.

5. SHIP VOLUME BUDGET
OMITTED

6. FREEBOARD AND STABILITY
OMITTED

7. SHIPBUILDING COST BREAKDOWN (US DOLLARS)

STEEL HULL COST... 9907429. note 7
OUTFITTING COST... 3223182.
MACHINERY COST.... 4015075.

BOW THRUSTER COST = 150000.
C.P. PROP. COST = 0.
UNLOADING EQUIPMENT COST = 1640246.

TOTAL EXTRA COST = 1790246.

SHIP PRICE (OR VALUE) 20307568. note 8
8. OPERATING INFORMATION

**OPERATING DRAFTS(FT)**
SUM. DRAFT...25.5  MIDSUM. DRAFT...25.1  INTER. SEASON DRAFT...24.5  WINTER DRAFT...23.4

**VOYAGE TIME PER ROUND TRIP**
CARGO HANDLING TIME(HR)... 7.2
DOCKING & LOCKING TIME(HR)... 1.9
TOTAL DELAY TIME(DAYS)... 0.54

SUMMER ROUND TRIP DAYS... 4.53  note 9
MIDSUMMER ROUND TRIP DAYS... 4.54  note 10
INTER. SEASON ROUND TRIP DAYS... 4.52
WINTER ROUND TRIP DAYS... 4.50  note 10

**NUMBER OF VOYAGES PER SEASON**
SUMMER... 6.6  MIDSUMMER... 27.1  note 11
INTER. SEASON... 10.2  WINTER... 10.0  note 12
TOTAL VOYAGES DURING ICE SEASON... 18.4
TOTAL VOYAGES PER YEAR... 72.3

**ROUND TRIP VOYAGE TIME DURING ICE SEASON**

<table>
<thead>
<tr>
<th>ICE SEASON</th>
<th>RUNNING DAYS</th>
<th>DELAY DAYS</th>
<th>STOPPING TIME IN ICE(HR)</th>
<th>VOYAGE DAYS</th>
<th>NUMBER OF VOYAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.8</td>
<td>0.8</td>
<td>0.0</td>
<td>4.0</td>
<td>note 13</td>
</tr>
<tr>
<td>2</td>
<td>4.2</td>
<td>1.0</td>
<td>0.0</td>
<td>5.1</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>4.1</td>
<td>1.1</td>
<td>0.0</td>
<td>5.2</td>
<td>2.9</td>
</tr>
<tr>
<td>4</td>
<td>4.6</td>
<td>1.2</td>
<td>0.0</td>
<td>5.3</td>
<td>3.1</td>
</tr>
<tr>
<td>5</td>
<td>5.5</td>
<td>1.3</td>
<td>0.0</td>
<td>6.8</td>
<td>2.6</td>
</tr>
<tr>
<td>6</td>
<td>5.3</td>
<td>1.5</td>
<td>0.0</td>
<td>5.8</td>
<td>1.9</td>
</tr>
<tr>
<td>7</td>
<td>5.3</td>
<td>1.6</td>
<td>0.0</td>
<td>6.9</td>
<td>2.2</td>
</tr>
</tbody>
</table>

**FUEL CONSUMPTION RATE(LB/HR)**
F.C.R. AT FULL POWER = 6442.8
F.C.R. DURING DFAY = 654.7
F.C.R. DURING UNLOADING(LB) = 4926.2
F.C.R. AT FULL POWER(LB/SHP-PR) = 0.39
F.C.R. AT PARTIAL POWER(LB/SHP-PR) = 0.50
L.O. RATE(LB/HR) = 32.2

(cont.)
### 9. OPERATING COST

<table>
<thead>
<tr>
<th>SEASON EXTENSION IN HALF MONTH INCREMENT</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec. 15</td>
<td>Jan. 1</td>
<td>Jan. 15</td>
<td>Feb. 1</td>
<td>Feb. 15</td>
<td>Mar. 1</td>
<td>Mar. 15</td>
<td>April 1</td>
<td></td>
</tr>
<tr>
<td>CREW COST.....</td>
<td>376952</td>
<td>404984</td>
<td>431316</td>
<td>458548</td>
<td>485780</td>
<td>513012</td>
<td>542244</td>
<td>567476</td>
</tr>
<tr>
<td>STORE &amp; SUPPLY</td>
<td>21989</td>
<td>23363</td>
<td>24737</td>
<td>26112</td>
<td>27436</td>
<td>28340</td>
<td>32235</td>
<td>31689</td>
</tr>
<tr>
<td>REPAIR &amp; MAINT</td>
<td>157940</td>
<td>167812</td>
<td>177683</td>
<td>188820</td>
<td>200907</td>
<td>214030</td>
<td>228285</td>
<td>243774</td>
</tr>
<tr>
<td>INSURANCE COST</td>
<td>175570</td>
<td>186623</td>
<td>197676</td>
<td>221390</td>
<td>247269</td>
<td>275494</td>
<td>406259</td>
<td>339773</td>
</tr>
<tr>
<td>OVERHEAD COST</td>
<td>121765</td>
<td>122765</td>
<td>123765</td>
<td>124765</td>
<td>125765</td>
<td>126765</td>
<td>127765</td>
<td>128765</td>
</tr>
<tr>
<td>TOWING COST...</td>
<td>18683</td>
<td>20433</td>
<td>21903</td>
<td>23458</td>
<td>24747</td>
<td>25704</td>
<td>26816</td>
<td>27907</td>
</tr>
<tr>
<td>LAYUP COST.....</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>25000</td>
<td>25000</td>
<td>10000</td>
</tr>
<tr>
<td>FUEL COST.....</td>
<td>446755</td>
<td>478925</td>
<td>508913</td>
<td>54014</td>
<td>569461</td>
<td>595221</td>
<td>624309</td>
<td>652919</td>
</tr>
<tr>
<td>TOTAL OP. COST</td>
<td>1394553</td>
<td>1479003</td>
<td>1560990</td>
<td>1658202</td>
<td>1756412</td>
<td>1804082</td>
<td>1908899</td>
<td>2002219</td>
</tr>
<tr>
<td>ANNUAL CAPITAL</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
</tr>
<tr>
<td>AVERAGE ANNUAL</td>
<td>3628384</td>
<td>3712834</td>
<td>3794821</td>
<td>3892033</td>
<td>3990243</td>
<td>4037913</td>
<td>4142730</td>
<td>4236050</td>
</tr>
<tr>
<td>TOTAL CARGO...</td>
<td>2033284</td>
<td>2160680</td>
<td>2267621</td>
<td>2380823</td>
<td>2474670</td>
<td>2544303</td>
<td>2625227</td>
<td>2704685</td>
</tr>
</tbody>
</table>

### 10. MEASURES OF MERIT

| RFR............ | 1.784 | 1.718 | 1.673 | 1.530 | 1.612 | 1.587 | 1.578 | 1.566 |
| NPV (IN $1000) | 32232 | 35552 | 38234 | 40976 | 43085 | 44885 | 46915 | 48206 |
| CRF............ | 0.2768 | 0.2942 | 0.3084 | 0.3223 | 0.3339 | 0.3434 | 0.3520 | 0.3605 |

**Note 17:**

**Note 18:**

**Note 19:**

**Note 20:**
TABLE 9
COMPUTER PRINT-OUT NOTES

1. The service speed shown is higher than the initial input speed because ice class requirements dictate a higher horsepower than would normally be required.

2. The horsepower figure shown is BHP for diesel plants, SHP for steam.

3. The restricted speed is 10 miles per hour. A 30% increase in power is assumed for shoal water.

4. Bow thruster weight includes water in tunnel.

5. "Total additional weight" applies only to outfitting items.

6. "Variable weight" comprises fresh water, stores, supplies, crew and their effects.

7. The computer program has not been instructed to drop unwarranted digits. We leave that to the user.


9. Round trip times vary slightly because of different times required to handle different quantities of cargo.

10. "Winter round trip days" excludes delays because of ice. (Those delays are recognized later.)

11. The voyages per season shown are fractional. This is slightly unrealistic and leads to minor errors. The program will eventually be refined to correct that shortcoming.
12. The voyages per winter season shown are uncorrected for ice delays. (That correction is made later.)

13. The ice season numbers correspond to half-month increments beyond the standard season, which ends December 15.

14. In extreme conditions the voyage days may exceed the half-month increment. The computer program correctly handles that situation by recording a fractional number of voyages.

15. Increment number 5 represents the last 13 days of February. Being shorter than normal, the number of voyages comes out low.

16. Voyage times are based on predicted ice conditions either at start of voyage or end of voyage, whichever is more severe. In other words, we assume that the worst conditions obtain throughout the time of the round trip. (This conservative factor offsets the inaccuracies of note 11.)

17. "Annual Capital" is annual cost of capital recovery or 11% of the investment.

18. "Average Annual" is average annual cost, the sum of the operating costs and capital recovery costs.

19. "Total Cargo" is tons of cargo carried per year.

20. The abnormally high values of CRF show that the assumed freight rate was too optimistic. Therefore the derived present values are also too optimistic, because both the annual returns and the discount factors are too high. (We assume that competition will drive freight rates down if rates of return are as high as indicated.)
### TABLE 10

**BEST MEASURES OF MERIT PREDICTED FOR PROPOSED 825-FT SELF-UNLOADER CARRYING PELLETIZED ORE FROM TWO HARBORS TO SOUTH CHICAGO**

(Numbers in parentheses indicate corresponding length of operating season in months.)

