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

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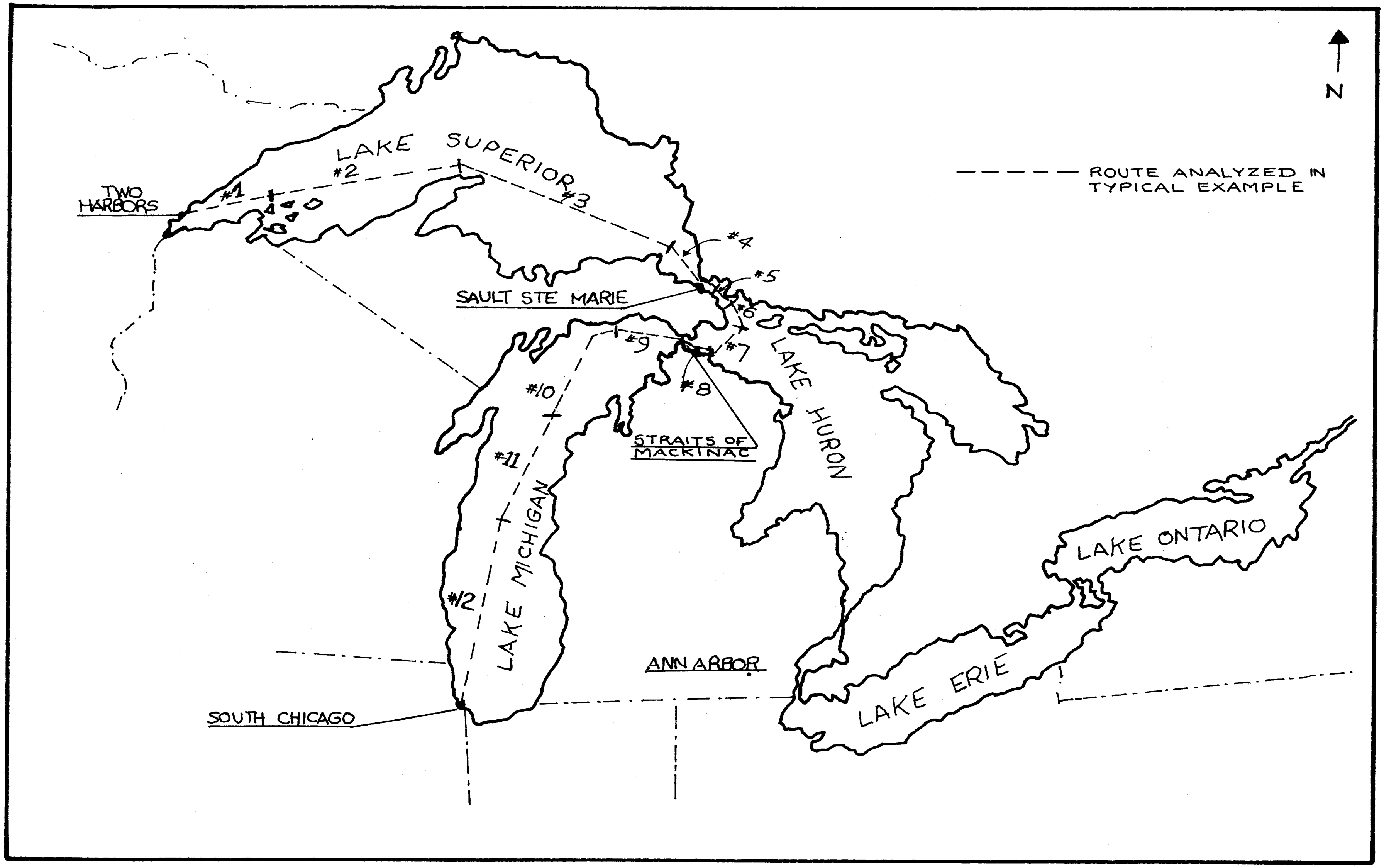

THE GREAT LAKES

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

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*Numbers in parenthesis indicate references in the Bibliography.

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:

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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

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SYMBOLS & ABBREVIATIONS

A	uniform annual returns before tax
B	beam
BHP	brake horsepower
C	annual transport capacity
C_B	block coefficient
CN	cubic number = $\frac{LBD}{100}$
CP	controllable pitch
CR	capital recovery factor
Δ	displacement at summer loadline, long tons, fresh water
D	depth
DW	deadweight
K	number in crew
L	length between perpendiculars
LS	lightship weight
M	operating months per year
N	economic life of a ship, or years remaining in case of an existing ship
NPV	net present value

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

APPENDICES

BIBLIOGRAPHY

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 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.

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

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 perpendiculars (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

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

where

C_M = 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

$$L_{OA} = fL \qquad [2]$$

where

$f \simeq 1.0115$ for transom stern ships
$f \simeq 1.026$ for cruiser stern ships

3. Dispacement

The summer load line dispacement (Δ) is based on the length between perpendiculars and long tons of fresh water:

$$\Delta = C_B \frac{LBT}{35.9} \qquad [3]$$

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:

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

Ice Class	q	X	Y
IA Super	0.40	1500	25,000
IA	0.35	1000	22,000
IB	0.30	500	18,500
IC	0.25	0	15,000

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:

$$CN = \frac{LBD}{100} \qquad [4]$$

6. Freeboard, Draft, and Displacement

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

$$T_{MS} = \text{mid-summer draft} = 1.025T \qquad [5]$$

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

$$T_I = 0.9625T \qquad [6]$$

and

$$T_W = 0.9177T \qquad [7]$$

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

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

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:

$$\Delta_{MS} = C_{B-MS} \frac{LBT_{MS}}{35.9} \qquad [9]$$

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):

$$W_S = 668 \left(\frac{CN}{1000} \right)^{0.75} \left(\frac{\frac{L}{D} + 2}{20} \right) \left(0.565 + \frac{C_B}{2} \right) \qquad [10]$$

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.

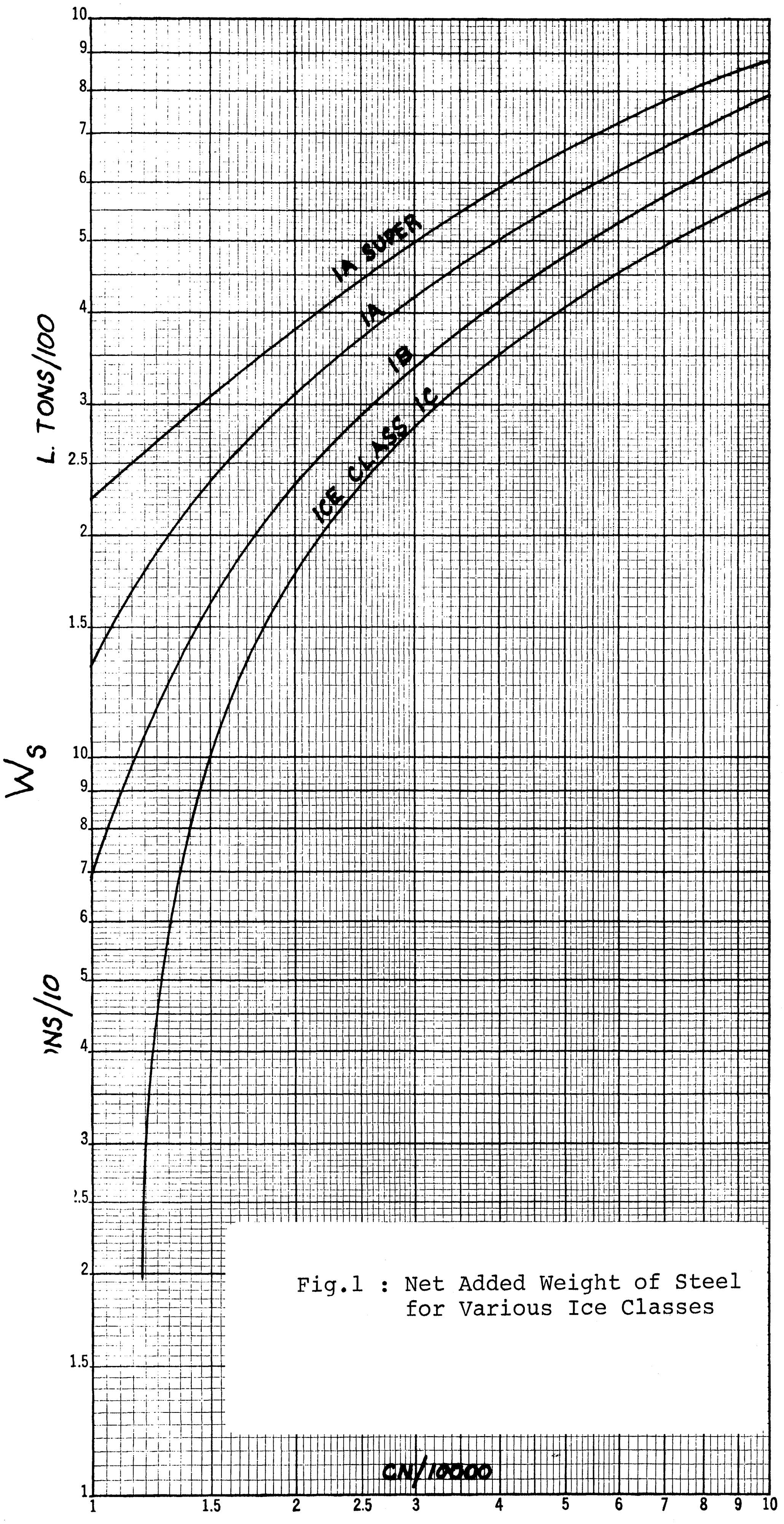


Fig.1 : Net Added Weight of Steel for Various Ice Classes

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:

$$W_o = 233\left(\frac{CN}{1000}\right)^{0.3} \qquad [11]$$

The weight of conveyor systems may be estimated as follows:

$$W_c = a\left(\frac{CN}{1000}\right)^{b} \qquad [12]$$

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:

Capacity in 1000 tons per hour	Shuttle Conveyor		Boom Conveyor	
	a	b	a	b
4	40	0.67	104	0.46
6	53	0.62	147	0.42
8	65	0.59	202	0.38
10	77	0.57	252	0.35
20	120	0.50	—	—

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:

$$W_M = a\left(\frac{SHP}{1000}\right)^{0.5} \qquad [13]$$

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:

$$DW = \Delta - LS \qquad [14]$$

where

LS = 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.

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

			Cost Component	
			Material ($)	Labor (man-hours)
Ship Component	Structure		$\$236\ W_S$	$130{,}000\left(\frac{W_S}{1000}\right)^{0.85}$
	Outfit		$\$2400\ W_O$	$280\ W_O$
	Machinery	Steam Turbine	Material, labor, overhead $\$900{,}000\left(\frac{SHP}{1000}\right)^{0.60}$ add 3% if 70% backing power is specified	
		Intermediate-speed Diesel	$\$550{,}000\left(\frac{BHP}{1000}\right)^{0.70}$	

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:

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

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:

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

where

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

and

a and b have the values shown below:

Capacity in 1000 tons per hour	Shuttle Conveyor a $1000	Shuttle Conveyor b	Boom Conveyor a $1000	Boom Conveyor b
4	224	0.31	442	0.23
6	280	0.31	597	0.22
8	337	0.30	794	0.19
10	395	0.30	922	0.19
20	800	0.30	___	___

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:

$$C = a\left(\frac{SHP}{1000}\right)^{0.60} \qquad [17]$$

where

C = added cost for a CP propeller installation, including shipyard profit

and

a = \$20,000 for steam turbine plants

= \$13,500 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.

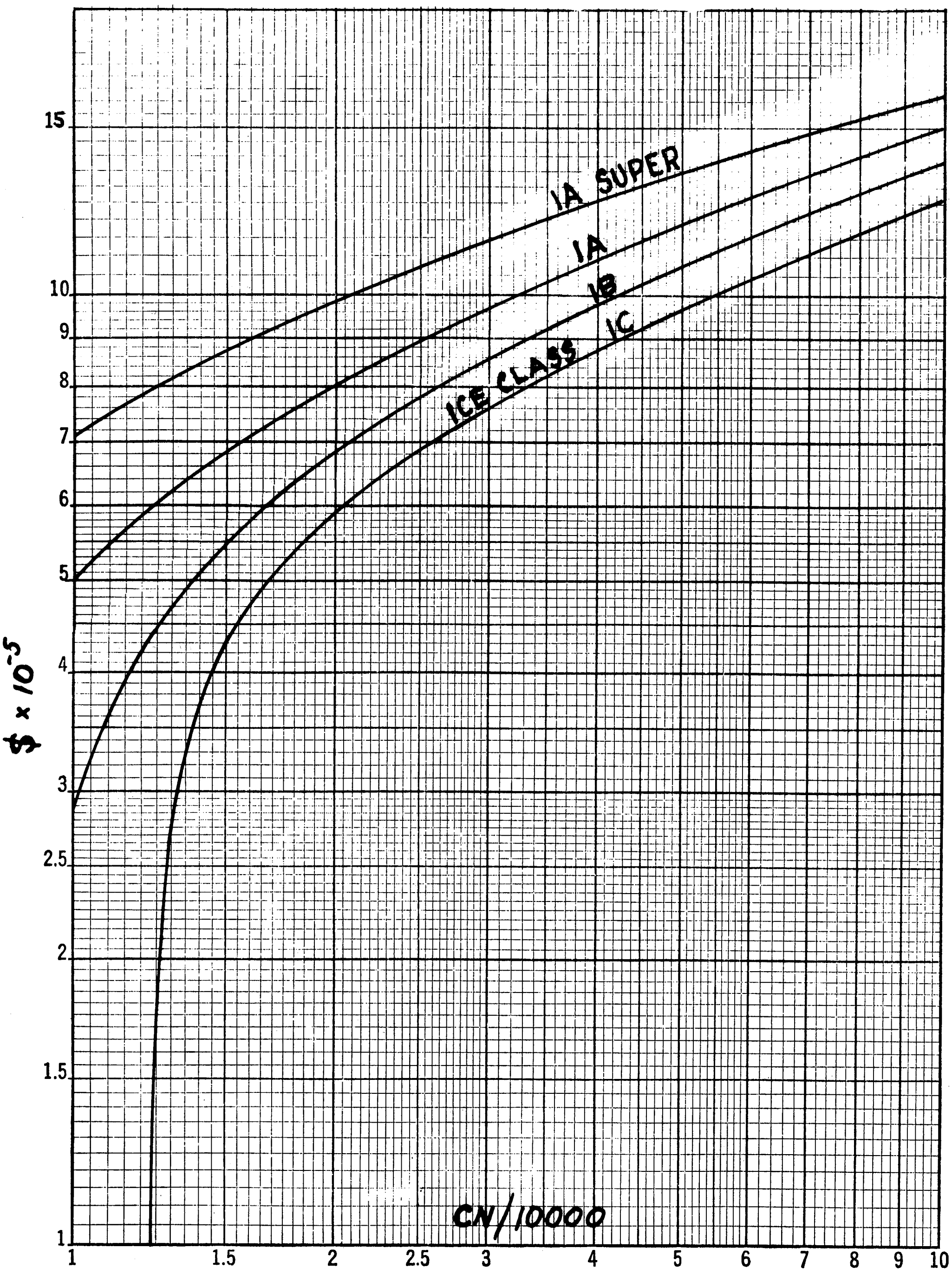


Fig.2 : Cost of Structura
Strengthening Con
of Existing Ships

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 2
JANUARY 15 ICE CONDITIONS
BETWEEN TWO HARBORS AND SOUTH CHICAGO

Leg (see Frontispiece)	Total Distance (st. miles)	Class I (<70% ice cover)	Class II (70%-90% ice cover)					Class III (>90% ice cover)				
			Distance (st. miles)	Thickness (inches)	Type	Temp (F)	Notes	Distance (st. miles)	Thickness (inches)	Type	Temp (F)	Notes
1. W. end L. Superior	47	41						6	15	sheet	10	
2. W. basin L. Superior	137	137										
3. Central basin L. Superior	150	150										
4. Whitefish Bay	22	11	11	8	brash	20						
5. Upper St. Mary's	17	7						10	11	sheet	20	
6. Lower St. Mary's	49							49	11	sheet	20	
7. Upper L. Huron	33	33										
8. Straits	20	4						16	8		25	1
9. Upper L. Mich.	51	16	5	8		25	1	30	8		25	1
10. Island area	49	49										
11. N. basin L. Michigan	90	90										
12. S. basin L. Michigan	146	146										
Total	811	684	16					111				