<table>
<thead>
<tr>
<th>Ice</th>
<th>Measure of Merit</th>
<th>Winter Weather Condition</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td></td>
<td>Mild</td>
<td>Normal</td>
<td>Severe</td>
</tr>
<tr>
<td>2</td>
<td>RFR</td>
<td>$1.59 (10.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NPV in millions</td>
<td>$44.6 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CRF</td>
<td>0.354 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1C</td>
<td>RFR</td>
<td>$1.60 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NPV in millions</td>
<td>$44.4 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CRF</td>
<td>0.349 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1B</td>
<td>RFR</td>
<td>$1.51 (11.5)</td>
<td>$1.57 (11.5)</td>
<td>$1.66 (9.5)</td>
</tr>
<tr>
<td></td>
<td>NPV in millions</td>
<td>$51.4 (11.5)</td>
<td>$48.2 (11.5)</td>
<td>$41.5 (11.5)</td>
</tr>
<tr>
<td></td>
<td>CRF</td>
<td>0.378 (11.5)</td>
<td>0.361 (11.5)</td>
<td>0.326 (11.5)</td>
</tr>
<tr>
<td>1A</td>
<td>RFR</td>
<td>$1.54 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NPV in millions</td>
<td>$51.5 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CRF</td>
<td>0.371 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1A</td>
<td>RFR</td>
<td>$1.53 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NPV in millions</td>
<td>$54.1 (11.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CRF</td>
<td>0.375 (11.5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 93 -
<table>
<thead>
<tr>
<th>Ice Class</th>
<th>Measure of Merit</th>
<th>8-Month Season</th>
<th>Extended Season</th>
<th>Gain from Extended Season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RFR</td>
<td>CRF</td>
<td>Ratio</td>
</tr>
<tr>
<td>2</td>
<td>NPV in millions</td>
<td>$1.75*</td>
<td>$31.6*</td>
<td>$1.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.59</td>
<td>$44.6</td>
<td>1.41</td>
</tr>
<tr>
<td>1C</td>
<td>NPV in millions</td>
<td>$1.60</td>
<td>$44.4</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0.349</td>
<td>1.24</td>
</tr>
<tr>
<td>1B</td>
<td>NPV in millions</td>
<td>$1.57</td>
<td>$48.2</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0.361</td>
<td>1.28</td>
</tr>
<tr>
<td>1A</td>
<td>NPV in millions</td>
<td>$1.54</td>
<td>$51.5</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0.371</td>
<td>1.32</td>
</tr>
<tr>
<td>Super</td>
<td>NPV in millions</td>
<td>$1.53</td>
<td>$54.1</td>
<td>1.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0.375</td>
<td>1.33</td>
</tr>
</tbody>
</table>

*These figures represent existing practice: an unreinforced ship operating over an 8-month season.
### TABLE 12
ECONOMIC IMPROVEMENT PREDICTED UNDER SEVERE WINTER OPERATIONS

Sample ship with 1B ice class operating in winter vs unreinforced ship operating over an 8-month season.

<table>
<thead>
<tr>
<th>Measure of Merit</th>
<th>Operation</th>
<th>Gain from Extended Season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unreinforced 8-Month Season</td>
<td>Ice Class 1B Extended Season</td>
</tr>
<tr>
<td>RFR</td>
<td>$1.75</td>
<td>$1.66</td>
</tr>
<tr>
<td>NPV in millions</td>
<td>$31.6</td>
<td>$41.5</td>
</tr>
<tr>
<td>CRF</td>
<td>0.282</td>
<td>0.326</td>
</tr>
</tbody>
</table>
### 9. OPERATING COST

#### ICE CLASS 1B, MILD WINTER

<table>
<thead>
<tr>
<th>Season Extension in Half Month Increment</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>CREW COST.....</td>
<td>376852</td>
<td>404084</td>
<td>431316</td>
<td>458548</td>
<td>485780</td>
<td>513912</td>
<td>540144</td>
<td>567476</td>
</tr>
<tr>
<td>STORE &amp; SUPPLY</td>
<td>21989</td>
<td>23363</td>
<td>24737</td>
<td>26112</td>
<td>27486</td>
<td>28860</td>
<td>30235</td>
<td>31609</td>
</tr>
<tr>
<td>REPAIR &amp; MAINT</td>
<td>157940</td>
<td>167812</td>
<td>177683</td>
<td>188820</td>
<td>200997</td>
<td>214039</td>
<td>228285</td>
<td>243774</td>
</tr>
<tr>
<td>INSURANCE COST</td>
<td>175570</td>
<td>186623</td>
<td>197676</td>
<td>221390</td>
<td>247269</td>
<td>275494</td>
<td>306259</td>
<td>339173</td>
</tr>
<tr>
<td>OVERHEAD COST</td>
<td>121765</td>
<td>122765</td>
<td>123765</td>
<td>124765</td>
<td>125765</td>
<td>126765</td>
<td>127765</td>
<td>128765</td>
</tr>
<tr>
<td>TOWING COST...</td>
<td>18683</td>
<td>20478</td>
<td>21996</td>
<td>23673</td>
<td>25179</td>
<td>26419</td>
<td>27821</td>
<td>29281</td>
</tr>
<tr>
<td>LAYUP COST......</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
</tr>
<tr>
<td>FUEL COST......</td>
<td>446755</td>
<td>479341</td>
<td>509945</td>
<td>541478</td>
<td>570325</td>
<td>596154</td>
<td>624917</td>
<td>654991</td>
</tr>
<tr>
<td>TOTAL OP. COST</td>
<td>1394553</td>
<td>1479464</td>
<td>1562116</td>
<td>1659781</td>
<td>1758298</td>
<td>1805731</td>
<td>1910522</td>
<td>2005665</td>
</tr>
<tr>
<td>ANNUAL CAPITAL</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
</tr>
<tr>
<td>AVERAGE ANNUAL</td>
<td>3628384</td>
<td>3713295</td>
<td>3795947</td>
<td>3893612</td>
<td>3992039</td>
<td>4039562</td>
<td>4144353</td>
<td>4239496</td>
</tr>
<tr>
<td>TOTAL CARGO...</td>
<td>2033284</td>
<td>2163960</td>
<td>2274408</td>
<td>2396472</td>
<td>2506130</td>
<td>2596378</td>
<td>2698364</td>
<td>2804679</td>
</tr>
</tbody>
</table>

### 10. MEASURES OF MERIT

<table>
<thead>
<tr>
<th></th>
<th>RFR</th>
<th>NPV (IN $1000)</th>
<th>CRF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.784</td>
<td>32232</td>
<td>0.2768</td>
</tr>
<tr>
<td></td>
<td>1.716</td>
<td>35653</td>
<td>0.2948</td>
</tr>
<tr>
<td></td>
<td>1.669</td>
<td>38443</td>
<td>0.3095</td>
</tr>
<tr>
<td></td>
<td>1.625</td>
<td>41466</td>
<td>0.3254</td>
</tr>
<tr>
<td></td>
<td>1.593</td>
<td>44093</td>
<td>0.3392</td>
</tr>
<tr>
<td></td>
<td>1.556</td>
<td>46549</td>
<td>0.3522</td>
</tr>
<tr>
<td></td>
<td>1.536</td>
<td>48859</td>
<td>0.3643</td>
</tr>
<tr>
<td></td>
<td>1.512</td>
<td>51398</td>
<td>0.3777</td>
</tr>
</tbody>
</table>
9. OPERATING COST

<table>
<thead>
<tr>
<th>SEASON EXTENSION</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN HALF MONTH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INCREMENT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CREW COST........</td>
<td>376852</td>
<td>404084</td>
<td>431316</td>
<td>458548</td>
<td>485780</td>
<td>513012</td>
<td>540244</td>
<td>567476</td>
</tr>
<tr>
<td>STORE &amp; SUPPLY</td>
<td>21989</td>
<td>23363</td>
<td>24737</td>
<td>26112</td>
<td>27486</td>
<td>28860</td>
<td>30235</td>
<td>31630</td>
</tr>
<tr>
<td>REPAIR &amp; MAINT</td>
<td>157940</td>
<td>167812</td>
<td>177683</td>
<td>188820</td>
<td>200907</td>
<td>214137</td>
<td>228285</td>
<td>243774</td>
</tr>
<tr>
<td>INSURANCE COST</td>
<td>175570</td>
<td>186623</td>
<td>197676</td>
<td>221390</td>
<td>247269</td>
<td>275494</td>
<td>306259</td>
<td>339773</td>
</tr>
<tr>
<td>OVERHEAD COST.</td>
<td>121765</td>
<td>122765</td>
<td>123765</td>
<td>124765</td>
<td>125765</td>
<td>126765</td>
<td>127765</td>
<td>128765</td>
</tr>
<tr>
<td>TOWING COST.....</td>
<td>18683</td>
<td>20333</td>
<td>21642</td>
<td>22867</td>
<td>23377</td>
<td>23762</td>
<td>24410</td>
<td>25044</td>
</tr>
<tr>
<td>LAYUP COST....</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
</tr>
<tr>
<td>FUEL COST......</td>
<td>446755</td>
<td>478400</td>
<td>508067</td>
<td>539498</td>
<td>568538</td>
<td>594489</td>
<td>623610</td>
<td>652177</td>
</tr>
<tr>
<td>TOTAL OP. COST</td>
<td>1394553</td>
<td>1478378</td>
<td>1559884</td>
<td>1656996</td>
<td>1754119</td>
<td>1801409</td>
<td>1905803</td>
<td>1999614</td>
</tr>
<tr>
<td>ANNUAL CAPITAL</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
<td>2233831</td>
</tr>
<tr>
<td>AVERAGE ANNUAL</td>
<td>3628384</td>
<td>3712209</td>
<td>3793715</td>
<td>3890827</td>
<td>3987950</td>
<td>4035249</td>
<td>4139634</td>
<td>4232445</td>
</tr>
<tr>
<td>TOTAL CARGO...</td>
<td>2033284</td>
<td>2153363</td>
<td>2248644</td>
<td>2337798</td>
<td>2374961</td>
<td>2402963</td>
<td>2450119</td>
<td>2496250</td>
</tr>
</tbody>
</table>

10. MEASURES OF MERIT

| RFR............. | 1.784   | 1.724   | 1.687   | 1.664   | 1.679   | 1.679   | 1.690   | 1.696   |
| NPV (IN $1000) | 32232   | 35322   | 37633   | 39600   | 39891   | 40352   | 40897   | 41517   |
| CRF............. | 0.2768  | 0.2930  | 0.3052  | 0.3156  | 0.3171  | 0.3195  | 0.3224  | 0.3257  |
### 9. OPERATING COST

<table>
<thead>
<tr>
<th>Season Extension in Half Month Increment</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>CREW COST..</td>
<td>376352</td>
<td>404084</td>
<td>431316</td>
<td>458543</td>
<td>485780</td>
<td>513012</td>
<td>540244</td>
<td>567476</td>
</tr>
<tr>
<td>STORE &amp; SUPPLY</td>
<td>21989</td>
<td>23363</td>
<td>24737</td>
<td>26112</td>
<td>27486</td>
<td>28860</td>
<td>30235</td>
<td>31609</td>
</tr>
<tr>
<td>REPAIR &amp; MAINT</td>
<td>152055</td>
<td>161559</td>
<td>171062</td>
<td>182687</td>
<td>196039</td>
<td>211398</td>
<td>229082</td>
<td>249457</td>
</tr>
<tr>
<td>INSURANCE COST</td>
<td>167681</td>
<td>178241</td>
<td>188801</td>
<td>220762</td>
<td>257473</td>
<td>299599</td>
<td>347895</td>
<td>403215</td>
</tr>
<tr>
<td>OVERHEAD COST</td>
<td>121765</td>
<td>122765</td>
<td>123765</td>
<td>124765</td>
<td>125765</td>
<td>126765</td>
<td>127765</td>
<td>128765</td>
</tr>
<tr>
<td>TOWING COST...</td>
<td>17740</td>
<td>19336</td>
<td>20679</td>
<td>22042</td>
<td>23143</td>
<td>23932</td>
<td>24848</td>
<td>25742</td>
</tr>
<tr>
<td>LAYUP COST.....</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>25000</td>
<td>25000</td>
<td>10000</td>
</tr>
<tr>
<td>FUEL COST......</td>
<td>373650</td>
<td>399652</td>
<td>423600</td>
<td>448404</td>
<td>471850</td>
<td>492482</td>
<td>515594</td>
<td>538226</td>
</tr>
<tr>
<td>TOTAL OP. COST</td>
<td>1306730</td>
<td>1383998</td>
<td>1458959</td>
<td>1558377</td>
<td>1662532</td>
<td>1721045</td>
<td>1840659</td>
<td>1954487</td>
</tr>
<tr>
<td>ANNUAL CAPITAL</td>
<td>2125355</td>
<td>2125355</td>
<td>2125355</td>
<td>2125355</td>
<td>2125355</td>
<td>2125355</td>
<td>2125355</td>
<td>2125355</td>
</tr>
<tr>
<td>AVERAGE ANNUAL</td>
<td>3432085</td>
<td>3509353</td>
<td>3594314</td>
<td>3683732</td>
<td>3787887</td>
<td>3846400</td>
<td>3966014</td>
<td>4079842</td>
</tr>
<tr>
<td>TOTAL CARGO...</td>
<td>1958227</td>
<td>2076155</td>
<td>2175406</td>
<td>2276033</td>
<td>2357415</td>
<td>2415684</td>
<td>2483380</td>
<td>2549404</td>
</tr>
</tbody>
</table>