Notes: See table 6

TABLE 3

FEBRUARY 15 ICE CONDITIONS

BETWEEN TWO HARBORS AND SOUTH CHICAGO

Leg (see Frontispiece)	Total Distance (st. miles)	Class I (<70% ice cover)	Class II (70%-90% ice cover)					Class III (>90% ice cover)				
			Distance (st. miles)	Thickness (inches)	Type	Temp (F)	Notes	Distance (st. miles)	Thickness (inches)	Type	Temp (F)	Notes
1. W. end L. Superior	47	3	18	18	sheet	10	2	26	18	sheet	10	7
2. W. basin L. Superior	137	116	21	18	sheet	25	3					
3. Central basin L. Superior	150	150										
4. Whitefish Bay	22	4						18	18	sheet	20	8
5. Upper St. Mary's	17							17	18	sheet	20	9
6. Lower St. Mary's	49							49	18	sheet	20	9
7. Upper L. Huron	33		25	17		10	4	8	17		10	10
8. Straits	20							20	17		10	10
9. Upper L. Mich.	51		11	17		10	5	40	17		10	10
10. Island area	49	44	5	17	sheet	10	6					
11. N. basin L. Michigan	90	90										
12. S. basin L. Michigan	146	136						10	5	refr. brash	20	11
Total	811	543	80					188				

Notes: See Table 6

TABLE 4
MARCH 15 ICE CONDITIONS
BETWEEN TWO HARBORS AND SOUTH CHICAGO

Leg (see Frontispiece)	**Total Distance** (st. miles)	**Class I** (<70% ice cover)	**Class II (70%-90% ice cover)**					**Class III (>90% ice cover)**				
			Distance (st. miles)	Thickness (inches)	Type	Temp (F)	Notes	Distance (st. miles)	Thickness (inches)	Type	Temp (F)	Notes
1. **W. end L. Superior**	47							47	18	sheet	32	13
2. **W. basin L. Superior**	137		137	18	sheet	32						
3. **Central basin L. Superior**	150	106	44	15	sheet	32						
4. **Whitefish Bay**	22							22	18	sheet	32	
5. **Upper St. Mary's**	17							17	15		32	14
6. **Lower St. Mary's**	49							49	15		32	
7. **Upper L. Huron**	33	20						13	15		30	15
8. **Straits**	20							20	15		30	
9. **Upper L. Mich.**	51							51	15		30	
10. **Island area**	49		25	12	sheet	30	12	24	12	sheet	30	16
11. **N. basin L. Michigan**	90	90										
12. **S. basin L. Michigan**	146	132						14	6	brash	32	17
Total	811	348	206					257				

Notes: See table 6

TABLE 5
APRIL 1 ICE CONDITIONS
BETWEEN TWO HARBORS AND SOUTH CHICAGO

Leg (see Frontispiece)	Total Distance (st. miles)	Class I (<70% ice cover)	Class II (70%-90% ice cover)					Class III (>90% ice cover)				
			Distance (st. miles)	Thickness (inches)	Type	Temp (F)	Notes	Distance (st. miles)	Thickness (inches)	Type	Temp (F)	Notes
1. W. end L. Superior	47	39						8	14	sheet	32	
2. W. basin L. Superior	137	98	39	14	sheet	32						
3. Central basin L. Superior	150	150										
4. Whitefish Bay	22	15						7	12	sheet	32	
5. Upper St. Mary's	17	6						11	12	sheet	32	
6. Lower St. Mary's	49	5						44	12	sheet	32	
7. Upper L. Huron	33	33										
8. Straits	20	5						15	8	sheet	32	
9. Upper L. Mich.	51	10	17	8	sheet	32		24	8	sheet	32	
10. Island area	49	49										
11. N. basin L. Michigan	90	90										
12. S. basin L. Michigan	146	140	6	6	brash	32						18
Total	811	640	62					109				

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.

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.

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):

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

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 = resistance due to cleaning broken ice out of the channel laterally by accelerative forces.

R_4 = water resistance, friction and wave-making, computed as if ice were not present.

Further, according to Kashteljan

$$R_1 = k_1 B m_o s h \qquad [19]$$

$$R_2 = k_2 B m_o g_i h^2 \qquad [20]$$

and

$$R_3 = k_3 B^{k_4} \frac{hV}{e_2} \qquad [21]$$

where the k coefficients have the values shown below (derived from model and full-scale tests on the Russian icebreaker <u>Ermak</u>):

$k_1 = 0.004$

$k_2 = 3.6$

$k_3 = 0.25$

$k_4 = 1.65$

and where

B = ship's beam in meters

m_o = Kashteljan's vertical ice force coefficient (a function of bow shape). See comments below.

s = ice strength in metric tons per square meter

h = ice thickness in meters

g_i = specific weight of ice in metric tons per cubic meter

V = ship's speed in meters per second

e_2 = Shimanshkij's lateral ice pressure coefficient. See table 7.

Kashteljan's vertical ice force coefficient, m_o, is intended as a measure of hull form efficiency in generating vertical forces. His definition of m_o 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_o 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

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

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

$$R_1 = C_o sh^2 \qquad [22]$$

$$R_2 = C_1 g_i Bh^2 \qquad [23]$$

$$R_3 = C_2 r_i BhV^2 \qquad [24]$$

where

C_o, C_1, and C_2 are coefficients of as yet undefined quantitative values for Great Lakes ore carrier hull forms

r_i = 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 $h \doteq 2$ ft (0.61m), 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:

$$R_1 + R_2 = k_1 Bm_o sh + k_2 Bm_o g_i h^2$$

$$\doteq Bm_o(k_1 sh + k_2 g_i h^2) \qquad [25]$$

d) Kashteljan's vertical ice force coefficient, m_o, does not seem altogether suited to our particular purpose. Therefore, we propose a modified version derived from Shimanshkij'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:

$$m = \frac{A}{e_1} \qquad [26]$$

where

A = empirically derived number that varies with ice conditions.

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

$$R_1 + R_2 = B \frac{A}{e_1} (k_1 sh + k_2 g_i h^2) \qquad [27]$$

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:

$$R_1 = k_1 sBhm = 0.004 sBhm \qquad [28]$$

$$R_2 = k_2 g_i Bh^2 m = 3.6\ g_i Bh^2 m \qquad [29]$$

$$R_3 = k_3 B^{k4} \frac{hV}{e_2} = 0.25 B^{1.65} \frac{hV}{1.55} \qquad [30]$$

R_4 = 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_1 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;

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

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.

*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:

$$R_{ip} = (R_{ip})_o \left(\frac{D}{D_o}\right)^s \left(\frac{h}{t_o}\right)^m \left(\frac{S}{S_o}\right)^n \left(\frac{t}{t_o}\right)^p \left(\frac{(L/B)_o}{L/B}\right)^q \left(\frac{C_{Bo}}{C_B}\right)^r \left(\frac{(B_1/B)_o}{B_1/B}\right)^k \qquad [31]$$

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} = pure ice resistance, metric tons

D = displacement, metric tons

h = ice thickness, meters

S = ice state, surface coverage in percent

T = draft of vessel, meters

L,B = length, beam of vessel

C_B = block coefficient

B_1 = 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

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

The following data belong to this standard case:

D_o = 10920 tons

h_o = 0.8 meter

S_o = state 8 = 0.8

T_o = 7.3 meter

$(L/B)_o$ = 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,

$$s = 0.753\ F_n^{0.278} \tag{33}$$

$$m = 0.308\ F_n^{-0.61} \tag{34}$$

$$n = 0.79\ F_n^{-0.49} \tag{35}$$

$$p = 1.759\ F_n^{0.75} + 0.35 \tag{36}$$

$$q = 2.5\ F_n^{0.455} - 0.60 \tag{37}$$

$$r = 38.36\ F_n^{2.356} + 1.25 \tag{38}$$

$$k = 0.039\ F_n^{-1.24} \tag{39}$$

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:

$$D = Di + Dw$$

in which

Di = distance through equivalent sheet ice

and

Dw = 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:

$$Di = DS^3$$

where

S = 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.

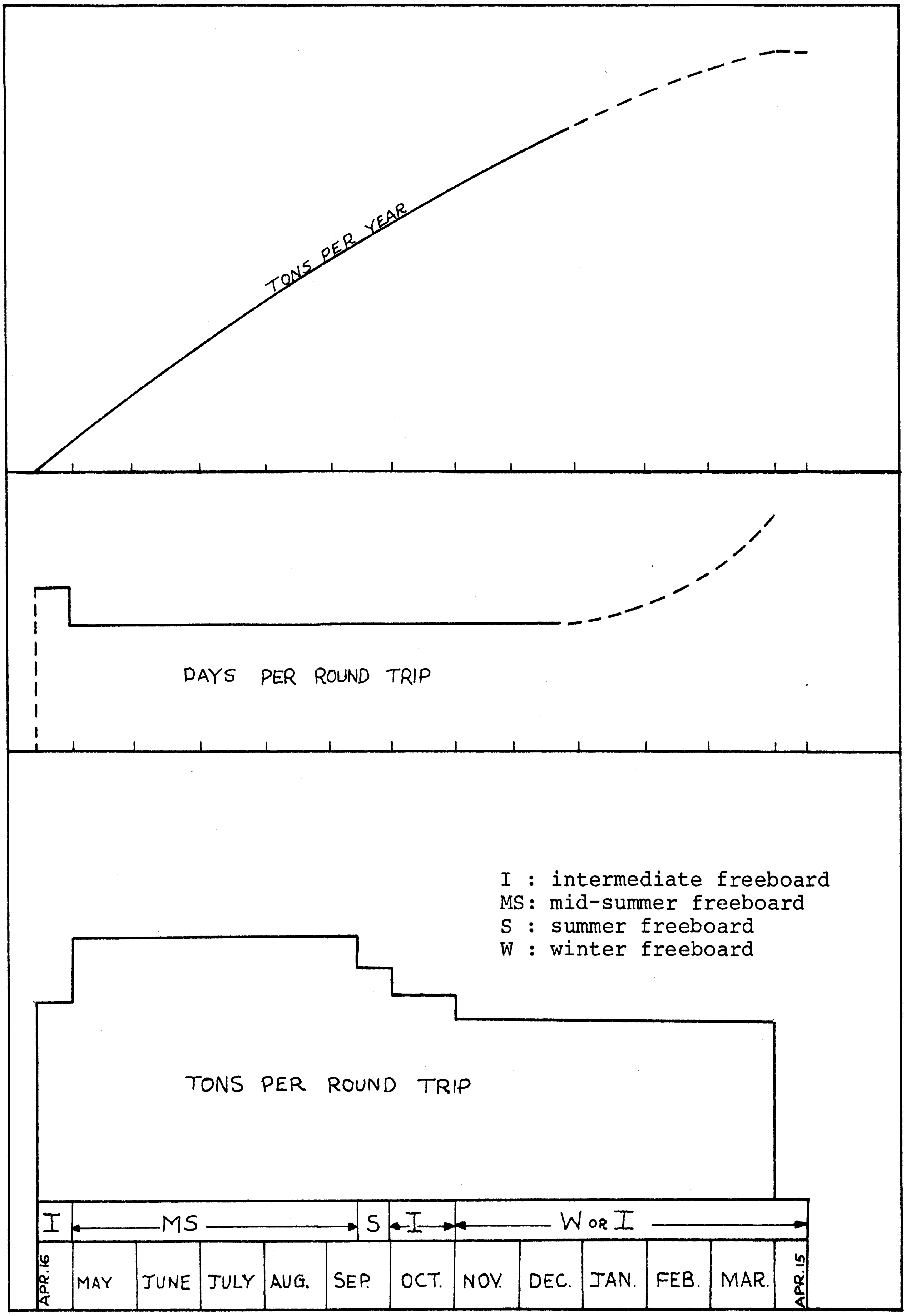


Fig. 3 : Influence of Cargo Capacity and Round Trip Time on Annual Transport Capacity

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.

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 icebreaker 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)

Cause of Delay / Date	Dec 15	Jan 15					Feb 15					Mar 15					April 1				
Ice Class		2	1C	1B	1A	1A S	2	1C	1B	1A	1A S	2	1C	1B	1A	1A S	2	1C	1B	1A	1A S
Loading Time*	0	0					0					0					0				
Unloading Time*	0	0					0					0					0				
Locks	0	1					1					1					1				
Docking & Undocking	0	1					1					1					1				
Weather	4	4					4					2					2				
Waiting for Ice-breaker, Slow Convoys, etc.	0	8	6	4	2	0	20	16	12	8	4	30	23	18	13	8	40	30	24	18	12
Total Hours	4	14	12	10	8	6	26	22	18	14	10	34	27	22	17	12	44	34	28	22	16

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.

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:

$$C_S = DW - Q \qquad [40]$$

where

DW = deadweight at summer loadline (see section B)

and

Q = 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 $4\left(\frac{SHP}{1000}\right) + 8$. The corresponding figure for intermediate speed geared diesels burning blended oil will be $3.8\left(\frac{BHP}{1000}\right) + 4$. When operating at reduced powers (as when in speed-restricted areas), the specific fuel consumption will increase according to these ratios:

Percent of Maximum Power	Relative Fuel Consumption per SHP - hr	
	Steam	Diesel
100	1.000	1.000
90	1.007	1.014
80	1.025	1.028
70	1.051	1.042
60	1.089	1.056
50	1.143	1.070

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.

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:

Service	Pounds Fuel per Hour
Domestic	85
Heating or cooling	85
Auxiliary machinery	80
Total	250

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:

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

where

K = 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:

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

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

3. Subsistence

Average subsistence costs can be taken as \$2.70 per man-day, or \$82.50 per man-month.

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:

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

where

K = number in crew

CN = 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:

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

where

P = initial investment in the case of a new design or the resale value in the case of an existing ship

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

$$\text{Annual cost of H \& M} = M\left(\$1000 + \frac{P}{1000}\right)(a)^{M-9} \qquad [46]$$

where

M = months of operation per year

and

a = 1.234 for ice class 2
 1.184 for ice class IC
 1.129 for ice class IB
 1.068 for ice class IA
 1.039 for ice class IA super

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:

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

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:

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

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 for ships without bow thrusters
= \$6 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:

Monthly cost of stores and supplies

$$= \$50\left(\frac{CN}{1000}\right) + \$37(K-10) \qquad [50]$$

where

K = 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:

Months of Operation	Cost
up to 10	$75,000
11	$25,000
11.5	$10,000

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:

$$\text{Overhead cost per year} = \$50{,}000 + \$2000M + \$1250\left(\frac{CN}{1000}\right) \qquad [51]$$

where

M = operating months per year

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.

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:

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

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 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

$$NPV = (SPW\text{-}10\%\text{-}N)A - P \qquad [53]$$

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:

$$CR = \frac{A}{P} \qquad [54]$$

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:

		Closing Date				
Weather Condition	Probability	Dec 15	Jan 15	Feb 15	Mar 15	April 15
Mild	25%	$2.00	1.95	1.90	1.85*	1.90
Normal	50%	$2.00	1.97	1.95*	1.98	2.05
Severe	25%	$2.00	1.98*	2.00	2.05	2.15

*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:

$$\text{RFR} = 0.25\$1.85 + 0.50\$1.95 + 0.25\$1.98$$

$$= \$0.4625 + \$0.975 + \$0.495 = \$1.9325$$

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 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 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 perpendiculars

Beam

Depth

Draft at summer load line

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 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 perpendiculars: 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)

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

Queuing 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.

(COMPUTER PRINT-OUT)

```
0. PRINCIPAL DESIGN INPUTS


     TRADE ROUTE...TWO HARB-GARY
     CARGO.........ORE PLTS
     SHIP STATUS...PROPOSED
     ICE CLASS.....I-B
     WINTER WEATHER.....NORMAL


     LENGTH B.P.... 825.0 FT             SERVICE SPEED.. 14.5 KNOT
     SUMMER DRAFT..  25.5 FT             BLOCK COEFF....  0.900
     BEAM.......... 105.0 FT             DEPTH..........   51.5 FT

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

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


     BOW THRUSTER... 1
     NUMBER OF CREW.... 24.
     DELAYS....  5.0 HOUR


     FREIGHT RATE/L.TON...($)  3.45
     DESIRED CRF BEFORE TAX....0.110
     DISCOUNT RATE BEFORE TAX..0.105
     LIFE EXPECTANCY.... 40
```

(cont.)

(COMPUTER PRINT-OUT, CONT.)

```
                 FINAL RESULTS OF BULK  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 SPEED...              17.88 MILE/HOUR

      EFFECTIVE H.P....             8663.

      MAXIMUM CON. H.P....        17113.   note 2

      HORSEPOWER USED IN RESTRICTED AREA.. 3801.   note 3


 3. FORM COEFFICIENTS AND RATIOS

      CB=          0.900

      CP=          0.906

      CM=          0.993

      L/D=        16.02

      L/B=         7.86

      B/D=         2.039

      B/T=         4.118

      T/D=         0.495
```

$\frac{V_K}{\sqrt{L}}$ → V/SQRT(L)= 0.540 ↙ $\frac{L}{\Delta^{1/3}}$

```
      LENGTH-DISP RATIO=  21.65

      CUBIC NUMBER...    44612.
```

(cont.)

```
4. WEIGHT BREAKDOWN (LONG TONS)

      STEEL HULL...    10755.7

      OUTFITTING...     1646.1

      MACHINERY...       788.1

      ADDED STEEL WEIGHT FOR ICE CLASS... 436.
      CONVEYOR WEIGHT=  848.     BOW THRUSTER WEIGHT=    70. 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.
      INTER. SEASON 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
```

(COMPUTER PRINT-OUT, CONT.)

```
8. OPERATING INFORMATION

       **OPERATING DRAFTS(FT)**
       SUM. DRAFT...25.5      MIDSUM. DRAFT...26.1
       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)...0.59

       SUMMER ROUND TRIP DAYS... 4.53  note 9
       MIDSUMMER ROUND TRIP DAYS... 4.54
       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**
       ICE      RUNNING       DELAY    STOPPING TIME  VOYAGE     NUMBER OF
      SEASON     DAYS         DAYS      IN ICE(HR)     DAYS       VOYAGES
          note 13                                               note 15
        1           3.8          0.8          0.0         4.6         3.5
        2           4.2          1.0          0.0         5.1         2.9
        3           4.1          1.1          0.0         5.2         3.1
        4           4.6          1.2          0.0         5.8         2.6
        5           5.5          1.3          0.0         6.8         1.9
        6           5.3          1.5          0.0         6.8         2.2
        7           5.3          1.6          0.0         6.9         2.2
                                                      note 14     note 16
       **FUEL CONSUMPTION RATE(LB/HR)**
       F.C.R. AT FULL POWER= 6442.8
       F.C.R. DURING DELAY= 654.7
       F.C.R. DURING UNLOADING(LB)=4926.2
       F.C.R. AT FULL POWER(LB/SHP-HR)=  0.38
       F.C.R. AT PARTIAL POWER (LB/SHP-HR)=  0.50
       L.O. RATE(LB/HR)=  32.2
```

(cont.)

(COMPUTER PRINT-OUT, CONCLUDED)

```
9. OPERATING COST

   SEASON EXTENSION         0          1          2          3          4          5          6          7
   IN HALF MONTH
   INCREMENT             Dec.15     Jan.1      Jan.15     Feb.1      Feb.15     Mar.1      Mar.15     April 1

   CREW COST.....        376852.    404084.    431316.    458548.    485780.    513012.    540244.    567476.

   STORE & SUPPLY         21989.     23363.     24737.     26112.     27486.     28860.     30235.     31609.

   REPAIR & MAINT        157940.    167812.    177683.    188820.    200907.    214030.    228285.    243774.

   INSURANCE COST        175570.    186623.    197676.    221390.    247269.    275494.    306259.    339773.

   OVERHEAD COST.        121765.    122765.    123765.    124765.    125765.    126765.    127765.    128765.

   TOWING COST...         18683.     20433.     21903.     23458.     24747.     25704.     26816.     27907.

   LAYUP COST....         75000.     75000.     75000.     75000.     75000.     25000.     25000.     10000.

   FUEL COST.....        446755.    478925.    508913.    540114.    569461.    595221.    624300.    652919.

   TOTAL OP. COST       1394553.   1479003.   1560990.   1658202.   1756412.   1804082.   1908899.   2002219.
                 note 17
   ANNUAL CAPITAL       2233831.   2233831.   2233831.   2233831.   2233831.   2233831.   2233831.   2233831.
                  note 18
   AVERAGE ANNUAL       3628384.   3712834.   3794821.   3892033.   3990243.   4037913.   4142730.   4236050.

                 note 19
   TOTAL CARGO...       2033284.   2160680.   2267621.   2380823.   2474670.   2544303.   2625227.   2704685.


10. MEASURES OF MERIT

   RFR...........          1.784      1.718      1.673      1.635      1.612      1.587      1.578      1.566

   NPV (IN $1000)         32232.     35552.     38234.     40976.     43085.     44885.     46515.     48206.
                  note 20
   CRF...........         0.2768     0.2942     0.3084     0.3223     0.3339     0.3434     0.3520     0.3609
```

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.

8. Ship price excludes owner-furnished materials.

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.

TABLE 9

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.)

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

TABLE 11

ECONOMIC IMPROVEMENTS PREDICTED FOR WINTER OPERATIONS

Based on sample ship described in text operating in normal winter conditions.

Ice Class	Measure of Merit	8-Month Season	Extended Season	Gain from Extended Season	
				Ratio	Increment
2	RFR	$1.75*	$1.59	0.91	(16¢ per ton)
	NPV in millions	$31.6*	$44.6	1.41	$13 million
	CRF	0.282*	0.354	1.26	—
1C	RFR	—	$1.60	0.91	(15¢ per ton)
	NPV in millions	—	$44.4	1.41	$11.8 million
	CRF	—	0.349	1.24	—
1B	RFR	—	$1.57	0.90	(18¢ per ton)
	NPV in millions	—	$48.2	1.52	$16.6 million
	CRF	—	0.361	1.28	—
1A	RFR	—	$1.54	0.88	(21¢ per ton)
	NPV in millions	—	$51.5	1.63	$19.9 million
	CRF	—	0.371	1.32	—
1A Super	RFR	—	$1.53	0.87	(22¢ per ton)
	NPV in millions	—	$54.1	1.71	$22.5 million
	CRF	—	0.375	1.33	—

*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.

Measure of Merit	Operation		Gain from Extended Season	
	Unreinforced 8-Month Season	Ice Class 1B Extended Season	Ratio	Increment
RFR	\$1.75	\$1.66	0.95	(9¢ per ton)
NPV in millions	\$31.6	\$41.5	1.31	\$9.9 million
CRF	0.282	0.326	1.16	____

ICE CLASS 1B , MILD WINTER

```
9. OPERATING CCST

   SEASON EXTENSION      0         1         2         3         4         5         6         7
   IN HALF MCNTH
   INCREMENT

   CREW COST.....     376852.   404084.   431316.   458548.   485780.   513012.   540244.   567476.

   STORE & SUPPLY      21989.    23363.    24737.    26112.    27486.    28860.    30235.    31609.

   REPAIR & MAINT     157940.   167812.   177683.   188820.   200907.   214030.   228285.   243774.

   INSURANCE COST     175570.   186623.   197676.   221390.   247269.   275494.   306259.   339773.

   OVERHEAD COST.     121765.   122765.   123765.   124765.   125765.   126765.   127765.   128765.

   TOWING COST...      18683.    20478.    21996.    23673.    25179.    26419.    27821.    29281.

   LAYUP COST....      75000.    75000.    75000.    75000.    75000.    25000.    25000.    10000.

   FUEL COST.....     446755.   479341.   509945.   541478.   570825.   596154.   624917.   654991.

   TOTAL OP. COST    1394553.  1479464.  1562116.  1659781.  1758208.  1805731.  1910522.  2005665.

   ANNUAL CAPITAL    2233831.  2233831.  2233831.  2233831.  2233831.  2233831.  2233831.  2233831.

   AVERAGE ANNUAL    3628384.  3713295.  3795947.  3893612.  3992039.  4039562.  4144353.  4239496.


   TOTAL CARGO...    2033284.  2163960.  2274408.  2396472.  2506130.  2596378.  2698364.  2804679.



10. MEASURES OF MERIT

   RFR...........       1.784     1.716     1.669     1.625     1.593     1.556     1.536     1.512

   NPV (IN $1000)      32232.    35653.    38443.    41466.    44083.    46549.    48859.    51398.

   CRF...........      0.2768    0.2948    0.3095    0.3254    0.3392    0.3522    0.3643    0.3777
```

ICE CLASS IB, SEVERE WINTER

9. OPERATING COST

SEASON EXTENSION IN HALF MONTH INCREMENT	0	1	2	3	4	5	6	7
CREW COST.....	376852.	404084.	431316.	458548.	485780.	513012.	540244.	567476.
STORE & SUPPLY	21989.	23363.	24737.	26112.	27486.	28860.	30235.	31609.
REPAIR & MAINT	157940.	167812.	177683.	188820.	200907.	214030.	228285.	243774.
INSURANCE COST	175570.	186623.	197676.	221390.	247269.	275494.	306259.	339773.
OVERHEAD COST.	121765.	122765.	123765.	124765.	125765.	126765.	127765.	128765.
TOWING COST...	18683.	20333.	21642.	22867.	23377.	23762.	24410.	25044.
LAYUP COST....	75000.	75000.	75000.	75000.	75000.	25000.	25000.	10000.
FUEL COST.....	446755.	478400.	508067.	539498.	568538.	594489.	623610.	652177.
TOTAL OP. COST	1394553.	1478378.	1559884.	1656996.	1754119.	1801409.	1905803.	1998614.
ANNUAL CAPITAL	2233831.	2233831.	2233831.	2233831.	2233831.	2233831.	2233831.	2233831.
AVERAGE ANNUAL	3628384.	3712209.	3793715.	3890827.	3987950.	4035240.	4139634.	4232445.
TOTAL CARGO...	2033284.	2153363.	2248644.	2337798.	2374961.	2402963.	2450119.	2496250.