### 10. MEASURES OF MERIT

<table>
<thead>
<tr>
<th></th>
<th>1.753</th>
<th>1.690</th>
<th>1.648</th>
<th>1.618</th>
<th>1.607</th>
<th>1.592</th>
<th>1.597</th>
<th>1.600</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFR</td>
<td>31619</td>
<td>34700</td>
<td>37200</td>
<td>39517</td>
<td>41167</td>
<td>42499</td>
<td>43565</td>
<td>44630</td>
</tr>
<tr>
<td>NPV (IN $1000)</td>
<td>0.2820</td>
<td>0.2991</td>
<td>0.3129</td>
<td>0.3258</td>
<td>0.3349</td>
<td>0.3423</td>
<td>0.3482</td>
<td>0.3541</td>
</tr>
</tbody>
</table>
### 9. OPERATING COST

<table>
<thead>
<tr>
<th>SEASON EXTENSION</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN HALF MONTH INCREMENT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CREW COST........</td>
<td>376852</td>
<td>404084</td>
<td>431316</td>
<td>458543</td>
<td>485780</td>
<td>513012</td>
<td>540244</td>
<td>567476</td>
</tr>
<tr>
<td>STORE &amp; SUPPLY</td>
<td>21989</td>
<td>23363</td>
<td>24737</td>
<td>26112</td>
<td>27486</td>
<td>28860</td>
<td>30235</td>
<td>31609</td>
</tr>
<tr>
<td>REPAIR &amp; MAINT</td>
<td>152055</td>
<td>161555</td>
<td>171062</td>
<td>182222</td>
<td>194763</td>
<td>208768</td>
<td>224455</td>
<td>242037</td>
</tr>
<tr>
<td>INSURANCE COST</td>
<td>170204</td>
<td>180921</td>
<td>191639</td>
<td>219602</td>
<td>251045</td>
<td>286268</td>
<td>325731</td>
<td>369911</td>
</tr>
<tr>
<td>OVERHEAD COST....</td>
<td>121765</td>
<td>122765</td>
<td>123765</td>
<td>124765</td>
<td>125765</td>
<td>126765</td>
<td>127765</td>
<td>128765</td>
</tr>
<tr>
<td>TOWING COST.....</td>
<td>17750</td>
<td>19374</td>
<td>20749</td>
<td>22131</td>
<td>23288</td>
<td>24101</td>
<td>25052</td>
<td>25983</td>
</tr>
<tr>
<td>LAYUP COST......</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>25000</td>
<td>25000</td>
<td>10000</td>
</tr>
<tr>
<td>FUEL COST........</td>
<td>373726</td>
<td>400106</td>
<td>424518</td>
<td>449993</td>
<td>473997</td>
<td>495172</td>
<td>518997</td>
<td>542467</td>
</tr>
<tr>
<td>TOTAL OP. COST</td>
<td>1309338</td>
<td>1387169</td>
<td>1462783</td>
<td>1558449</td>
<td>1657121</td>
<td>1707944</td>
<td>1817475</td>
<td>1918185</td>
</tr>
<tr>
<td>ANNUAL CAPITAL</td>
<td>21600038</td>
<td>2160038</td>
<td>2160038</td>
<td>2160038</td>
<td>2160038</td>
<td>2160038</td>
<td>2160038</td>
<td>2160038</td>
</tr>
<tr>
<td>AVERAGE ANNUAL</td>
<td>3469376</td>
<td>3547207</td>
<td>3622821</td>
<td>3718437</td>
<td>3817159</td>
<td>3867982</td>
<td>3977513</td>
<td>4078223</td>
</tr>
<tr>
<td>TOTAL CARGO......</td>
<td>1940404</td>
<td>2059187</td>
<td>2159739</td>
<td>2262339</td>
<td>2345443</td>
<td>2404947</td>
<td>2474457</td>
<td>2542536</td>
</tr>
</tbody>
</table>

### 10. MEASURES OF MERIT

| RFR............... | 1.788 | 1.723 | 1.677 | 1.644 | 1.627 | 1.608 | 1.607 | 1.604 |
| NPV (IN $1000)    | 30704 | 33808 | 36344 | 38798 | 40516 | 41960 | 43178 | 44432 |
| CRF............... | 0.2742 | 0.2911 | 0.3050 | 0.3181 | 0.3277 | 0.3356 | 0.3422 | 0.3495 |
### 9. OPERATING COST

<table>
<thead>
<tr>
<th>SEASON EXTENSION IN HALF MONTH INCREMENT</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>CREW COST......</td>
<td>376852</td>
<td>404084</td>
<td>431316</td>
<td>458948</td>
<td>485780</td>
<td>513712</td>
<td>540244</td>
<td>567476</td>
</tr>
<tr>
<td>STORE &amp; SUPPLY</td>
<td>21989</td>
<td>23363</td>
<td>24737</td>
<td>26112</td>
<td>27948</td>
<td>29860</td>
<td>30523</td>
<td>31609</td>
</tr>
<tr>
<td>REPAIR &amp; MAINT</td>
<td>163438</td>
<td>173653</td>
<td>183868</td>
<td>194794</td>
<td>206226</td>
<td>218189</td>
<td>230710</td>
<td>243814</td>
</tr>
<tr>
<td>INSURANCE COST</td>
<td>180799</td>
<td>192179</td>
<td>203559</td>
<td>221916</td>
<td>241252</td>
<td>261614</td>
<td>283049</td>
<td>305606</td>
</tr>
<tr>
<td>OVERHEAD COST...</td>
<td>127165</td>
<td>122765</td>
<td>123765</td>
<td>124705</td>
<td>125765</td>
<td>126765</td>
<td>127765</td>
<td>128765</td>
</tr>
<tr>
<td>TOWING COST...</td>
<td>19505</td>
<td>21379</td>
<td>22942</td>
<td>24639</td>
<td>26085</td>
<td>27186</td>
<td>28453</td>
<td>29703</td>
</tr>
<tr>
<td>LAYUP COST.....</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>25000</td>
<td>25000</td>
<td>10000</td>
</tr>
<tr>
<td>FUEL COST......</td>
<td>517760</td>
<td>555872</td>
<td>591682</td>
<td>629020</td>
<td>664088</td>
<td>694801</td>
<td>729709</td>
<td>764185</td>
</tr>
<tr>
<td>TOTAL OP. COST</td>
<td>1477106</td>
<td>1568292</td>
<td>1656866</td>
<td>1754739</td>
<td>1851680</td>
<td>1958425</td>
<td>1991561</td>
<td>2081155</td>
</tr>
<tr>
<td>ANNUAL CAPITAL</td>
<td>2305731</td>
<td>2305731</td>
<td>2305731</td>
<td>2305731</td>
<td>2305731</td>
<td>2305731</td>
<td>2305731</td>
<td>2305731</td>
</tr>
<tr>
<td>AVERAGE ANNUAL</td>
<td>3782837</td>
<td>3874023</td>
<td>3962597</td>
<td>4060520</td>
<td>4157411</td>
<td>4201156</td>
<td>4300892</td>
<td>4386886</td>
</tr>
<tr>
<td>TOTAL CARGO...</td>
<td>2112483</td>
<td>2248132</td>
<td>2361298</td>
<td>2484172</td>
<td>2588921</td>
<td>2668618</td>
<td>2760372</td>
<td>2850658</td>
</tr>
</tbody>
</table>

### 10. MEASURES OF MERIT

| RFR............. | 1.791  | 1.723  | 1.678  | 1.635  | 1.606  | 1.574  | 1.558  | 1.539  |
| NPV (IN $1000)  | 33361  | 36884  | 39706  | 42733  | 45226  | 47387  | 49414  | 51528  |
| CRF............. | 0.2772 | 0.2552 | 0.3096 | 0.3652 | 0.3378 | 0.3438 | 0.3591 | 0.3699 |
### 9. OPERATING COST

<table>
<thead>
<tr>
<th>Season Extension</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew Cost</td>
<td>376852</td>
<td>404084</td>
<td>431316</td>
<td>458548</td>
<td>485780</td>
<td>513012</td>
<td>540244</td>
<td>567476</td>
</tr>
<tr>
<td>Store &amp; Supply</td>
<td>21989</td>
<td>23363</td>
<td>24737</td>
<td>26112</td>
<td>27436</td>
<td>28860</td>
<td>30235</td>
<td>31609</td>
</tr>
<tr>
<td>Repair &amp; Maint</td>
<td>168651</td>
<td>179192</td>
<td>189733</td>
<td>200763</td>
<td>211971</td>
<td>223545</td>
<td>235434</td>
<td>247646</td>
</tr>
<tr>
<td>Insurance Cost</td>
<td>185833</td>
<td>197527</td>
<td>209222</td>
<td>225051</td>
<td>241421</td>
<td>258315</td>
<td>275760</td>
<td>293769</td>
</tr>
<tr>
<td>Overhead Cost</td>
<td>121765</td>
<td>122765</td>
<td>123765</td>
<td>124765</td>
<td>125765</td>
<td>126765</td>
<td>127765</td>
<td>128765</td>
</tr>
<tr>
<td>Towing Cost</td>
<td>20224</td>
<td>22213</td>
<td>23869</td>
<td>25710</td>
<td>27303</td>
<td>28539</td>
<td>29956</td>
<td>31362</td>
</tr>
<tr>
<td>Layup Cost</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>75000</td>
<td>25000</td>
<td>25000</td>
<td>10000</td>
<td></td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>537504</td>
<td>631809</td>
<td>673769</td>
<td>717747</td>
<td>759178</td>
<td>795471</td>
<td>837032</td>
<td>878298</td>
</tr>
<tr>
<td>Total Op. Cost</td>
<td>1557815</td>
<td>1655950</td>
<td>1751407</td>
<td>1853641</td>
<td>1953899</td>
<td>1999503</td>
<td>2101421</td>
<td>2188921</td>
</tr>
<tr>
<td>Annual Capital</td>
<td>2374943</td>
<td>2374943</td>
<td>2374943</td>
<td>2374943</td>
<td>2374943</td>
<td>2374943</td>
<td>2374943</td>
<td>2374943</td>
</tr>
<tr>
<td>Average Annual</td>
<td>3932758</td>
<td>4030893</td>
<td>4126350</td>
<td>4228584</td>
<td>4328842</td>
<td>4374446</td>
<td>4476364</td>
<td>4563864</td>
</tr>
<tr>
<td>Total Cargo</td>
<td>2179870</td>
<td>2323132</td>
<td>2442457</td>
<td>2575058</td>
<td>2689836</td>
<td>2778832</td>
<td>2880938</td>
<td>2982250</td>
</tr>
</tbody>
</table>