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

ICE CLASS 2, NORMAL WINTER

```
9. OPERATING COST

   SEASON EXTENSION      0        1        2        3        4        5        6        7
   IN HALF MONTH
   INCREMENT

   CREW COST.....     376852.  404084.  431316.  458548.  485780.  513012.  540244.  567476.

   STORE & SUPPLY      21989.   23363.   24737.   26112.   27486.   28860.   30235.   31609.

   REPAIR & MAINT     152055.  161559.  171062.  182687.  196039.  211398.  229082.  249457.

   INSURANCE COST     167681.  178241.  188801.  220762.  257473.  299599.  347895.  403215.

   OVERHEAD COST.     121765.  122765.  123765.  124765.  125765.  126765.  127765.  128765.

   TOWING COST...      17740.   19336.   20679.   22042.   23143.   23932.   24848.   25742.

   LAYUP COST....      75000.   75000.   75000.   75000.   75000.   25000.   25000.   10000.

   FUEL COST.....     373650.  399652.  423600.  448464.  471850.  492482.  515594.  538226.

   TOTAL OP. COST    1306730. 1383998. 1458959. 1558377. 1662532. 1721045. 1840659. 1954487.

   ANNUAL CAPITAL    2125355. 2125355. 2125355. 2125355. 2125355. 2125355. 2125355. 2125355.

   AVERAGE ANNUAL    3432085. 3509353. 3584314. 3683732. 3787887. 3846400. 3966014. 4079842.


   TOTAL CARGO...    1958227. 2076155. 2175406. 2276063. 2357415. 2415684. 2483380. 2549404.



10. MEASURES OF MERIT

   RFR...........       1.753    1.690    1.648    1.618    1.607    1.592    1.597    1.600

   NPV (IN $1000)      31619.   34700.   37200.   39517.   41167.   42499.   43565.   44630.

   CRF...........      0.2820   0.2991   0.3129   0.3258   0.3349   0.3423   0.3482   0.3541
```

ICE CLASS IC , NORMAL WINTER

9. OPERATING COST

SEASON EXTENSION IN HALF MONTH INCREMENT	0	1	2	3	4	5	6	7
CREW COST.....	376852.	404084.	431316.	458548.	485780.	513012.	540244.	567476.
STORE & SUPPLY	21989.	23363.	24737.	26112.	27486.	28860.	30235.	31609.
REPAIR & MAINT	152055.	161559.	171062.	182252.	194763.	208768.	224455.	242037.
INSURANCE COST	170204.	180921.	191639.	219652.	251045.	286268.	325731.	369911.
OVERHEAD COST.	121765.	122765.	123765.	124765.	125765.	126765.	127765.	128765.
TOWING COST...	17750.	19374.	20749.	22151.	23288.	24101.	25052.	25983.
LAYUP COST....	75000.	75000.	75000.	75000.	75000.	25000.	25000.	10000.
FUEL COST.....	373726.	400106.	424518.	449993.	473997.	495172.	518997.	542407.
TOTAL OP. COST	1309338.	1387169.	1462783.	1558449.	1657121.	1707944.	1817475.	1918185.
ANNUAL CAPITAL	2160038.	2160038.	2160038.	2160038.	2160038.	2160038.	2160038.	2160038.
AVERAGE ANNUAL	3469376.	3547207.	3622821.	3718487.	3817159.	3867982.	3977513.	4078223.
TOTAL CARGO...	1940404.	2059187.	2159739.	2262339.	2345443.	2404947.	2474457.	2542536.

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.	38756.	40516.	41960.	43178.	44432.
CRF..........	0.2742	0.2911	0.3050	0.3181	0.3277	0.3356	0.3422	0.3490

ICE CLASS IA, NORMAL WINTER

9. OPERATING COST

SEASON EXTENSION IN HALF MONTH INCREMENT	0	1	2	3	4	5	6	7
CREW COST.....	376852.	404084.	431316.	458548.	485780.	513012.	540244.	567476.
STORE & SUPPLY	21989.	23363.	24737.	26112.	27486.	28860.	30235.	31609.
REPAIR & MAINT	163438.	173653.	183868.	194794.	206226.	218189.	230710.	243814.
INSURANCE COST	180799.	192179.	203559.	221916.	241252.	261614.	283049.	305606.
OVERHEAD COST.	121765.	122765.	123765.	124765.	125765.	126765.	127765.	128765.
TOWING COST...	19505.	21379.	22942.	24639.	26085.	27186.	28453.	29703.
LAYUP COST....	75000.	75000.	75000.	75000.	75000.	25000.	25000.	10000.
FUEL COST.....	517760.	555872.	591682.	629020.	664088.	694801.	729709.	764185.
TOTAL OP. COST	1477106.	1568292.	1656866.	1754789.	1851680.	1895425.	1995161.	2081155.
ANNUAL CAPITAL	2305731.	2305731.	2305731.	2305731.	2305731.	2305731.	2305731.	2305731.
AVERAGE ANNUAL	3782837.	3874023.	3962597.	4060520.	4157411.	4201156.	4300892.	4386886.
TOTAL CARGO...	2112483.	2248132.	2361298.	2484172.	2588921.	2668618.	2760372.	2850858.

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.	42753.	45226.	47387.	49414.	51528.
CRF...........	0.2772	0.2952	0.3096	0.3252	0.3378	0.3488	0.3591	0.3699

ICE CLASS IA SUPER, NORMAL WINTER

9. OPERATING COST

SEASON EXTENSION IN HALF MONTH INCREMENT	0	1	2	3	4	5	6	7
CREW COST.....	376852.	404084.	431316.	458548.	485780.	513012.	540244.	567476.
STORE & SUPPLY	21989.	23363.	24737.	26112.	27486.	28860.	30235.	31609.
REPAIR & MAINT	168651.	179192.	189733.	200763.	211971.	223545.	235434.	247646.
INSURANCE COST	185833.	197527.	209222.	225061.	241421.	258315.	275760.	293769.
OVERHEAD COST.	121765.	122765.	123765.	124765.	125765.	126765.	127765.	128765.
TOWING COST...	20224.	22213.	23869.	25710.	27303.	28539.	29956.	31362.
LAYUP COST....	75000.	75000.	75000.	75000.	75000.	25000.	25000.	10000.
FUEL COST.....	587504.	631809.	673769.	717747.	759178.	795471.	837032.	878298.
TOTAL OP. COST	1557815.	1655950.	1751407.	1853641.	1953899.	1999503.	2101421.	2188921.
ANNUAL CAPITAL	2374943.	2374943.	2374943.	2374943.	2374943.	2374943.	2374943.	2374943.
AVERAGE ANNUAL	3932758.	4030893.	4126350.	4228584.	4328842.	4374446.	4476364.	4563864.
TOTAL CARGO...	2179870.	2323132.	2442457.	2575068.	2689836.	2778832.	2880938.	2982250.

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	0.2945	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 treatment 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 expect that a shipowner who allocates all of his operating profits 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 important 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 without the special tax treatment. The task is complicated because the tax exemptions are not uniform over the life of the ship;

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.

I. 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).

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

$$A' = A - \text{tax} \qquad \boxed{A1}$$

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:

$$\text{Tax} = tA$$

$$A' = A - \text{Tax} = A - tA = A(1 - t) \qquad \boxed{A2}$$

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.

$$I_B = A_B - \frac{P_B}{H}$$

$$I_B = (CR - i_B - H)P_B - \frac{P_B}{H}$$

$$I_B = P_B\left[(CR - i_B - H) - \frac{1}{H}\right] \qquad \boxed{A3}$$

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

$$\text{Taxable income} = A - I_B$$

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

$$\begin{aligned} A' &= A - \text{Tax} = A - t(A - I_B) \\ &= A - tA + tI_B \\ &= A(1 - t) + tI_B \qquad \boxed{A4} \end{aligned}$$

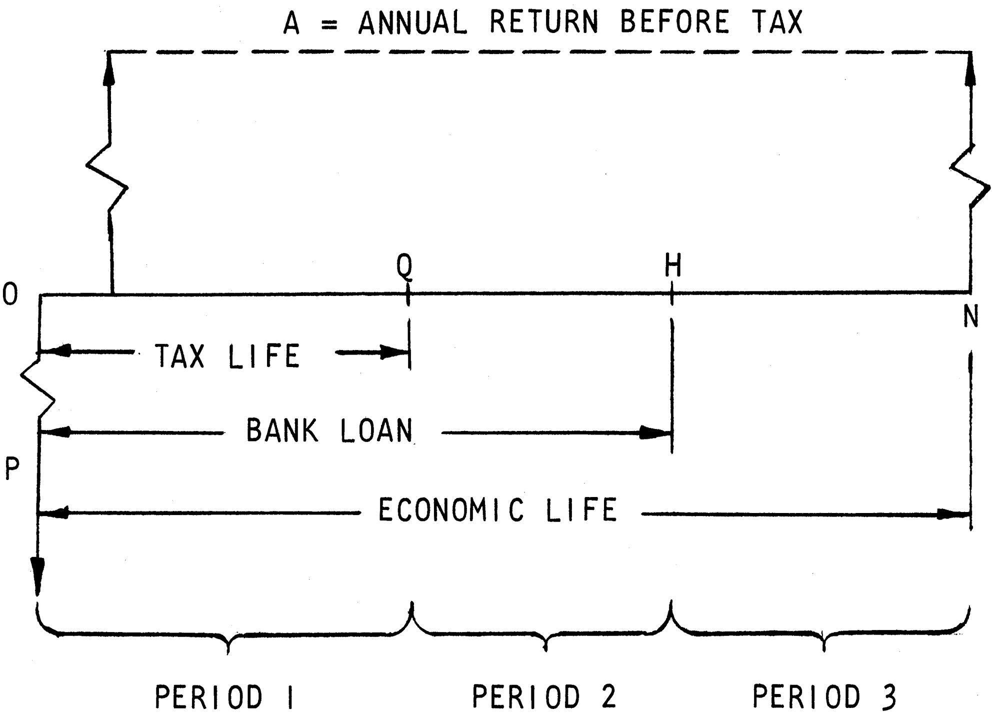


Fig. A1: Time Scale for Analysis Before New Tax Law

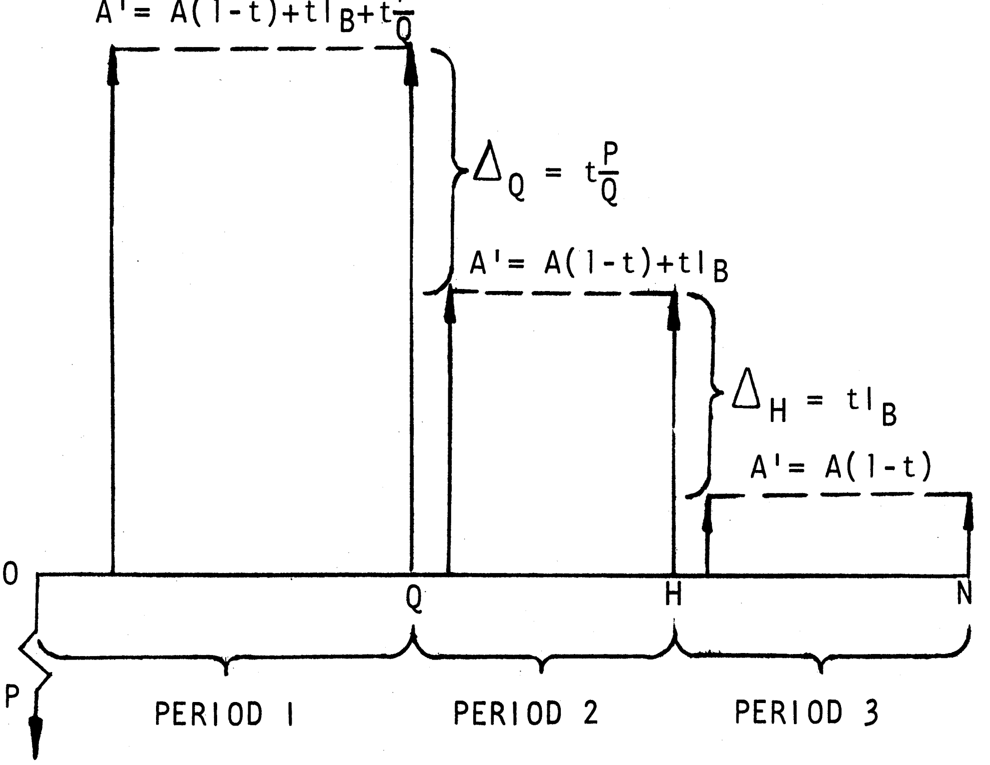


Fig. A2: Cash Flow Diagram Before New Tax Law

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

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

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

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

$$= A - tA + tI_B + t\frac{P}{Q}$$

$$= A(1 - t) + tI_B + t\frac{P}{Q} \qquad \boxed{A5}$$

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 (Δ) 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:

$$NPV = (SPW - i' - N)A(1 - t) + (SPW - i' - H)tI_B +$$

$$(SPW - i' - Q)t\frac{P}{Q} - P \qquad \boxed{A6}$$

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:

$$P = (SPW - i' - N)A(1 - t) + (SPW - i' - H)tI_B + (SPN - i' - Q)t\frac{P}{Q} \qquad [A7]$$

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:

$$A = \frac{P - (SPW - i' - H)tI_B - (SPW - i' - Q)t\frac{P}{Q}}{(SPW - i' - N)(1 - t)} \qquad [A8]$$

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:

A = unknown
i' = 10%
P = \$20 million
N = 50 yr

$Q = 20$ yr
$t = 48\%$
$P_B = \$10$ million
$H = 30$ 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):

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

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

$$= \$10M(0.0726-0.0333)$$

$$= \$10M\cdot 0.0393 = \$0.393M$$

M = million

Next, substituting known numbers into equation A8:

$$A = \frac{\$20M-(SPW\text{-}10\%\text{-}30)(0.48)\$0.393M-(SPW\text{-}10\%\text{-}20)(0.48)\frac{\$20M}{20}}{(SPW\text{-}10\%\text{-}50)(1-0.48)}$$

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

$$= \frac{\$20M-\$1.777M-\$4.085M}{5.154} = \frac{\$14.14M}{5.154} = \$2.743M$$

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'):

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

$$CR' = (CR\text{-}10\%\text{-}50) = 0.1009$$

$$\frac{CR}{CR'} = \frac{0.137}{0.1009} = 1.36$$

(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 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:

Time Period	Span of Years	Returns Before and After Tax
1	0 to F	$A' = A$
2 (like old 1)	F to Q	$A' = A(1-t) + tI_B + t\frac{P}{Q}$
3 (like old 2)	Q to H	$A' = A(1-t) + tI_B$
4 (like old 3)	H to N	$A' = A(1-t)$

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,

$$F = \frac{P}{D} \qquad \boxed{A9}$$

where

D = discretionary income during initial period of operation.

Figure A3 indicates the distribution of income during the initial period.

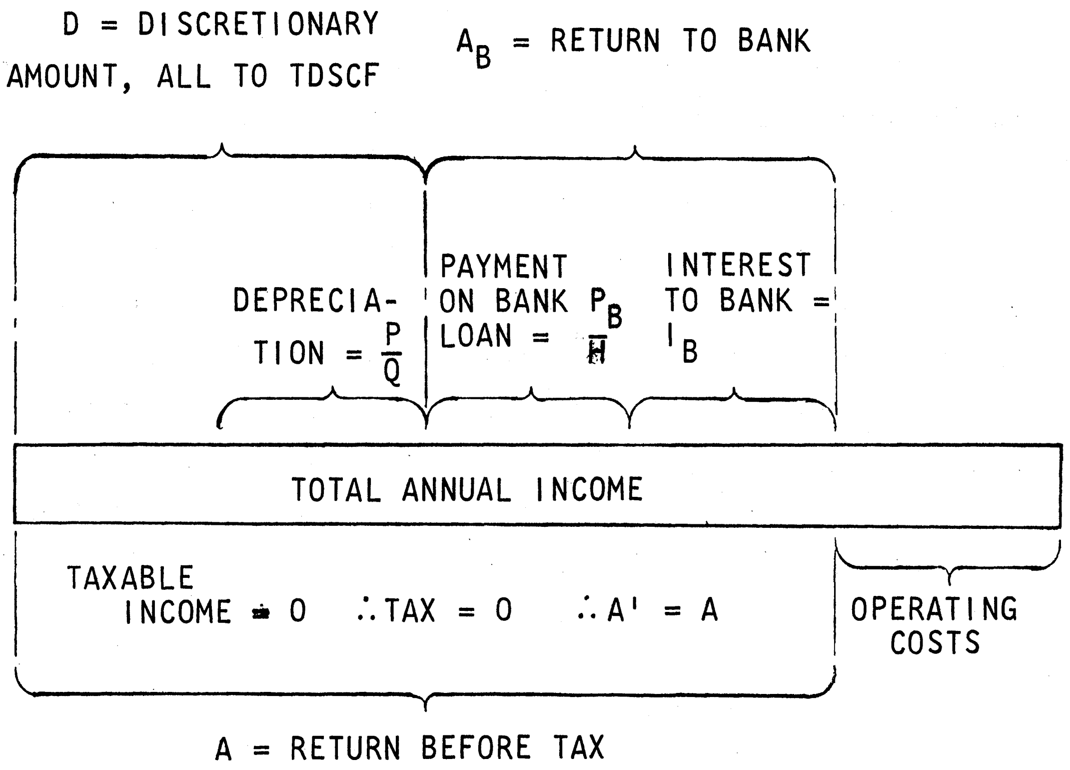


Fig. A3: Distribution of Annual Income During Initial Period (Under New Tax Law)

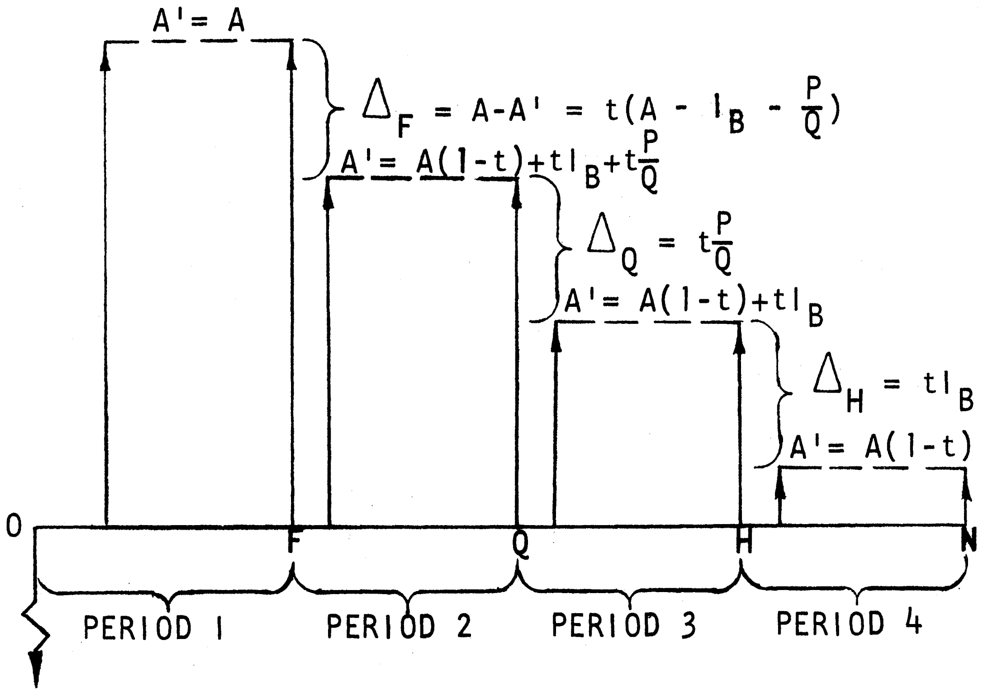


Fig. A4: Cash Flow Diagram Under New Tax Law

As we can see from Figure A3,

$$D = A - A_B$$

Substituting into equation A9:

$$F = \frac{P}{A - A_B} \qquad [A10]$$

or,

$$F = \frac{P}{(CR)P - A_B} \qquad [A11]$$

where

CR = 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:

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

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

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

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

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

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

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

$$A\left[(SPW\text{-}i'\text{-}N)(1-t) + (SPW\text{-}i'\text{-}F)t\right]$$

solving for A:

$$A = \frac{P-(SPW\text{-}i'-H)tI_B-(SPW\text{-}i'-Q)t\frac{P}{Q}+(SPW\text{-}i'-F)t(\frac{P}{Q}+I_B)}{(SPW\text{-}i'-N)(1-t) + (SPW\text{-}i'-F)t}$$

regrouping terms in the numerator:

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

and

$$A = \frac{P-P\frac{t}{Q}\left[(SPW\text{-}i'-Q)+(SPW\text{-}i'-F)\right]+tI_B\left[(SPW\text{-}i'-H)-(SPW\text{-}i'-F)\right]}{(SPW\text{-}i'-N)(1-t) + (SPW\text{-}i'-F)t} \quad [A13]$$

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

$$\boxed{CR = \frac{1-\frac{t}{Q}\ (SPW\text{-}i'-Q)+(SPW\text{-}i'-F)+t\frac{I_B}{P}\left[(SPW\text{-}i'-H)-(SPW\text{-}i'-F)\right]}{(SPW\text{-}i'-N)(1-t)+(SPW\text{-}i'-F)t}} \quad [A14]$$

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-i'-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 A11 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.

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 =

$$\frac{1-\frac{0.48}{20}\,(\text{SPW-}10\%\text{-}20)-(\text{SPW-}10\%\text{-F})-0.48\frac{\$0.393\text{M}}{\$20\text{M}}\left[(\text{SPW-}10\%\text{-}30)-(\text{SPW-}10\%\text{-F})\right]}{(\text{SPW-}10\%\text{-}50)0.52+(\text{SPW-}10\%\text{-F})0.48}$$

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

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

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:

$$F=\frac{P}{(CR)P-A_B} \qquad [\text{A11}]$$

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

$$A_B = (CR\text{-}i_B\text{-}H)P_B \qquad \boxed{A16}$$

In our case:

$$A_B = (CR\text{-}6\%\text{-}30)\$10M$$

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

so

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

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

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

From interest tables:

$$(CR\text{-}10\%\text{-}13.5) = 7.23$$

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)

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

	Before New Law	After New Law
CR	0.16	0.11
CR'	0.1009	0.1009
$\frac{CR}{CR'}$	1.59	1.09

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:

	Before New Law	After New Law	Ratio
All-equity investment	0.154	0.115	1.34
50% bank loan	0.137	0.110	1.24
100% bank loan	0.120	0.105	1.14

The corresponding annual costs of capital recovery would be:

	Before New Law	After New Law	Ratio
All-equity investment	\$3,080,000	\$2,300,000	1.34
50% bank loan	2,740,000	2,200,000	1.24
100% bank loan	2,400,000	2,100,000	1.14

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.

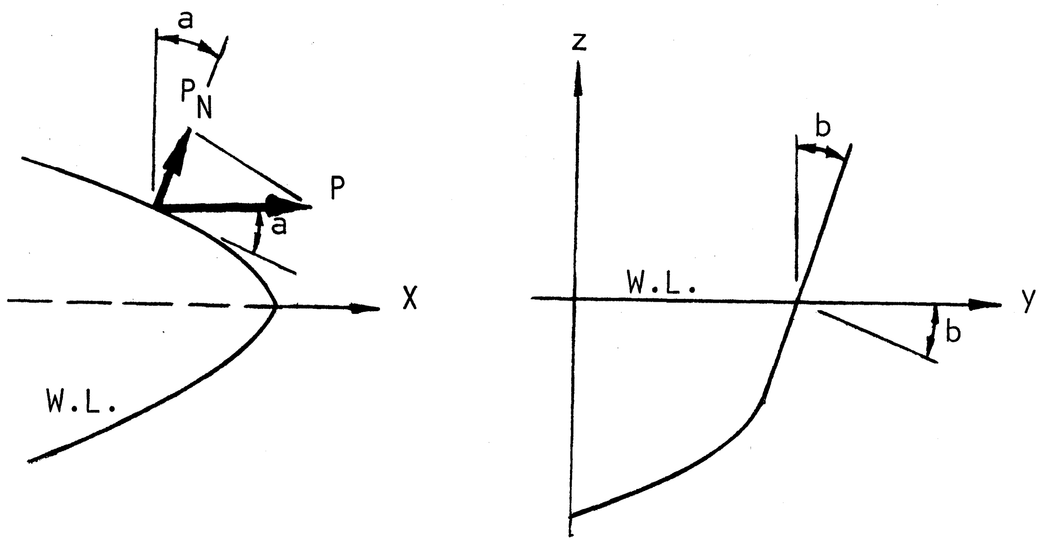
Such a theory can be deduced by suitable adaptation of methods originally developed for different ships and conditions. When at a later stage direct test results for Great Lakes ships become available, they can be used to further substantiate the present estimating method and to improve the accuracy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

I. 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.



$$p_N = p\,(\cos a) \simeq p\, n_x$$

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

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

$$\hat{n} = \frac{\tan a}{\sqrt{1 + \tan^2 a + \tan^2 b}}\,\hat{i} + \frac{1}{\sqrt{1 + \tan^2 a + \tan^2 b}}\,\hat{j} + \frac{\tan b}{\sqrt{1 + \tan^2 a + \tan^2 b}}\,\hat{k}$$

The components of the pressure p_N are, nondimensionally

$$\frac{\vec{p}_N}{p} = \frac{p_N}{p} \cdot \hat{n}$$

$$= \frac{\tan^2 a}{1 + \tan^2 a + \tan^2 b}\,\hat{i} + \frac{\tan a}{1 + \tan^2 a + \tan^2 b}\,\hat{j} + \frac{\tan a \quad \tan b}{1 + \tan^2 a + \tan^2 b}\,\hat{k}$$

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,

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

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

$$\frac{P_z}{p} = \int_{x_B}^{L_x} \frac{\tan a \quad \tan b \sqrt{1 + \tan^2 a}}{1 + \tan^2 a + \tan^2 b}\, dx$$

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

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

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

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.

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

Ship	e_1	e_2
24,000 HP icebreaker	1.9	3.13
12,000 HP icebreaker	2.17	3.40
J. Stalin	2.03	3.25
Ermak	2.41	3.52
Timber freighter	0.33	1.83
Timber freighter	0.54	2.28
Timber freighter	0.80	2.71
Far East cargo ship	0.41	2.34

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. (11), 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

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):

$$\begin{aligned} R_{ICE} &= R_1 + R_2 + R_3 + R_4 \\ &= k_1 B m_o s h + k_2 B m_o g_i h^2 \\ &+ k_3 B^{k_4} \cdot \frac{hV}{e_2} + R_4 \end{aligned}$$

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/meter^2

h = ice thickness, meters

$m_o = 1 + (1/e_1)$ = Kashteljan's vertical ice force coefficient (see comments below).

g_i = specific weight of ice, metric tons/meter^3

e_2 = Shimanshkij'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 Ermak:

$k_1 = 0.004$
$k_2 = 3.6$
$k_3 = 0.25$
$k_4 = 1.65$

The coefficient $m_o = 1 + (1/e_1) = 1 + (P_x/P_z) = (P_x + P_z)/P_z$ 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 Ermak tests with m_o 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:

$$\begin{aligned} R_{ICE} &= R_1 + R_2 + R_3 + R_4 \\ &= C_o sh^2 + C_1 g_i Bh^2 + C_2 r_i BhV^2 + R_4 \end{aligned}$$

where

r_i = mass density of ice,
C_o, C_1, C_2 = coefficients determined experimentally are as described before.

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

Resistance Component	Kashteljan, et al.	Lewis and Edwards
R_1	$k_1 Bm_o sh$	$C_o sh^2$
R_2	$k_2 Bm_o g_i h^2$	$C_1 g_i Bh^2$
R_3	$k_3 B^{1.65} hV/e_2$	$C_2 r_i BhV^2$

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_o, 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

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

where the coefficient

$$m = A_o/e_1$$

was introduced to allow adaptation of Kashteljan's equation to bulk carrier experience.