### 10. MEASURES OF MERIT

| RFR             | 1.804 | 1.735 | 1.689 | 1.642 | 1.609 | 1.574 | 1.554 | 1.530 |
| NPV (in $1000)  | 34151 | 37854 | 40810 | 44131 | 46895 | 49339 | 51680 | 54129 |
| CRF             | 0.2762 | 0.2545 | 0.3092 | 0.3256 | 0.3393 | 0.3514 | 0.3630 | 0.3752 |
IV. PRELIMINARY CONCLUSIONS

1. We have developed a logical mathematical model for predicting the economic characteristics of bulk carriers operating for any length of season on the Great Lakes. The model is versatile and can easily be made to handle all reasonable combinations of design variables, trade routes, cargoes, and financial arrangements.

2. We have also developed a computer program that incorporates the essential elements of the mathematical model described above. The computer program should prove to be a versatile and valuable tool quite aside from its application to extended season economics.

3. Several of the more important input figures are still only tentative. Consequently, any conclusions drawn from current output figures must also be only tentative.

4. Tables 11 and 12 indicate considerable economic advantage from an extended season even under the assumption of severe ice conditions. Thus, despite the caveat of conclusion 3, we may feel confident in predicting that winter operations will prove economically beneficial to the owners of Great Lakes ships. This benefit should eventually flow back to the public in the form of lowered costs of steel and steel products.

5. To make accurate and reliable economic projections with the model, we need further data on ice conditions, on ship speed and delays in ice, and on costs of ice strengthening. These topics merit high priority in future research and development.
APPENDIX I

THE NEW TAX LAW AND ITS EFFECT ON
THE ANNUAL COST OF CAPITAL RECOVERY

The new U.S. merchant marine act contains special tax treat-
ment for owners of U.S.-flag ships operating on the Great
Lakes. In effect, corporate income taxes will be waived on
any earnings that are set aside for the eventual construction
of replacement tonnage. Payments on shipbuilding loans will
be treated in like fashion. Many key details of the act have
not yet been interpreted. Nevertheless, we may reasonably ex-
pect that a shipowner who allocates all of his operating pro-
fits to the construction fund or to repay a bank loan, will pay
no income taxes during the initial years of operation of a new
ship. This tax-free status will presumably continue until the
cumulative amount deposited equals the initial investment. If
financing is through a long-term bank loan, the years required
to build the fund up to its limit may approach the useful life
of the ship.

Under the new law, then, shipowners will be able to make impor-
tant reductions in their annual costs of capital recovery.
This will result in lower costs of transport on the Great Lakes.
It will also stimulate marginal investments aimed at producing
future marginal returns. In other words, under the new law,
the added costs of making ships ice-worthy will be more easily
justified by the added incomes to be produced in future years.

We can analyze the impact of this new tax treatment by assuming
a uniform level of before-tax returns (A dollars per year), and
then determining the after-tax returns (A') both with and with-
out the special tax treatment. The task is complicated because
the tax exemptions are not uniform over the life of the ship;

- 103 -
APPENDIX I: THE NEW TAX LAW

depreciation plans, depreciable life, and interest paid on loans will all modify the relative values of the returns before and after tax.

We have purposely omitted consideration of President Nixon's proposed first-year 5% investment tax credit. If the proposal is adopted, it would strongly encourage bigger investments. That, in turn, would tend to favor increased levels of ice strengthening. See (20) for details on handling the tax credit.

1. **ANALYSIS UNDER PREVIOUS TAX PLAN**

Let us look first at the general situation before the new law went into effect. We shall make a number of standard simplifying assumptions:

1. The investment \((P)\) is made in a single payment upon delivery of the ship.
2. The annual before-tax returns \((A)\) are uniform throughout the economic life of the ship \((N)\).
3. A portion of the investment is financed from the owner's equity capital, the rest through a bank loan \((P_B)\) payable in uniform annual amounts \((A_B)\) at annual interest rate \((i_B)\) over a period of \(H\) years.
4. The tax rate is \(t\%\), the depreciation period for taxes is \(Q\) years, and straightline depreciation is used with zero disposal value.

We shall assume, further, that the bank loan period \((H)\) is shorter than the economic life of the ship \((N)\) but longer than the tax life \((Q)\). Actually, the latter assumption is not important; the final result comes out the same whether \(H\) is longer or shorter than \(Q\) (22).
APPENDIX I: THE NEW TAX LAW

Given all of these assumptions, we can show how the tax varies during each of the significant time periods shown in figure A1. This will allow us to relate returns before and after tax, because

\[ A' = A - \text{tax} \quad [A1] \]

We shall analyze the three time periods in reverse order, putting the simplest first. In period 3 there are no tax shields and the entire before-tax return is subject to tax:

\[ \text{Tax} = tA \]

\[ A' = A - \text{Tax} = A - tA = A(1 - t) \quad [A2] \]

During period 2, the annual interest \((I_B)\) paid on the bank loan is exempt from tax. This amount varies from year to year, but we shall make one more simplifying step and treat \(I_B\) as uniform and equal to the average annual amount.

\[ I_B = A_B - \frac{P_B}{H} \]

\[ I_B = (CR - I_B - H)P_B - \frac{P_B}{H} \]

\[ I_B = P_B \left( CR - I_B - H \right) - \frac{1}{H} \quad [A3] \]

Keeping this equation in mind, let us look at how \(I_B\) affects the tax:

Taxable income = \(A - I_B\)

\[ \text{Tax} = t(A - I_B) \]

\[ A' = A - \text{Tax} = A - t(A - I_B) \]

\[ = A - tA + tI_B \]

\[ = A(1 - t) + tI_B \quad [A4] \]
Fig. A1: Time Scale for Analysis Before New Tax Law

Fig. A2: Cash Flow Diagram Before New Tax Law
APPENDIX I: THE NEW TAX LAW

In period 1, both $l_B$ and the annual depreciation charge $\frac{P}{Q}$ reduce the tax base:

$$\text{Taxable income} = A - l_B - \frac{P}{Q}$$

$$\text{Tax} = t(A - l_B - \frac{P}{Q})$$

$$A' = A - \text{Tax} = A - t(A - l_B - \frac{P}{Q})$$

$$= A - tA + tl_B + \frac{tP}{Q}$$

$$= A(1 - t) + tl_B + \frac{P}{Q}$$  \[A5\]

We can summarize the solutions for $A'$ on a cash flow diagram as in figure A2.

In any measure of merit we may care to use, we shall need to find the present value of the after-tax returns ($A'$). To do this, it will be convenient to find the differences ($A$) between the $A'$ values during each of the time periods. This is easily done by inspection and the values are shown in figure A2.

If we now assume that we can predict the before-tax returns ($A$), we can find the net present value of our entire cash flow pattern as follows:

$$\text{NPV} = (SPW - i' - N)A(1 - t) + (SPW - i' - H)tl_B +$$

$$+ (SPW - i' - Q)\frac{P}{Q} - P$$  \[A6\]

In this case the interest rate ($i'$) is a minimum acceptable value dictated by management. Conversely, instead of assigning a value to the interest rate, we can by trial and error
find its one value that will make the net present value equal to zero. This derived value of \( i' \) is the DCF rate of return or yield. If NPV = 0, then we have:

\[
P = (SPW - i' - N)A(1 - t) + (SPW - i' - H)t_B + (SPN - i' - Q)t_P^P \quad \frac{Q}{Q} \tag{A7}
\]

If our measure of merit is required freight rate, then we must start with a specified target value for \( i' \) and find the corresponding required value of the before-tax returns (A). (This value of \( i' \) would normally be appreciably higher than used in NPV.) Solving equation A7 for A, we find:

\[
A = \frac{P - (SPW - i' - H)t_B - (SPW - i' - Q)t_P^P}{(SPW - i' - N)(1 - t)} \tag{A8}
\]

In summary thus far, we have developed equations by which we can quantify the profitability of long-term investments despite the complexities of bank loans and short tax depreciation periods. Let us illustrate this by using equation A8 to find the annual return (A) required to meet an owner's specified yield (\( i' \)) of 10% (based on total investment). Assume we have a $20 million ship with a useful life of 50 years, a tax life of 20 years, a tax rate of 48%, and a bank loan equal to half the investment, payable in uniform annual installments over 30 years at 6% interest. Recapitulating:

\[
\begin{align*}
A & = \text{unknown} \\
i' & = 10\% \\
P & = $20 \text{ million} \\
N & = 50 \text{ yr}
\end{align*}
\]
APPENDIX I: THE NEW TAX LAW

\[ Q = 20 \, \text{yr} \]
\[ t = 48\% \]
\[ P_B = \$10 \, \text{million} \]
\[ H = 30 \, \text{yr} \]
\[ I_B = 6\% \]

Before substituting these numbers into equation A8, we should solve equation A3 for the average annual interest paid to the bank \((I_B)\):\

\[ I_B = P_B \left( CR - I_B - H \right) \frac{-1}{H} \tag{A3} \]

\[ = 10M \left( CR - 6\% - 30 \right) \frac{-1}{30} \]

\[ = 10M \cdot 0.0726 - 0.0333 \]

\[ = 10M \cdot 0.0393 = 0.393M \]

\( M = \text{million} \)

Next, substituting known numbers into equation A8:

\[ A = \frac{20M - (SPW - 10\% - 30)(0.48) \cdot 0.393M - (SPW - 10\% - 20)(0.48) \cdot 20M}{(SPW - 10\% - 50)(1 - 0.48)} \]

\[ = \frac{20M - 9.425(0.48) \cdot 0.393M - (8.511)0.48}{9.911(0.52)} \]

\[ = \frac{20M - 1.777M - 4.085M}{5.154} = \frac{14.14M}{5.154} = 2.743M \]
APPENDIX I: THE NEW TAX LAW

Thus, the annual cost of capital recovery is $2.743 million. Adding the annual operating costs will give the average annual cost. Dividing that by the annual tons of cargo carried will give the required freight rate. While we have the annual cost of capital recovery in front of us, let us find the capital recovery factor before tax (CR) and compare it to the capital recovery factor after tax (CR′):

\[
CR = \frac{A}{P} = \frac{$2.743M}{$20M} = 0.137
\]

\[
CR' = (CR-10\%-50) = 0.1009
\]

\[
\frac{CR}{CR'} = \frac{0.137}{0.1009} = 1.36
\]

(The corresponding yields before and after tax would show the same 36% difference in relative magnitude.)