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

C. Similar to Lewis and Edwards we define

$$R_1 = C_o s B h^2 \cdot m$$

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

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

$$C_o = \frac{k_1}{h}$$

$$C_1 = k_2$$

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

$$R_1 + R_2 = mBh^2 C_o s \left(1 + \frac{C_1 g_i}{C_o s_o} \cdot \frac{s_o}{s} \right)$$

with

$$\frac{C_1 g_i}{C_o s_o} = \frac{R_2}{R_1} = \frac{k_2 h g_i}{k_1 s_o}$$ 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. <u>Discussion</u>:

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 <u>Ermak</u> for 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 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 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)

$$R_3 = 0.25B^{1.65} \cdot \frac{hV}{e_2}$$

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.

$$R_{ip} = (R_{ip})_o \left(\frac{D}{D_o}\right)^s \left(\frac{t}{t_o}\right)^m \left(\frac{S}{S_o}\right)^n \left(\frac{d}{d_o}\right)^p \left(\frac{(L/B)_o}{L/B}\right)^q$$

$$\left(\frac{C_{Bo}}{C_B}\right)^r \left(\frac{(B_1/B)_o}{B_1/B}\right)^k$$

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} = pure ice resistance, metric tons
D = displacement, metric tons
t = ice thickness, meters
S = ice state, surface coverage in percent
d = draft of vessel, meter
L, B = length, beam of vessel
C_B = block coefficient
B_l = 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 tons
t_o = 0.8 meter
S_o = state 8 = 0.8
d_o = 7.3 meters
$(L/B)_o$ = 6.6
C_{Bo} = 0.65
$(B_l/B)_o$ = 15

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

$$s = 1 - \frac{m + p}{3}$$

$$m = 0.267\ F_n^{-0.67}$$

$$n = 0.785\ F_n^{-0.493}$$

$$p = 1.65\ F_n^{0.42} + 0.35$$

$$q = 1.93\ F_n^{0.42} - 0.60$$

$$r = 32.4\ F_n^{2.27} + 1.25$$

$$k = 0.034\ F_n^{-1.31}$$

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:

Ice Class	Minimum Required SHP
IA Super	0.40 Δ + 1,500, but not more than 25,500
IA	0.35 Δ + 1,000, but not more than 22,000
IB	0.30 Δ + 500, but not more than 18,500
IC	0.25 Δ , but not more than 15,000

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 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 <u>required</u> 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

N = rev per second

V_s = ship velocity in feet per second

D_p = propeller diameter in feet

w = 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 = 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,

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

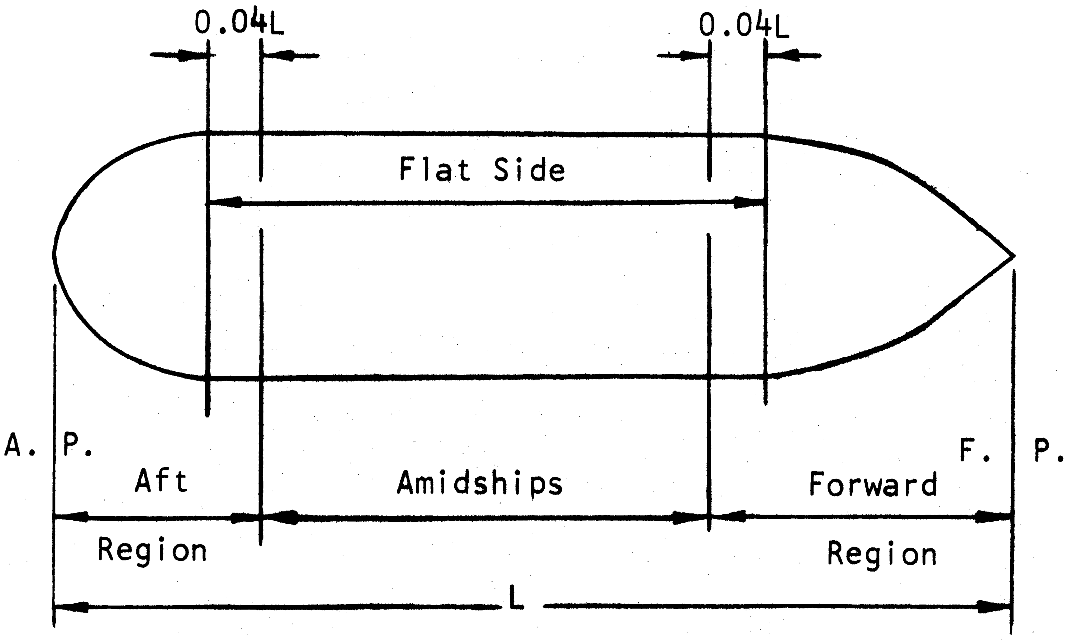
ICE STRENGTHENING AND STEEL WEIGHTS

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;

Class	Ice Condition
IA - Super	extreme ice
IA	severe ice
IB	medium ice
IC	light ice

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.



ICE BELT REGIONS

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.

I. TWO ICE-BELT CONCEPT

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

Ice Class	Vertical Extent of Ice Belt
IA-Super:	from 750mm above LWL to 600mm below BWL
IA:	from 600mm above LWL to 500mm below BWL
IB&IC:	from 500mm above LWL to 500mm below BWL

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:

Ice Class	
IA-Super:	$b_w = (LWL-BWL) + 4.43$
IA:	$b_w = (LWL-BWL) + 3.61$
IB&IC:	$b_w = (LWL-BWL) + 3.28$

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.

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

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

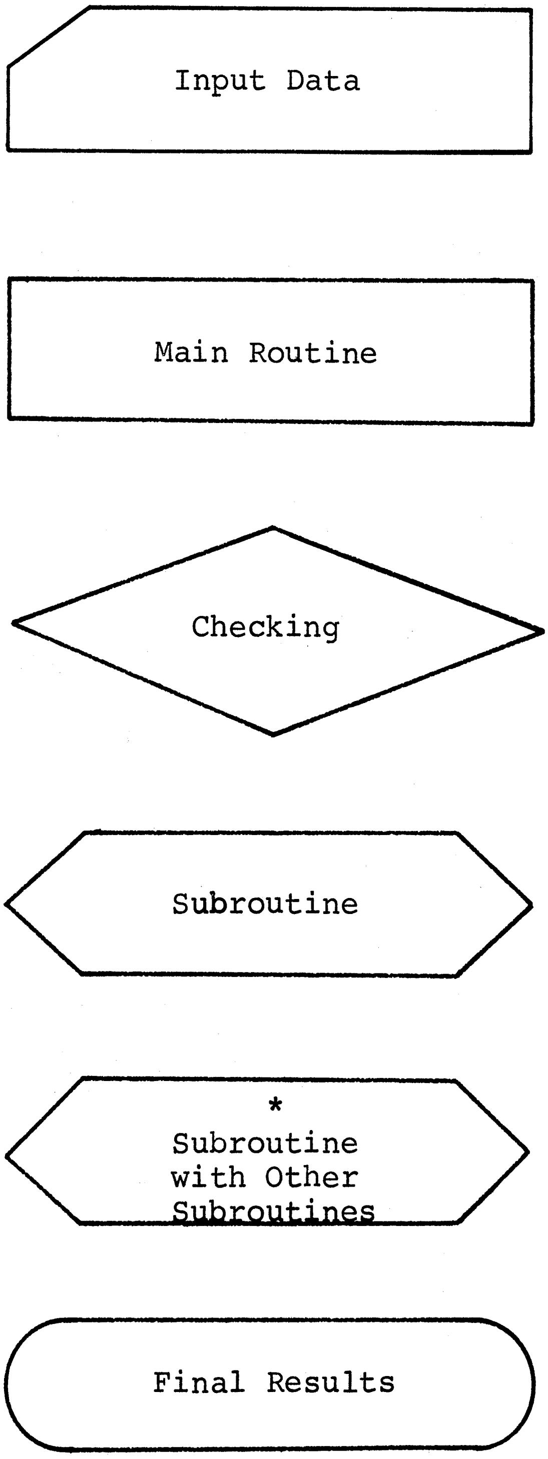
There will also be some savings in the framing requirements of the ship but not quite to the same degree as the plating.

The concept of two separate ice belts merits consideration in future studies.

APPENDIX IV

FLOW CHART

FLOW CHART ANNOTATION



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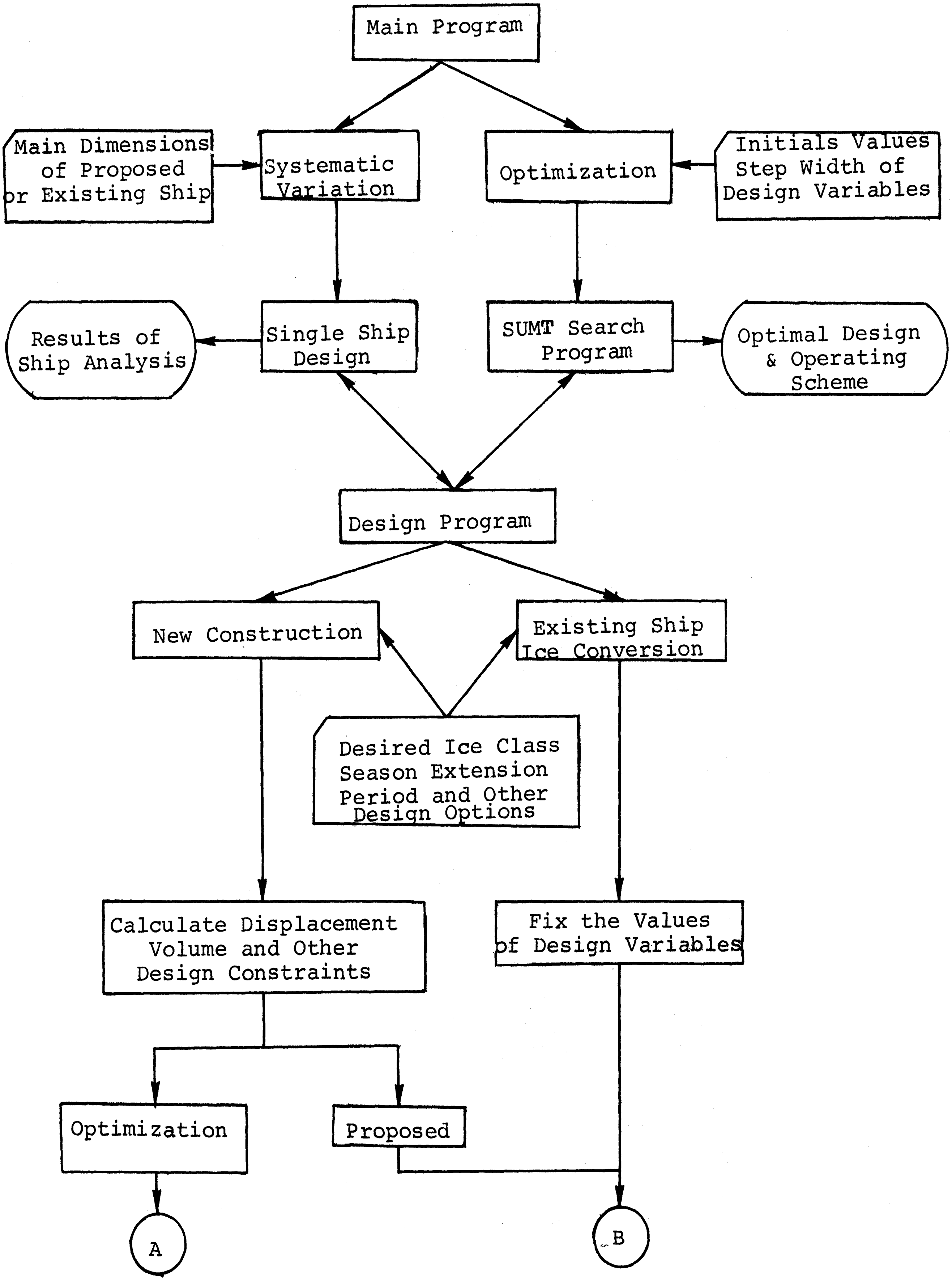

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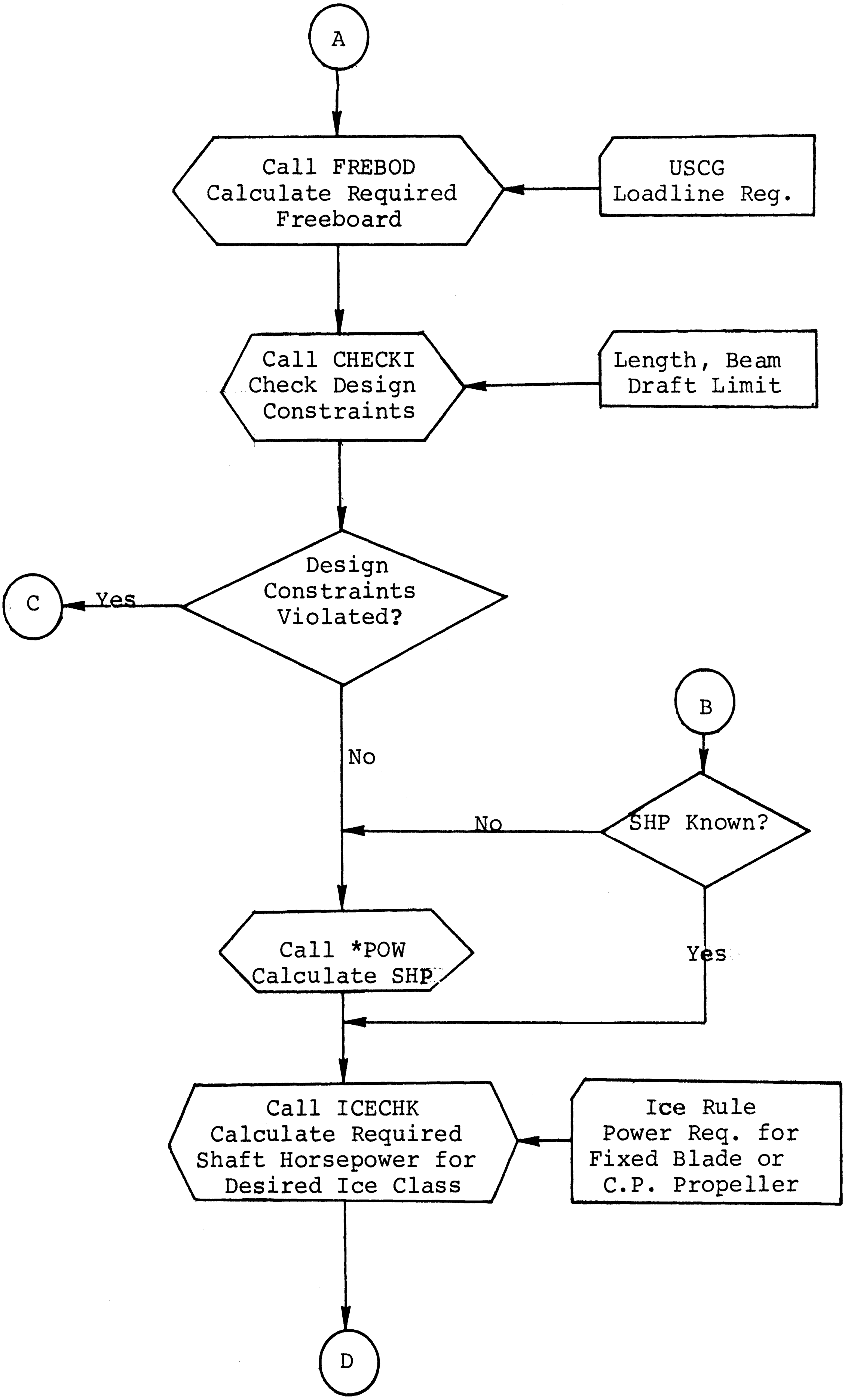

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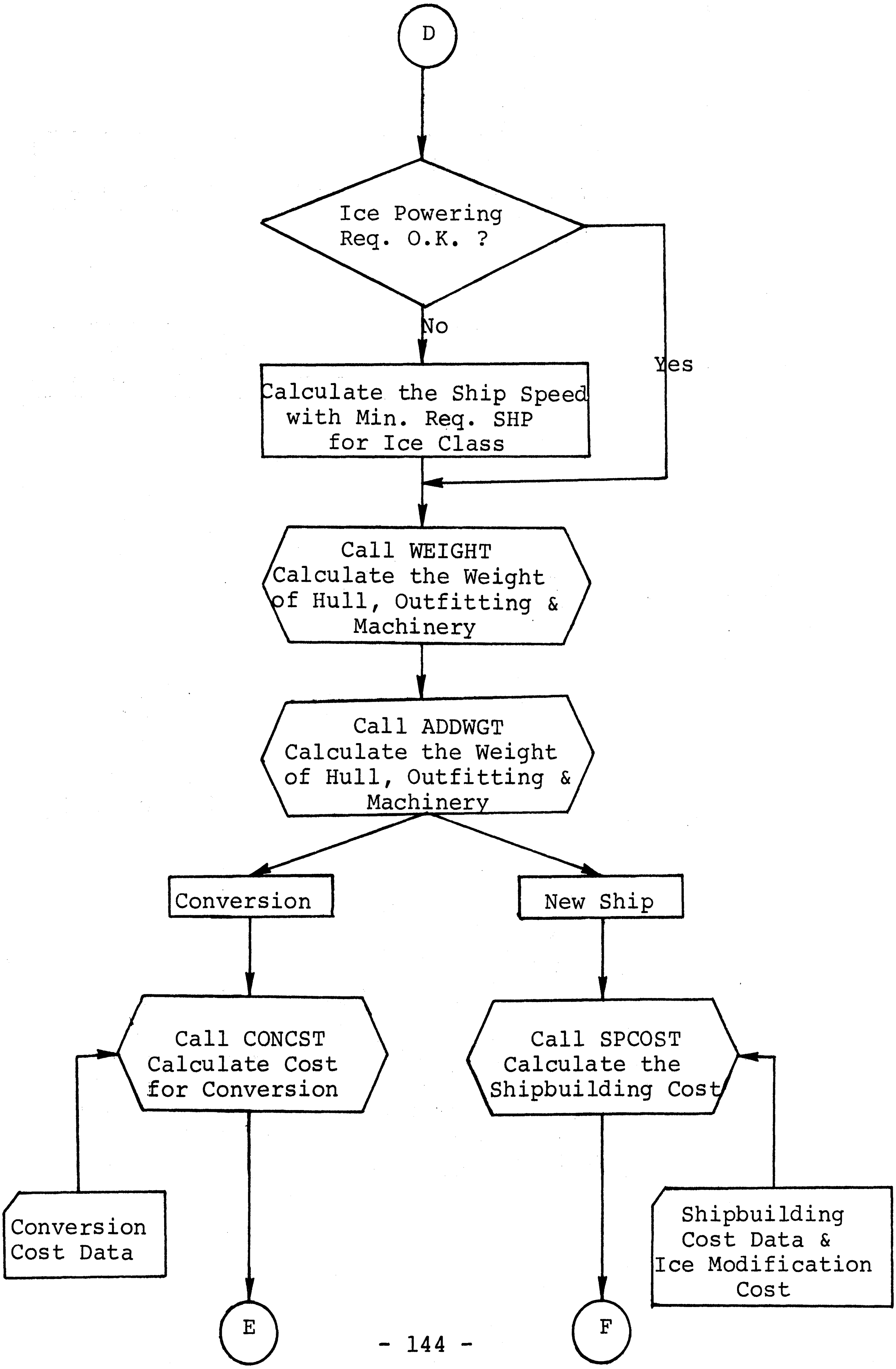
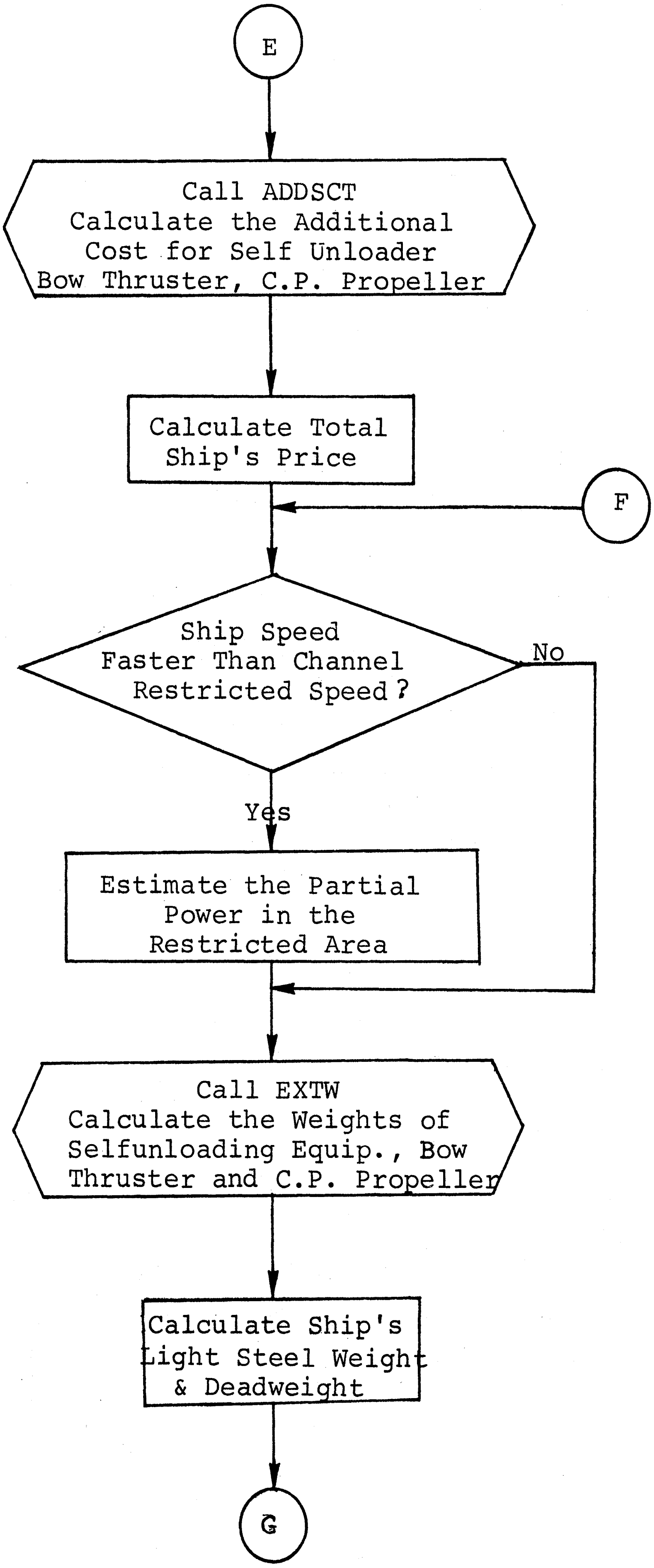
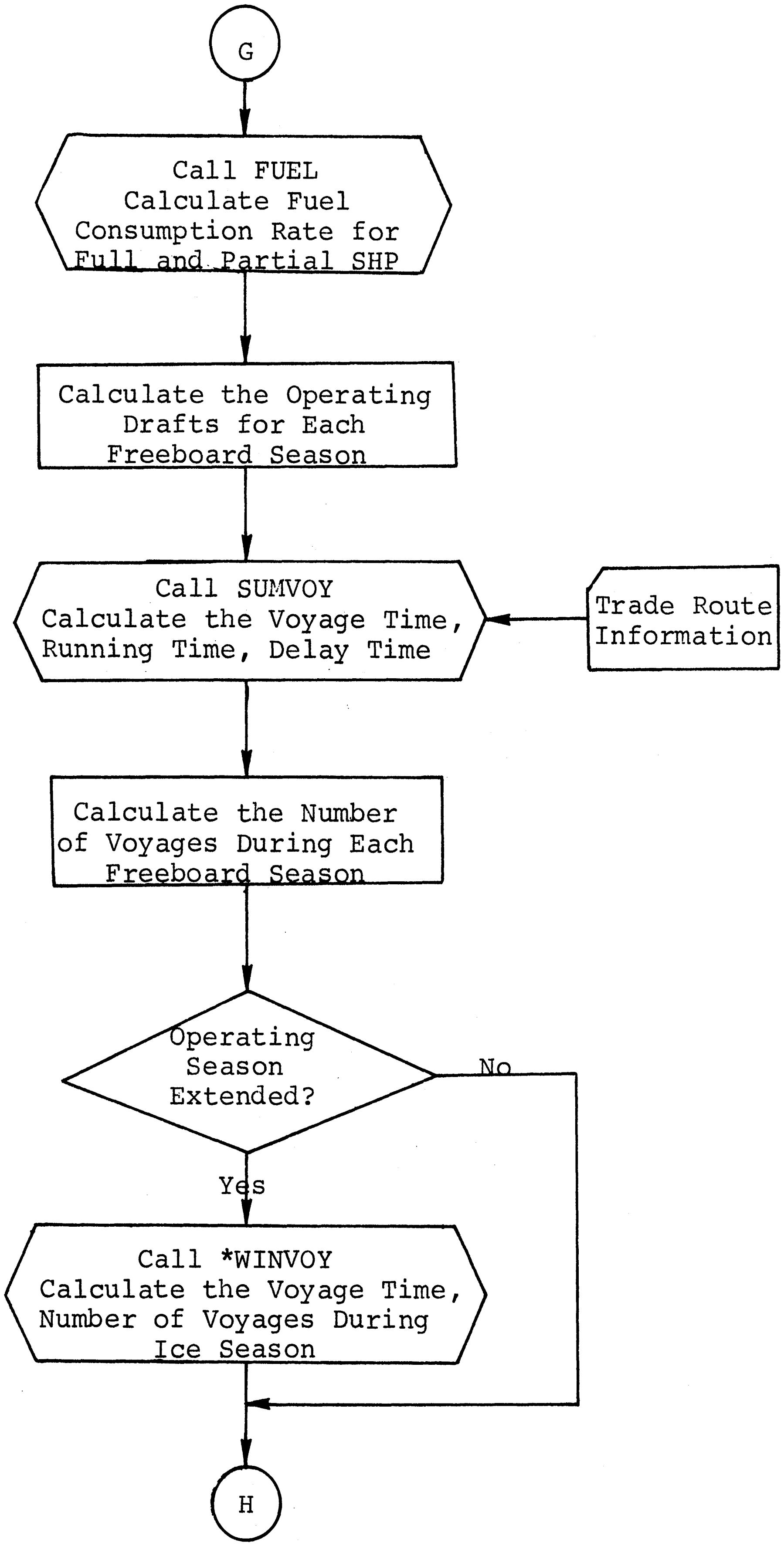
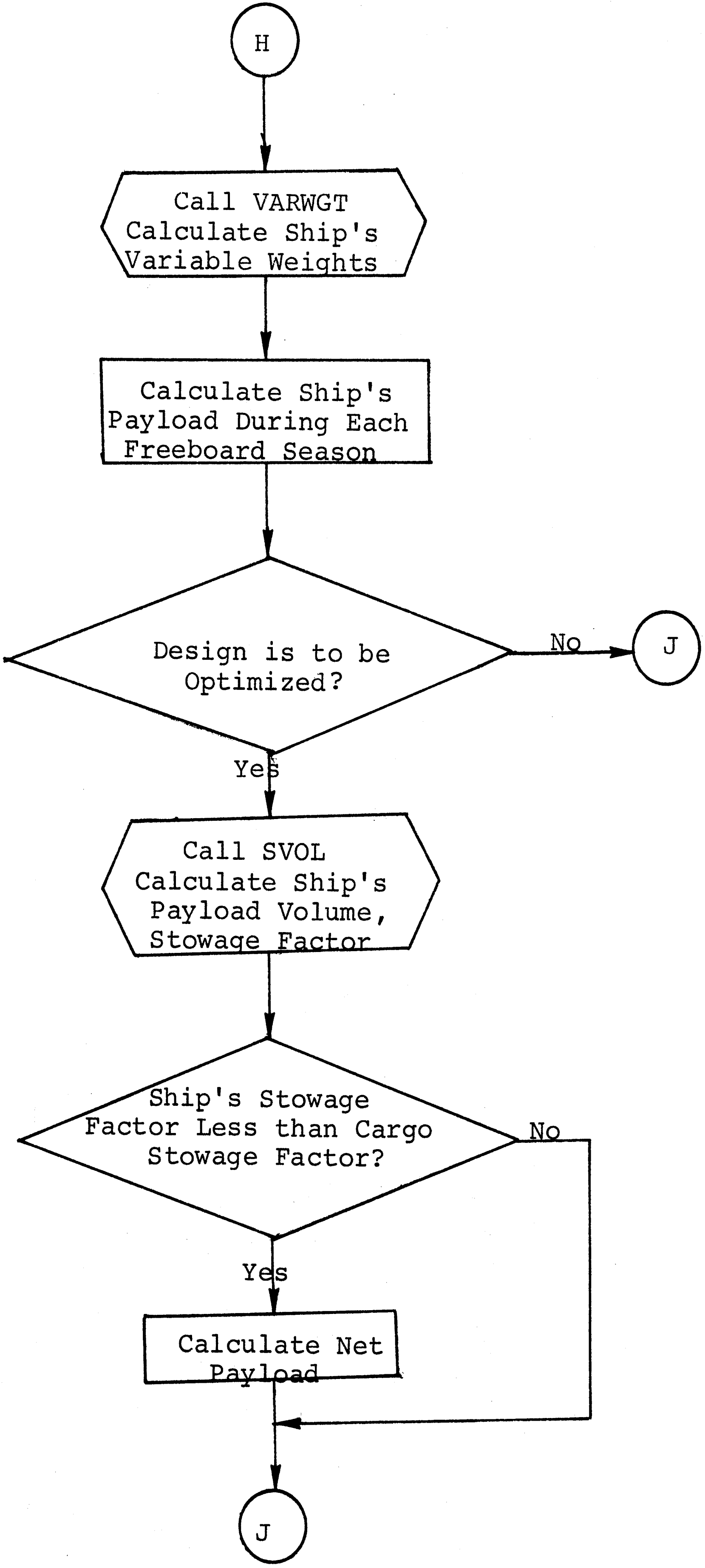