II. ANALYSIS UNDER NEW TAX PLAN

As mentioned at the start, taxes will now be waived on funds that are set aside for the eventual construction of replacement tonnage or that go to repay loans used to finance an existing ship. We can assume that most shipowners on the Great Lakes will want to handle their returns in a way that will free them completely from taxes during the initial years of the life of the ship. We shall assume also that the Treasury Department will permit funds to be deposited at such a rate, but will limit the cumulative amount in the fund to the initial cost of the ship. (These points among others remain to be interpreted.) We shall assume further that income from external investments made
APPENDIX I: THE NEW TAX LAW

with the funds will be handled in a way that will have no impact on the arrangements mentioned above.

Given the above suppositions, plus all of those discussed in the previous section, we now have four time periods to examine: the three that existed under the previous tax plan (see figure A1) plus a new initial period during which all discretionary income is put into the tax-deferred ship construction fund (TDSCF). The relationship between returns before and after tax are exactly the same as they were before except that during the new period 1 there are no taxes. The following table summarizes this:

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Span of Years</th>
<th>Returns Before and After Tax</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 to F</td>
<td>( A' = A )</td>
</tr>
<tr>
<td>2 (like old 1)</td>
<td>F to Q</td>
<td>( A' = A(1-t) + t\frac{B}{Q} )</td>
</tr>
<tr>
<td>3 (like old 2)</td>
<td>Q to H</td>
<td>( A' = A(1-t) + tB )</td>
</tr>
<tr>
<td>4 (like old 3)</td>
<td>H to N</td>
<td>( A' = A(1-t) )</td>
</tr>
</tbody>
</table>

In the table above, \( F \) is the number of years required to bring the deposits in the TDSCF up to the initial investment. In short,

\[
F = \frac{P}{D} \tag{A9}
\]

where

\( D \) = discretionary income during initial period of operation.

Figure A3 indicates the distribution of income during the initial period.
Fig. A3: Distribution of Annual Income During Initial Period (Under New Tax Law)

\[ D = \text{DISCRETIONARY AMOUNT, ALL TO TDSCF} \]
\[ A_B = \text{RETURN TO BANK} \]

\[ \text{DEPRECIATION} = \frac{P}{Q} \]
\[ \text{PAYMENT ON BANK} = P_B \]
\[ \text{INTEREST TO BANK} = \frac{H}{l_B} \]

TOTAL ANNUAL INCOME

TAXABLE INCOME = 0 \implies \text{TAX} = 0 \implies A' = A

A = \text{RETURN BEFORE TAX}

Fig. A4: Cash Flow Diagram Under New Tax Law
APPENDIX I: THE NEW TAX LAW

As we can see from Figure A3,

\[ D = A - A_B \]

Substituting into equation A9:

\[ F = \frac{P}{A - A_B} \]  \hspace{1cm} \text{(A10)}

or,

\[ F = \frac{P}{(CR)P - A_B} \]  \hspace{1cm} \text{(A11)}

where

\[ CR = \text{capital recovery factor before tax} \]

We can, as before, analyze the cash flow of figure A4 to find NPV, yield, or return before tax. To derive yield, for example, we set the investment equal to the present worth of the income:

\[ P = (SPW - i' - N)A(1-t) + (SPW - i' - H)tI_B + (SPW - i' - Q)t\frac{P}{Q} \]

\[ + (SPW - i' - F)t(A - \frac{P}{Q} - I_B) \]  \hspace{1cm} \text{(A12)}

Putting all terms that include A on the right side of the equation, we have:

\[ P - (SPW - i' - H)tI_B - (SPW - i' - Q)t\frac{P}{Q} = A(SPW - i' - N)(1-t) \]

\[ + (SPW - i' - F)t(A - \frac{P}{Q} - I_B) \]

\[ = A(SPW - i' - N)(1-t) + A(SPW - i' - F)t - (SPW - i' - F)t(\frac{P}{Q} + I_B) \]

\[ P - (SPW - i' - H)tI_B - (SPW - i' - Q)t\frac{P}{Q} + (SPW - i' - F)t(\frac{P}{Q} + I_B) = \]

\[ A \left[ (SPW - i' - N)(1-t) + (SPW - i' - F)t \right] \]
APPENDIX I: THE NEW TAX LAW

solving for A:

\[ A = \frac{P - (SPW^{-1} - H) + (SPW^{-1} - Q) \frac{P}{Q} \cdot (SPW^{-1} - F) \frac{P}{Q} + B}{(SPW^{-1} - N)(1-t) + (SPW^{-1} - F)t} \]

regrouping terms in the numerator:

\[ A = \frac{P - P(\frac{SPW^{-1} - Q}{Q} + P(\frac{SPW^{-1} - F}{Q} - t + B[(SPW^{-1} - H) - (SPW^{-1} - F)]}{(SPW^{-1} - N)(1-t) + (SPW^{-1} - F)t}} \]

and

\[ A = \frac{P - P \frac{t}{Q}[(SPW^{-1} - Q) + (SPW^{-1} - F)] + B[(SPW^{-1} - H) - (SPW^{-1} - F)]}{(SPW^{-1} - N)(1-t) + (SPW^{-1} - F)t} \]  \[ \text{[A13]} \]

If we divide both sides of the equation by the initial investment \( P \), we obtain the before-tax capital recovery factor.

\[ CR = \frac{1 - \frac{t}{Q}[(SPW^{-1} - Q) + (SPW^{-1} - F) + \frac{B}{P}[(SPW^{-1} - H) - (SPW^{-1} - F)]}{(SPW^{-1} - N)(1-t) + (SPW^{-1} - F)t} \]  \[ \text{[A14]} \]

Thus, if we start with an owner's specified yield \( i' \), we can use equation A14 to find the required capital recovery factor before tax (CR) and the corresponding uniform annual return before tax (A). This is not easy, however, because both numerator and denominator contain the term \( (SPW^{-1} - F) \); and this means that we must know how many years are in period \( F \) before we can solve for \( A \). But, if we turn to equation A13 we see that to find \( F \), we must first know that which we set out to find in the first place, namely CR. All of which means that we have met ourselves coming back and so must use trial-and-error procedures to solve equation A14 for CR.
APPENDIX I: THE NEW TAX LAW

We can illustrate this by reworking the numerical example of section 1. The object is to find the required uniform annual return before tax (A), given the new tax law plus the other inputs, namely:

- Specified yield \( i \) = 10%
- Investment \( P \) = $20 million
- Economic life \( N \) = 50 yr
- Tax life \( Q \) = 20 yr
- Tax rate \( t \) = 48%
- Bank loan \( P_B \) = $10 million
- Bank loan period \( H \) = 30 yr
- Bank interest rate \( i_B \) = 6%
- Annual interest payments to bank \( I_B \) = $0.393 million

If we substitute those numbers into equation A14, we have:

\[
CR = \frac{1 - 0.48 \left( \frac{SPW-10\%-20}{20} - \frac{SPW-10\%-F}{20} \right) - 0.48 \frac{0.393}{20}}{(SPW-10\%-50)0.52 + (SPW-10\%-F)0.48}
\]

\[
= \frac{1 - 0.024 \left( 8.514 - (SPW-10\%-F) \right) - 0.00943 \left( 9.427 - (SPW-10\%-F) \right)}{5.16 + 0.48(SPW-10\%-F)}
\]

\[
= \frac{0.707 + 0.0334(SPW-10\%-F)}{5.16 + 0.48(SPW-10\%-F)} \tag{A15}
\]

Now we must make a guess at CR in order to find a trial value of \( F \). Our first intuitive guess is \( CR = 11\% \). Turning to equation A11:

\[
F = \frac{P}{(CR)P - A_B} \tag{A11}
\]
APPENDIX I: THE NEW TAX LAW

Before going on, we must calculate the annual return to the bank ($A_B$):

$$A_B = (CR - i_B - H)P_B$$  \[ A16 \]

In our case:

$$A_B = (CR - 6\% - 30) \times 10M$$

$$A_B = 0.0726 \times 10M = 0.726M$$

so

$$F = \frac{\$20M}{0.11\$20M - 0.726M} = \frac{\$20M}{\$2.2M - 0.726M} = \frac{\$20M}{1.474M}$$

$$F \approx 13.5 \text{ years}$$

From interest tables:

$$(CR - 10\% - 13.5) = 7.23$$

Substituting into equation A15:

$$CR = \frac{0.707 + 0.0334(7.23)}{5.16 + 0.48(7.23)} = \frac{0.707 + 0.241}{5.16 + 3.46}$$

$$CR = \frac{0.948}{8.62} = 0.11$$

Error = intuitive CR-derived CR

$$= 0.11 - 0.11 = 0$$

(a fortunate coincidence)
APPENDIX I: THE NEW TAX LAW

We can now compare annual costs of capital recovery corresponding to the specified yield of 10% both before and after the new tax law:

<table>
<thead>
<tr>
<th></th>
<th>Before New Law</th>
<th>After New Law</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>0.16</td>
<td>0.11</td>
</tr>
<tr>
<td>CR'</td>
<td>0.1009</td>
<td>0.1009</td>
</tr>
<tr>
<td>CR*</td>
<td>1.59</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Thus, under the old law, the tax required a 59% increase in annual costs of capital recovery whereas it now requires an increase of less than 10%.

In further illustration of the benefits of the new tax law, we have studied other typical financing schemes for the same $20 million ship dealt with in the foregoing sections. Given all of the aforementioned assumptions, we found the following before-tax capital recovery factors:

<table>
<thead>
<tr>
<th></th>
<th>Before New Law</th>
<th>After New Law</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-equity investment</td>
<td>0.154</td>
<td>0.115</td>
<td>1.34</td>
</tr>
<tr>
<td>50% bank loan</td>
<td>0.137</td>
<td>0.110</td>
<td>1.24</td>
</tr>
<tr>
<td>100% bank loan</td>
<td>0.120</td>
<td>0.105</td>
<td>1.14</td>
</tr>
</tbody>
</table>

The corresponding annual costs of capital recovery would be:

<table>
<thead>
<tr>
<th></th>
<th>Before New Law</th>
<th>After New Law</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-equity investment</td>
<td>$3,080,000</td>
<td>$2,300,000</td>
<td>1.34</td>
</tr>
<tr>
<td>50% bank loan</td>
<td>$2,740,000</td>
<td>$2,200,000</td>
<td>1.24</td>
</tr>
<tr>
<td>100% bank loan</td>
<td>$2,400,000</td>
<td>$2,100,000</td>
<td>1.14</td>
</tr>
</tbody>
</table>
APPENDIX I: THE NEW TAX LAW

Capital costs make up roughly two-thirds of the total cost of water transport. It is therefore obvious from the figures cited above that the new tax law should have a pronounced tendency to lower shipping costs on the Great Lakes.
APPENDIX II

SPEED AND POWER IN ICE

Estimating the powering requirements for Great Lakes bulk carriers operating in ice is a difficult task owing to the almost complete lack of full scale observation, model measurements, and theoretical foundations.

A semi-empirical method of power estimation has been developed for the present study. A few experiences with bulk carriers operating in ice were examined. These included observations in the Baltic fleets and the voyage records of a few Great Lakes ships during the past year's extended season. However, since these data are very crude and meager, and limited to just a few ship types and ice conditions, we must rely on theory for representing the parametric influences of hull shape, power plant and propulsion system, as well as ice condition.

Such a theory can be deduced by suitable adaptation of methods originally developed for different ships and conditions. When at a later stage direct test results for Great Lakes ships become available, they can be used to further substantiate the present estimating method and to improve the accuracy of prediction.

Different powering estimates are derived for ships continuously breaking ice and for their operation in broken ice in the track of an icebreaker or another ship, or in open pack ice.

1. **ICE PRESSURE COEFFICIENTS**

Shimanshkij (10) first introduced a set of ice pressure or
force coefficients in order to establish certain "conditional standards of ice qualities of a ship." His classical definitions are still adhered to in evaluating the relative effectiveness of hull shapes in ice.

His basic hypotheses simply states that the magnitude of the normal ice pressure in the ice belt, in essence in the waterline, equals a uniform pressure $p$, in the direction of motion multiplied by the direction cosine between the normal to the surface and the motion vector.

\[ p_N = p \cos a \approx p n_x \]

\[ = p \frac{\tan a}{\sqrt{1 + \tan^2 a + \tan^2 b}} \]

where

- $a$ = angle between the tangent to the waterline and the $x$-direction
- $b$ = angle between the tangent to a transverse frame and the $y$-direction
The unit normal vector to the surface is

\[ \hat{n} = \frac{\tan a}{\sqrt{1 + \tan^2 a + \tan^2 b}} \hat{i} + \frac{\tan b}{\sqrt{1 + \tan^2 a + \tan^2 b}} \hat{k} \]

The components of the pressure $p_N$ are, nondimensionally

\[ \hat{p}_N = \frac{p_N}{p} \cdot \hat{n} = \frac{\tan^2 a}{1 + \tan^2 a + \tan^2 b} \hat{i} + \frac{\tan a}{1 + \tan^2 a + \tan^2 b} \hat{j} + \frac{\tan a \tan b}{1 + \tan^2 a + \tan^2 b} \hat{k} \]

The total force over one half of the forebody is obtained by integrating the components of this pressure over

\[ ds = \sqrt{1 + \tan^2 a} \, dx \] along the waterline, from bow, $x_B$, to maximum beam at $L_x$, as follows,

\[ \frac{P_x}{p} = \frac{L_x}{x_B} \frac{\tan^2 a \sqrt{1 + \tan^2 a}}{1 + \tan^2 a + \tan^2 b} \, dx \]

\[ \frac{P_y}{p} = \frac{L_x}{x_B} \frac{\tan a \sqrt{1 + \tan^2 a}}{1 + \tan^2 a + \tan^2 b} \, dx \]


\[ \frac{P_z}{P} = \sqrt{\frac{\tan a \tan b \sqrt{1 + \tan^2 a}}{1 + \tan^2 a + \tan^2 b}} \int_{x_B}^{L_x} \, dx \]

The force in the \( x \)-direction equals the thrust \( T \), reduced by the thrust deduction effect \( t \). In algebraic form, \( 2P_x = T(1-t) \). It is of interest to define

\[ e_1 = \frac{P_z}{P_x} = \frac{\sqrt{\int_{x_B}^{L_x} \frac{\tan a \tan b \sqrt{1 + \tan^2 a}}{1 + \tan^2 a + \tan^2 b} \, dx}}{\sqrt{\int_{x_B}^{L_x} \frac{\tan^2 a \sqrt{1 + \tan^2 a}}{1 + \tan^2 a + \tan^2 b} \, dx}} \]

\[ e_2 = \frac{P_y}{P_x} = \frac{\sqrt{\int_{x_B}^{L_x} \frac{\tan a \sqrt{1 + \tan^2 a}}{1 + \tan^2 a + \tan^2 b} \, dx}}{\sqrt{\int_{x_B}^{L_x} \frac{\tan^2 a \sqrt{1 + \tan^2 a}}{1 + \tan^2 a + \tan^2 b} \, dx}} \]

These coefficients were originally introduced by Shimanskij. They measure the fraction of the axial force \( P_x \) (proportional to thrust) that is converted by the hull shape into vertical \( (P_z) \) and lateral \( (P_y) \) force action.

Note that similar coefficients were also used by Melberg, et al. (13). However, there are several misprints in their equations 4 and 5.
APPENDIX II: SPEED AND POWER IN ICE

The table below gives a few examples for $e_1$ and $e_2$ calculated by Shimanskij.

<table>
<thead>
<tr>
<th>Ship</th>
<th>$e_1$</th>
<th>$e_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>24,000 HP icebreaker</td>
<td>1.9</td>
<td>3.13</td>
</tr>
<tr>
<td>12,000 HP icebreaker</td>
<td>2.17</td>
<td>3.40</td>
</tr>
<tr>
<td>J. Stalin</td>
<td>2.03</td>
<td>3.25</td>
</tr>
<tr>
<td>Ermak</td>
<td>2.41</td>
<td>3.52</td>
</tr>
<tr>
<td>Timber freighter</td>
<td>0.33</td>
<td>1.83</td>
</tr>
<tr>
<td>Timber freighter</td>
<td>0.54</td>
<td>2.28</td>
</tr>
<tr>
<td>Timber freighter</td>
<td>0.80</td>
<td>2.71</td>
</tr>
<tr>
<td>Far East cargo ship</td>
<td>0.41</td>
<td>2.34</td>
</tr>
</tbody>
</table>

II. RESISTANCE FORMULAS FOR CONTINUOUS-MODE ICEBREAKING

The breaking of solid sheets of ice by a ship is a complex physical process in which many different kinds of energy losses are involved. There is a fair amount of literature on the subject of resistance in ice, mainly for icebreakers. However, only recently, especially in the work by Kashteljan, et al. (II), was there any systematic attempt made to split the continuous-mode ice resistance into its physical components according to the categories of energy losses. This, however, is indispensable for any meaningful extrapolation of test results to other ship types and ice conditions. The approach of
APPENDIX II: SPEED AND POWER IN ICE

Kashteljan, et al. was also adopted, and indeed substantially improved, in recent U.S. Coast Guard icebreaker design work by Melberg, Lewis, Edwards and other (12 and 13).

Kashteljan's ice resistance equation reads (resistances in metric tons):

\[ R_{ICE} = R_1 + R_2 + R_3 + R_4 \]
\[ = k_1 B m_0 s h + k_2 B m_0 g_i h^2 \]
\[ + k_4 B^4 \frac{h V}{e_2} + R_4 \]

where

- \( R_1 \) = icebreaking resistance, corresponding to work done in breaking the ice.
- \( R_2 \) = resistance due to submergence of broken ice, turning the broken ice, and other effects proportional to the weight of the broken ice.
- \( R_3 \) = resistance due to cleaning broken ice out of the channel laterally by accelerative forces.
- \( R_4 \) = water resistance, friction and wave, computed approximately as if ice was not present, which appears permissible at low speed.
- \( B \) = ship beam, meters
- \( s \) = ice strength, metric tons/meter²
- \( h \) = ice thickness, meters
- \( m_0 = 1 + (1/e_1) \) = Kashteljan's vertical ice force coefficient (see comments below).
- \( g_i \) = specific weight of ice, metric tons/meter³
- \( e_2 \) = Shimanshkiij's lateral ice force coefficient
- \( V \) = ship speed, meters/sec.

The coefficients \( k_1, k_2, k_3, k_4 \) were determined by Kashteljan, et al. (11) from model and full scale tests of the
Russian icebreaker \textit{Ermak}:

\begin{align*}
k_1 &= 0.004 \\
k_2 &= 3.6 \\
k_3 &= 0.25 \\
k_4 &= 1.65
\end{align*}

The coefficient \( m_0 = 1 + (1/e_1) = 1 + (P_x/P_z) = (P_x + P_z)/P_z \) is intended as a measure of hull form efficiency in generating vertical forces, but it is defined in a rather arbitrary fashion. It would seem that \((P_x/P_z)\) would serve this purpose better. However, since the coefficients \( k_1 \) to \( k_4 \) were derived from the \textit{Ermak} tests with \( m_0 \) appearing in the first two terms, we must stick to all of Kashteljan's definitions in the context of his equation.

Kashteljan's equation was further criticized by Lewis and Edwards (12), who rederived the resistance expressions from slightly different physical assumptions and arrived at the modified formulation:

\[ R_{\text{ICE}} = R_1 + R_2 + R_3 + R_4 \\
= C_0 s h^2 + C_1 g_i B h^2 + C_2 r_i B h V^2 + R_4 \]

where

\[ r_i = \text{mass density of ice}, \]
\[ C_0, C_1, C_2 = \text{coefficients determined experimentally are as described before}. \]

Comparison in the following table shows some fundamental differences in the exponents of \( h, B, \) and \( V. \)

<table>
<thead>
<tr>
<th>Resistance Component</th>
<th>Kashteljan, et al.</th>
<th>Lewis and Edwards</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 )</td>
<td>( k_1 B m_0 s h )</td>
<td>( C_0 s h^2 )</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>( k_2 B m_0 g_i h^2 )</td>
<td>( C_1 g_i B h^2 )</td>
</tr>
<tr>
<td>( R_3 )</td>
<td>( k_3 B 1.65 h V / e_2 )</td>
<td>( C_2 r_i B h V^2 )</td>
</tr>
</tbody>
</table>

- 125 -
APPENDIX II: SPEED AND POWER IN ICE

Although in the physical reasoning we are largely in agreement with Lewis and Edwards' assumptions, we cannot use their equations for our powering estimates because suitable values for the coefficients $C_0$, $C_1$, $C_2$ are not known for bulk carriers. Moreover, a dependence on hull form coefficients is not shown in their expressions.

Therefore, we shall seek a compromise between the two approaches, relying on Kashteljan for certain relative magnitudes, and on Lewis and Edwards for the systematic tendencies.

III. COMPROMISE FORMULA FOR CONTINUOUS-MODE ICE RESISTANCE

A. From Kashteljan's equation for zero speed, we derive the ratio of $R_1$ and $R_2$:

$$\frac{R_1}{R_2} = \frac{k_1 s}{k_2 h g_i}$$

B. We assume from limited operating data of Great Lakes bulk carriers that the limiting ice thickness these present ships can overcome is $h = 2$ ft. The thrust delivered in this condition, and hence the limiting resistance, can be estimated for the given propulsion plant as discussed later. This resistance can be equated to Kashteljan's zero speed prediction

$$R_1 + R_2 = m \cdot B(k_1 s h + k_2 g_i h^2),$$

where the coefficient

$$m = A_0/e_1$$

was introduced to allow adaptation of Kashteljan's equation to bulk carrier experience.
APPENDIX II: SPEED AND POWER IN ICE

Shimanskij's coefficient $e_1$ can be found for the given bulk carrier hull form, so that we can solve for $A_0$.

C. Similar to Lewis and Edwards we define

$$R_1 = C_0 s B h^2 \cdot m$$
$$R_2 = C_1 g_i B h^2 \cdot m$$

and derive the coefficients by equating these expressions to the corresponding ones by Kashteljan:

$$C_0 = \frac{k_1}{h}$$
$$C_1 = k_2$$

D. The terms $R_1$ and $R_2$ from section C may be combined into

$$R_1 + R_2 = m B h^2 C_0 s \left( 1 + \frac{C_1 g_i}{C_0 s_o} \cdot \frac{s_o}{s} \right)$$

with

$$\frac{C_1 g_i}{C_0 s_o} = \frac{R_2}{R_1} = \frac{k_2 h g_i}{k_1 s_o}$$

from section A, and $s_o = standard\ reference\ ice\ strength$

$s = actual\ ice\ strength$

The ratio $s/s_o$ is a function of ice temperature and other ice condition factors, and will be given in the data base.

E. Discussion:

The expression for the zero speed ice resistance derived under section D is somewhat provisional. It presumes (section A) that bulk carriers will have the same percentage ratio of $R_1$ and $R_2$ as did the icebreaker Ernak for which Kashteljan's coefficients were derived.
APPENDIX II: SPEED AND POWER IN ICE

Further, it implies to a degree that the mechanism of breaking ice by the bulk carrier is still essentially vertical bending as in the icebreaker. In reality, this is doubtful because shear, cleavage and buckling failure of the ice sheet may play a greater part with the blunt bulk carrier bow. Further efforts must be undertaken to determine the actual failure mechanisms for ice being cut by blunt bows.

Meanwhile, the use of the expression of section D does not necessarily imply the same type of ice sheet failure Kashteljan envisioned, since the coefficient \( m \) was introduced to reach agreement with actual bulk carrier ice cutting performance. All we assume by using the above equation is that the dependence on \( B, h, \) and \( s \) has the same functional character as deduced by earlier investigators.

In summary, we have deduced a parametric equation for the zero speed ice resistance based on the physical assumptions by Kashteljan and Lewis and Edward. This equation is adapted to direct observation and bulk carrier operating practice by means of input information on only three elements:

* The limiting ice thickness the ship can break.
* The ratio of ice cutting to ice submergence resistance.
* The dependence of ice strength on temperature and seasonal condition.

F. The Speed Dependent Component of Ice Resistance

Part of the ice resistance depends on ship speed. In cleaning the broken ice out of the ship's channel, the ice floes have to be moved faster as ship speed increases.
APPENDIX II: SPEED AND POWER IN ICE

and the kinetic energy imparted to them in their lateral and rotational motion is also raised. To represent this resistance component, we shall follow Kashteljan, et al. (11)

\[ R_3 = 0.25B^{1.65} \frac{hV}{e_2} \]

Although we share the physical reservations of Lewis and Edwards, we have no other quantitative relation which contains the hull shape influence \((e_2)\). At low velocity this term is obviously dominated by the other components of ice resistance, and at high ship speeds the entire ice resistance becomes small relative to the water resistance, which relaxes the accuracy requirements on this term.

IV. ICE RESISTANCE IN BROKEN ICE

The complex physical process of a ship moving through broken ice in the track of an icebreaker or another vessel or through open pack ice has been studied by numerous authors (11, 14--19).

Bronnikov's (18) approach to estimating the resistance of cargo ships going through pack ice appears to be best suited for the present purpose. Bronnikov proposes an equation expressing the pure ice resistance in terms of the parametric influences of ice condition and principal ship characteristics.

\[
R_{ip} = (R_{ip})_0 \left( \frac{D}{D_0} \right)^s \left( \frac{t}{t_0} \right)^m \left( \frac{S}{S_0} \right)^n \left( \frac{d}{d_0} \right)^p \left( \frac{L/B}{L/B_0} \right)^q \left( \frac{C_{BO}}{C_{BO}} \right)^r \left( \frac{(L/B)_o}{L/B} \right)^k
\]
APPENDIX II: SPEED AND POWER IN ICE

where the subscript zero denotes a standard arctic cargo ship, which was tested by Bronnikov, and the quantities without subscript are for the actual ship in question.

All quantities are in metric units and are defined as follows:

\[ R_{ip} = \text{pure ice resistance, metric tons} \]
\[ D = \text{displacement, metric tons} \]
\[ t = \text{ice thickness, meters} \]
\[ S = \text{ice state, surface coverage in percent} \]
\[ d = \text{draft of vessel, meter} \]
\[ L, B = \text{length, beam of vessel} \]
\[ C_B = \text{block coefficient} \]
\[ B_1 = \text{width of channel or lead in pack ice} \]

The pure ice resistance of the standard reference vessel, \((R_{ip})_o\), is given in Table 5 of Bronnikov's article (18) for Froude numbers, \(F_n\), from 0.075 to 0.275, and may be approximated by

\[ (R_{ip})_o = 977 \ F_n^{1.42} \]

The following data belong to this standard case:

\[ D_o = 10920 \text{ tons} \]
\[ t_o = 0.8 \text{ meter} \]
\[ S_o = \text{state 8 = 0.8} \]
\[ d_o = 7.3 \text{ meters} \]
\[ (L/B)_o = 6.6 \]
\[ C_{Bo} = 0.65 \]
\[ (B_1/B)_o = 15 \]

Bronnikov found the values of the exponents for his ice resistance equation from model tests as

\[ s = 1 - \frac{m + p}{3} \]
\[ m = 0.267 \ F_n^{-0.67} \ - 130 - \]
APPENDIX II: SPEED AND POWER IN ICE

\[ n = 0.785 F_n^{-0.493} \]
\[ p = 1.65 F_n^{0.42} + 0.35 \]
\[ q = 1.93 F_n^{0.42} - 0.60 \]
\[ r = 32.4 F_n^{2.27} + 1.25 \]
\[ k = 0.034 F_n^{-1.31} \]

The values of \( D, t, d, L/B \) will be derived from the actual ice conditions and bulk carrier characteristics. The surface coverage and width of channel ratio in the track of an icebreaker or other bulk carrier may be reasonably estimated as

\[ S = 0.8 \]
\[ B_1/B = 1.5 \]

This summarizes the relationships for the estimation of broken ice resistance, which will be checked for consistency with other available reference data.

V. INSTALLED SHAFT HORSEPOWER

In existing bulk carriers the installed design shaft horsepower is known, and the actual values can be given as inputs to the present program.

For ship conversions or new designs, various levels of ice adaptation will be assumed following the Finnish ice rules (6) whose standard ice classes are becoming universally adopted rapidly. The powering requirements under these classes are as follows:
APPENDIX II: SPEED AND POWER IN ICE

<table>
<thead>
<tr>
<th>Ice Class</th>
<th>Minimum Required SHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA Super</td>
<td>0.40 Δ + 1,500, but not more than 25,500</td>
</tr>
<tr>
<td>IA</td>
<td>0.35 Δ + 1,000, but not more than 22,000</td>
</tr>
<tr>
<td>IB</td>
<td>0.30 Δ + 500, but not more than 18,500</td>
</tr>
<tr>
<td>IC</td>
<td>0.25 Δ , but not more than 15,000</td>
</tr>
</tbody>
</table>

Δ = displacement in metric tons.

The required SHP is reduced by 10 percent if the ship is fitted with a controllable pitch propeller. The astern power for steam turbines must be at least 70 percent of the actual SHP.

It will be assumed that the full installed horsepower is used in the ice whenever feasible, i.e. except in cases of speed restrictions or voluntary slow-downs.

The effectiveness of the Finnish ice power margins will be investigated by the program, which will predict smaller speed losses in ice for the stronger power plants.

VI. SPEED ESTIMATION

The estimation of the obtainable speed of a given ship with a given power plant and propeller, operating in given ice conditions, will be based on the following known inputs:

*Characteristic curves for the main propulsion engine of the available shaft horsepower against RPM. These curves
APPENDIX II: SPEED AND POWER IN ICE

will depend on the type of engine:
Steam turbine
Diesel-electric drive

*Formulas for the total resistance $R_T$, including the ice resistance, from the previous sections. This will yield the required thrust ($T_{REQ}$) at a given speed, $V_s$:

$$ T_{REQ} = \frac{R_T}{1-t} $$

*Equations for the propeller performance in terms of $K_T$, $K_Q$ based on the Troost B4.70 series.

For this purpose, the pitch ratio $P/D_p$ will be a known input for existing ships, whereas it will be optimally selected for summer operating conditions in converted or new ships. In controllable pitch propeller installations the pitch will be adjusted at reduced speed in ice in order to keep the full power available at all times.

In each case, the unknown ship speed, $V_s$, and propeller revolutions can be found by trial and error from the condition that the available thrust must equal the required one in the steady state. A step-by-step procedure may be outlined as follows:

1. Estimate a ship speed.
2. Calculate the total resistance and required thrust at this speed.
3. Estimate the RPM of the propeller.
4. Find the advance ratio

$$ J = \frac{V_A}{N \cdot D_p} = \frac{V_s(1-w)}{N \cdot D_p} $$

where
APPENDIX II: SPEED AND POWER IN ICE

\[ N = \text{rev per second} \]
\[ V_s = \text{ship velocity in feet per second} \]
\[ D_p = \text{propeller diameter in feet} \]
\[ w = \text{wake fraction} \]

5. Calculate \( K_Q \) from regression equation for B4.70 propeller

6. Calculate horsepower absorbed by propeller
\[ P_s = C \cdot K_Q \cdot rN^3 \cdot D_p^5 \]

where
\[ C = \text{conversion constant, and compare to horsepower delivered by engine at the same RPM, using engine characteristics.} \]

7. If the propeller horsepower is less than engine horsepower, increase RPM estimate, and vice versa, and return to step 3. Iterate until agreement is satisfactory.

8. For final J-value calculate \( K_T \) from regression equation, and solve for propeller thrust
\[ T = K_T \cdot rN^2 D_p^4 \]

9. Allow for thrust loss of propeller in ice by a percentage reduction: say about 10 percent in an average case in reference to Figures 3 and 4 of Enkvist and Johansson (23). This furnishes the available thrust \( (T_{AV}) \) in ice
\[ T_{AV} = 0.9 \cdot K_T \cdot rN^2 D_p^4 \]

10. If the available thrust is below the required thrust, reduce speed estimate and return to step 1. Iterate until agreement is satisfactory. If at zero speed still not enough thrust is available,
APPENDIX II: SPEED AND POWER IN ICE

conclude ship is stuck.

11. For final condition, return \( V_s, N, P_s(SHP), T. \)

In the case of controllable pitch propellers, steps 3 through 7 should be repeated several times for different settings of \( P/D_p \) within a reasonable range. In connection with step 8 the highest thrust and best pitch setting must then be selected. This procedure presumes that the controllable pitch propeller performance can be approximated closely enough by the fixed blade B4.70 series. Further, a cavitation check should be added at a later stage.
APPENDIX III

ICE STRENGTHENING AND STEEL WEIGHS

In the present investigation, we assume that Great Lakes ships are to be reinforced or designed according to the Finnish Ice Class Rules (6).

There are four classes in the ice rules:

<table>
<thead>
<tr>
<th>Class</th>
<th>Ice Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA - Super</td>
<td>extreme ice</td>
</tr>
<tr>
<td>IA</td>
<td>severe ice</td>
</tr>
<tr>
<td>IB</td>
<td>medium ice</td>
</tr>
<tr>
<td>IC</td>
<td>light ice</td>
</tr>
</tbody>
</table>

The rules specify that the ship's hull (shell and framing) around the ice line be strengthened to withstand the additional pressure produced by ice. As the pressure varies from bow to stern, the ice belt of the ship is divided into three regions as shown below.
APPENDIX III: ICE STRENGTHENING

The vertical extension of the belt to be strengthened for ice is given as a function of the ice class as well as the ice region described above.

Scantlings of frames and shell plating are governed by the pressure between the ship's hull and the ice. This pressure is assumed to be a function of the ship's installed horsepower and displacement.

Although converting an existing ship into an ice class ship (machinery replacement included) is not always economically feasible, such a possibility is not ruled out in the present parametric study.

R.A. Stearn, Inc., and Marine Consultants and Designers were employed as consultants to estimate the extra weight and the corresponding costs to ice-strengthen the Great Lakes ships for all four classes, using the Finnish Rules.

The figures supplied by R.A. Stearn are based on the assumption that the cost for converting an existing ship to an ice class type, will be the same as the additional cost needed to ice strengthen a new ship for the same ice class type.

Marine Consultants and Designers investigated mainly the costs necessary to adapt (while still in the design stage) a 1000-ft Great Lakes bulk carrier to various ice class ships.

Optimization techniques may be applied to obtain the least amount of steel (plate and stiffeners) necessary to ice-strengthen a ship. It is however, of second order of importance and will not be included. The data provided by the consultants are considered adequate from a parametric point of view, and are used in the present study.
APPENDIX III: ICE STRENGTHENING

1. TWO ICE-BELT CONCEPT

According to the Finnish ice regulations, the vertical extension of the ice belt is to be as shown below:

<table>
<thead>
<tr>
<th>Ice Class</th>
<th>Vertical Extent of Ice Belt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A-Super:</td>
<td>from 750mm above LWL to 600mm below BWL</td>
</tr>
<tr>
<td>1A:</td>
<td>from 600mm above LWL to 500mm below BWL</td>
</tr>
<tr>
<td>1B&amp;IC:</td>
<td>from 500mm above LWL to 500mm below BWL</td>
</tr>
</tbody>
</table>

In the above, LWL refers to the loadline in the loaded condition, BWL in the ballast condition.

In terms of total ice belt reinforcing plate width, $b_w$ in ft, we have for:

<table>
<thead>
<tr>
<th>Ice Class</th>
<th>$b_w$ formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A-Super:</td>
<td>$b_w = (LWL-BWL) + 4.43$</td>
</tr>
<tr>
<td>1A:</td>
<td>$b_w = (LWL-BWL) + 3.61$</td>
</tr>
<tr>
<td>1B&amp;IC:</td>
<td>$b_w = (LWL-BWL) + 3.28$</td>
</tr>
</tbody>
</table>

Thus the smallest width of plate that would need reinforcing would vary between 3.28 to 4.43 ft, i.e. $(LWL-BWL) = 0$.

One way to accomplish the latter condition is to provide ballast capacity equal to the cargo deadweight. This will allow one to keep the ship moving always loaded at the same water line. The required maximum ice belt width will in this case always be less than 4.50 ft.

Great Lakes bulk carriers in general travel either fully loaded or in a relatively light ballast condition. As a result there are two major water lines to be considered. Thus, if $b_w$ from the formulas above exceeds twice the constant term (i.e. 6.56 ft to 8.83 ft depending on the ship's ice class), two separate narrow ice belts could be used to provide more economically all the protection the hull needs.
APPENDIX III: ICE STRENGTHENING

For example if a ship of $(LWL-BWL) = 12$ ft is to be reinforced for ice class 1B, then the saving in the area of thicker plating will be

\[
\frac{(12 + 3.28) - (3.28 \times 2)}{12 + 3.28} = 56.7\% \]

There will also be some savings in the framing requirements of the ship but not quite to the same degree as the plating.

The concept of two separate ice belts merits consideration in future studies.
APPENDIX IV
FLOW CHART

FLOW CHART ANNOTATION

Input Data

Main Routine

Checking

Subroutine

* Subroutine with Other Subroutines

Final Results
APPENDIX IV: FLOW CHART

A

Call FREBOD
Calculate Required Freeboard

USCG
Loadline Reg.

Call CHECKI
Check Design Constraints

Length, Beam
Draft Limit

Design
Constraints
Violated?

C Yes

No

B

SHP
Known?

No

Call *POW
Calculate SHP

Yes

Call ICECHK
Calculate Required Shaft Horsepower for Desired Ice Class

Ice Rule
Power Req. for Fixed Blade or C.P. Propeller

D

- 143 -
APPENDIX IV: FLOW CHART

D

Ice Powering Req. O.K. ?

No

Calculate the Ship Speed with Min. Reg. SHP for Ice Class

Yes

Call WEIGHT Calculate the Weight of Hull, Outfitting & Machinery

Call ADDWGT Calculate the Weight of Hull, Outfitting & Machinery

Conversion

New Ship

Call CONCST Calculate Cost for Conversion

Conversion Cost Data

- 144 -

Call SPCOST Calculate the Shipbuilding Cost

Shipbuilding Cost Data & Ice Modification Cost
APPENDIX IV: FLOW CHART

E

Call ADDSCT
Calculate the Additional Cost for Self Unloader Bow Thruster, C.P. Propeller

Calculate Total Ship's Price

F

Ship Speed Faster Than Channel Restricted Speed?

No

Yes

Estimate the Partial Power in the Restricted Area

Call EXTW
Calculate the Weights of Selfunloading Equip., Bow Thruster and C.P. Propeller

Calculate Ship's Light Steel Weight & Deadweight

G

- 145 -
APPENDIX IV: FLOW CHART

G

Call FUEL
Calculate Fuel Consumption Rate for Full and Partial SHP

Calculate the Operating Drafts for Each Freeboard Season

Call SUMVOY
Calculate the Voyage Time, Running Time, Delay Time

Trade Route Information

Calculate the Number of Voyages During Each Freeboard Season

Operating Season Extended?

No

Yes

Call *WINVOY
Calculate the Voyage Time, Number of Voyages During Ice Season

H
APPENDIX IV: FLOW CHART

Call VARWGT
Calculate Ship's Variable Weights

Calculate Ship's Payload During Each Freeboard Season

Design is to be Optimized?

Yes

Call SVOL
Calculate Ship's Payload Volume, Stowage Factor

Ship's Stowage Factor Less than Cargo Stowage Factor?

No

Yes

Calculate Net Payload

J
APPENDIX IV: FLOW CHART

J

Call STABLE
Calculate Ship's GM and Rolling Period

Call OPCOST
Calculate Crew Cost, Repair and Maint. Cost, Fuel Cost, etc.
During Regular and Ice Season

Regular & Ice Season Operating Cost Data

Calculate the Amount of Cargo Transported During Regular and Ice Season

Calculate the Annual Capital Cost

Calculate the Average Annual Cost During Regular Season and Each Extension Period

Calculate the Annual Return Before Tax

K
APPENDIX I

K

Calculate RFR During Regular Season and Each Extension Season

New Construction

Calculate the Net Present Value and Capital Recovery Factor During Regular and Each Extension Season

Conversion

Calculate the Differential Net Present Value and Capital Recovery Factor During Each Extension Season

C

Return to Main Program
**APPENDIX IV: FLOW CHART**

*POW
Calculate Ship's SHP

Call POWER
Estimate the Ship's Resistance Coeff, (Cr, Cf) from Regression Result

Calculate Total Ship's Resistance

Propulsive Efficiency Known?

Yes

No

Call *PEFF
Calculate Propulsive Efficiency

Caculate Ship's Shaft Horsepower

Return

- 150 -
*PEFF
Calculate Ship's Propulsive Efficiency

Calculate Hull, Relative Rotative Efficiency

Open Water Efficiency is to be Optimized?

Yes

Call *EOMAX
Search for Best Open Water Efficiency

Estimate Open Water Efficiency

Calculate Propulsive Efficiency

Return

APPENDIX IV: FLOW CHART
APPENDIX IV: FLOW CHART

*EOMAX
Search the Best Open Water Efficiency

Call ETAO
Calculate $K_t$, $K_q$ and Open Water Efficiency with Any Set of Advance Ratio and Pitch Dia. Ratio

Call EOLMT
Check the Feasible RPM Range

Search the Best Open Water Efficiency By SUMT

Return
APPENDIX IV: FLOW CHART

*WINVOY
Calculate the Voyage Time During Ice Season

Calculate the Running Time in Open Water Area

Call SPDICE
Estimate the Ship Speed in Ice with Known Thickness and Condition

Calculate the Running Time in Ice Regions

Calculate the Voyage Time During Each Extension Period

Calculate the Number of Voyages During Each Extension Season

Return
BIBLIOGRAPHY

A. References Cited in Report


8. R. A. Stearn, Inc.: Contract reports to Department of Naval Architecture and Marine Engineering, University of Michigan, 1971.


B. Other References


52. B. Michel, Ice Pressure on Engineering Structures, Presented to Northern California Section, The Society of Naval Architects and Marine Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, June 1970.


54. F. C. Michelsen, T. H. Little, P. Y. Chang, Library Search for Literature in the Field of Structure with Special Reference to Publications Which are Pertinent to the Design and Construction of Icebreakers, Department of Naval Architecture and Marine Engineering, University of Michigan, January 1968.