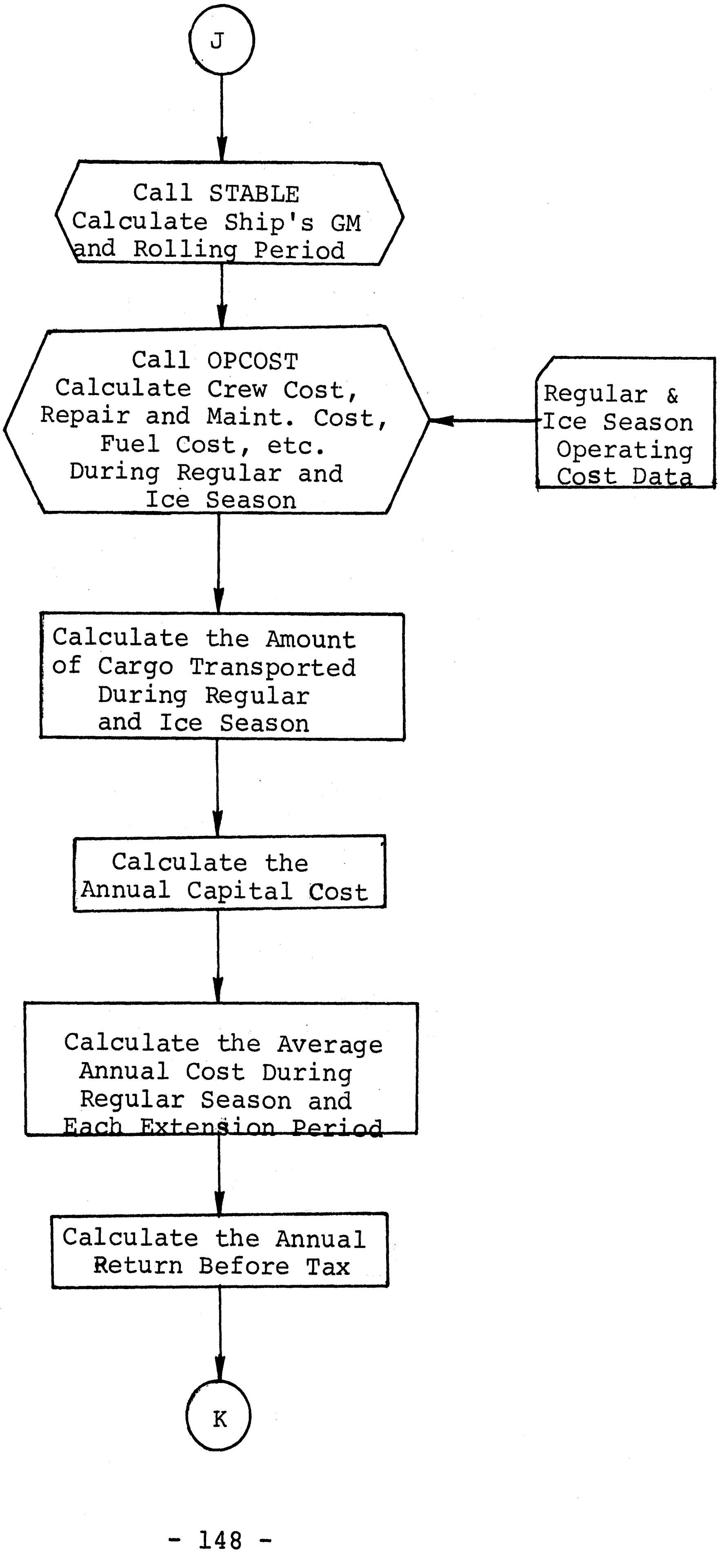

E
Call ADDSCT
Calculate the Additional
Cost for Self Unloader
Bow Thruster, C.P. Propeller
Calculate Total
Ship's Price
F
Ship Speed
Faster Than Channel
Restricted Speed ?
No
Yes
Estimate the Partial
Power in the
Restricted Area
Call EXTW
Calculate the Weights of
Selfunloading Equip., Bow
Thruster and C.P. Propeller
Calculate Ship's
Light Steel Weight
& Deadweight
G

APPENDIX IV: FLOW CHART

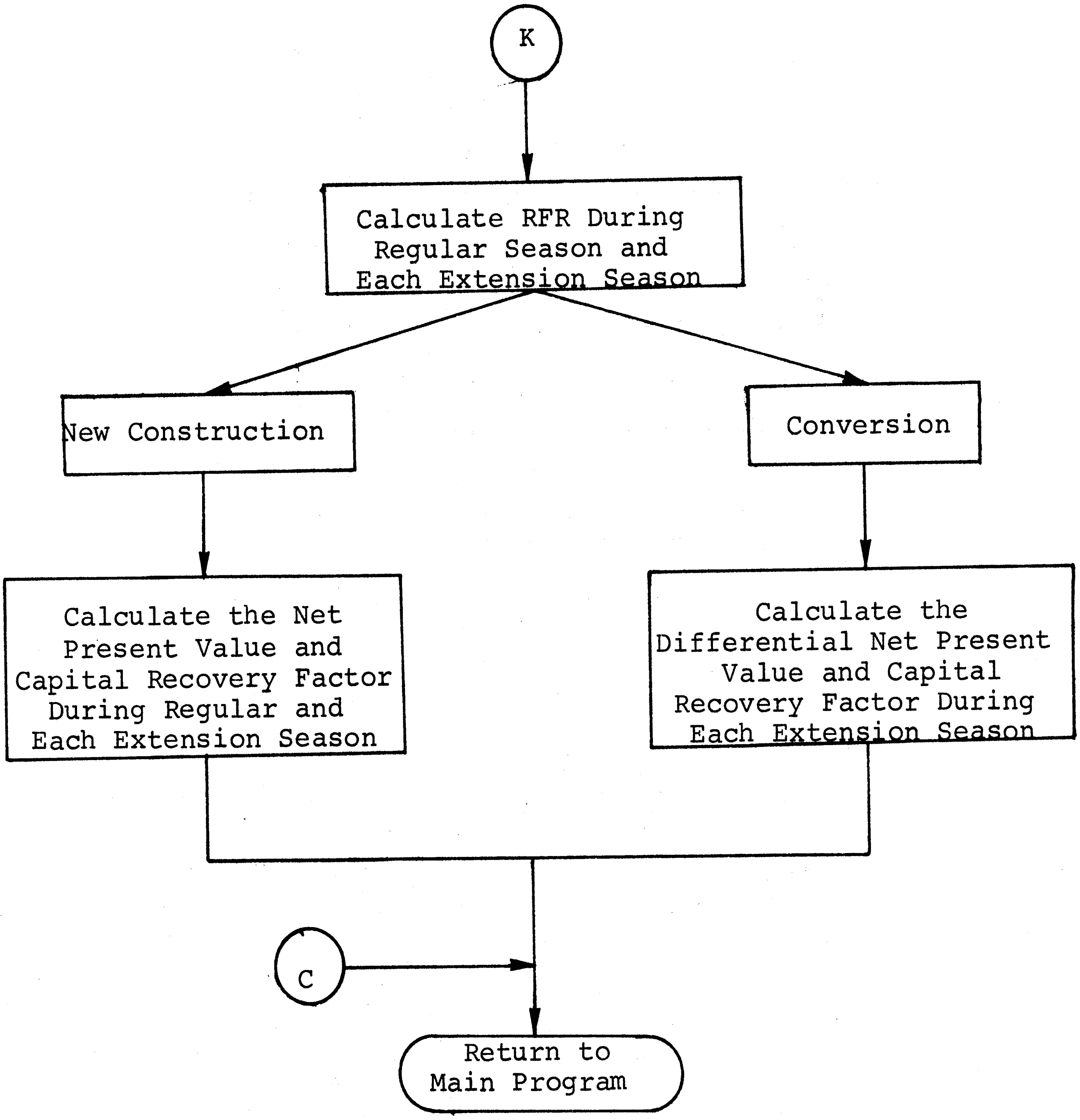



H
Call VARWGT Calculate Ship's Variable Weights
Calculate Ship's Payload During Each Freeboard Season
Design is to be Optimized?
No
J
Yes
Call SVOL Calculate Ship's Payload Volume, Stowage Factor
Ship's Stowage Factor Less than Cargo Stowage Factor?
No
Yes
Calculate Net Payload
J

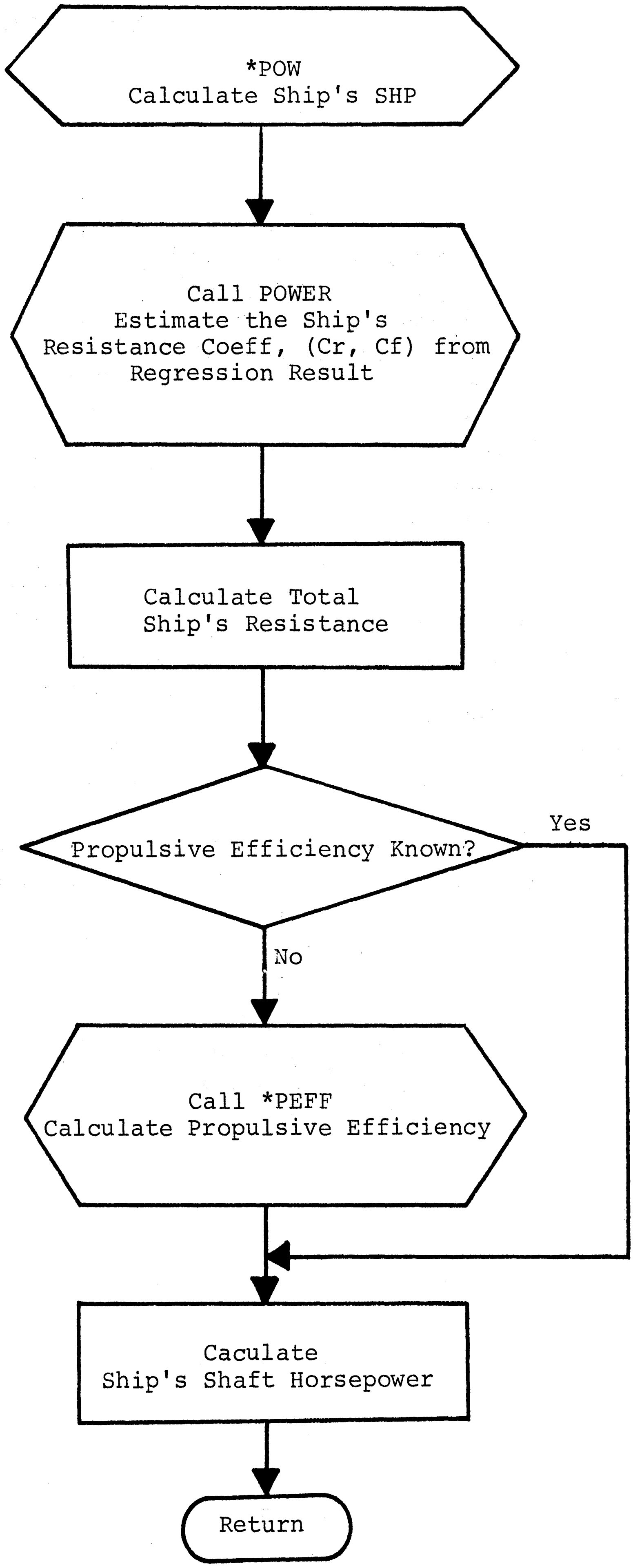
APPENDIX IV: FLOW CHART



APPENDIX I


K
Calculate RFR During Regular Season and Each Extension Season
New Construction
Conversion
Calculate the Net Present Value and Capital Recovery Factor During Regular and Each Extension Season
Calculate the Differential Net Present Value and Capital Recovery Factor During Each Extension Season
C
Return to Main Program

APPENDIX IV: FLOW CHART



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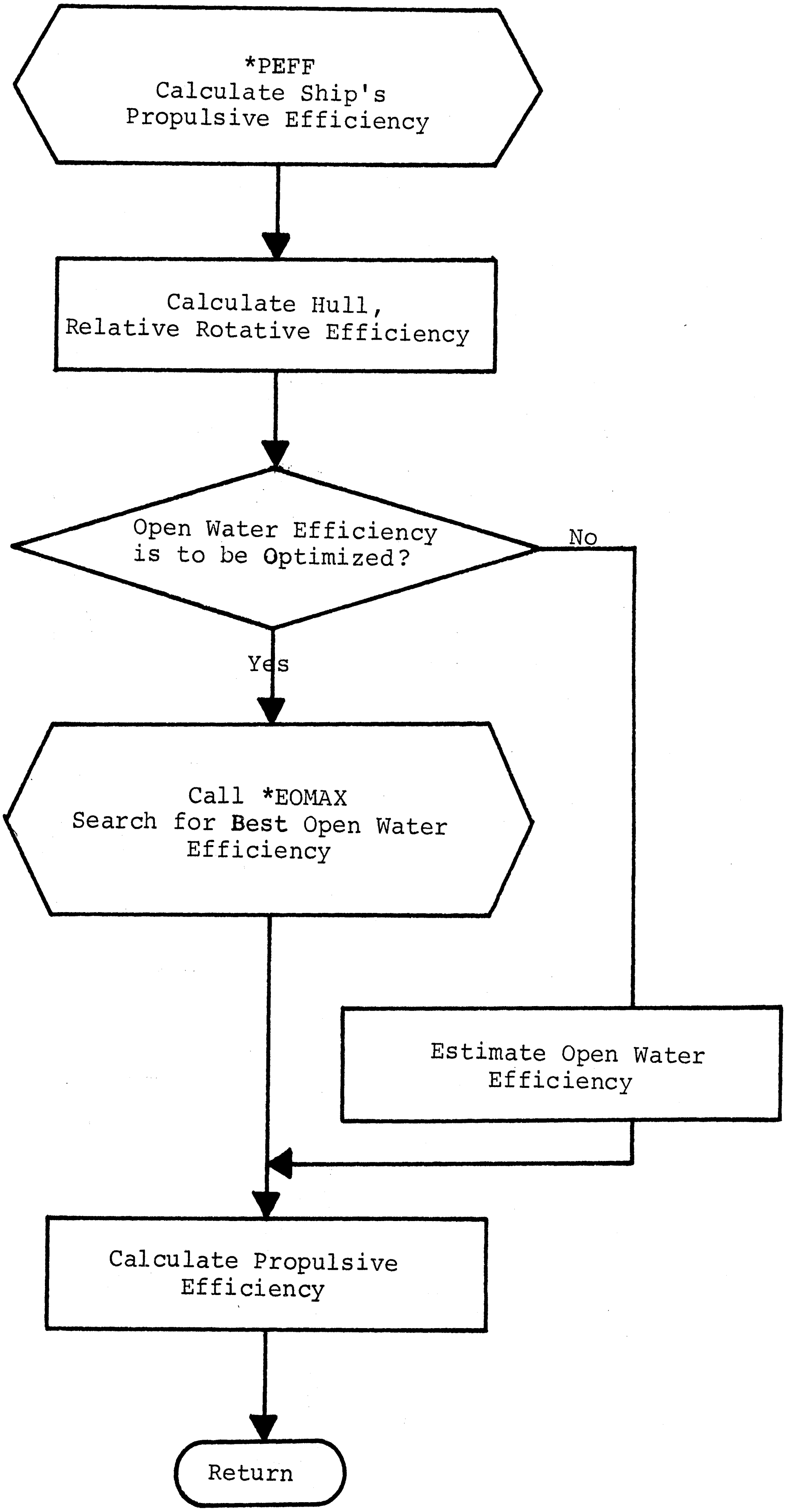

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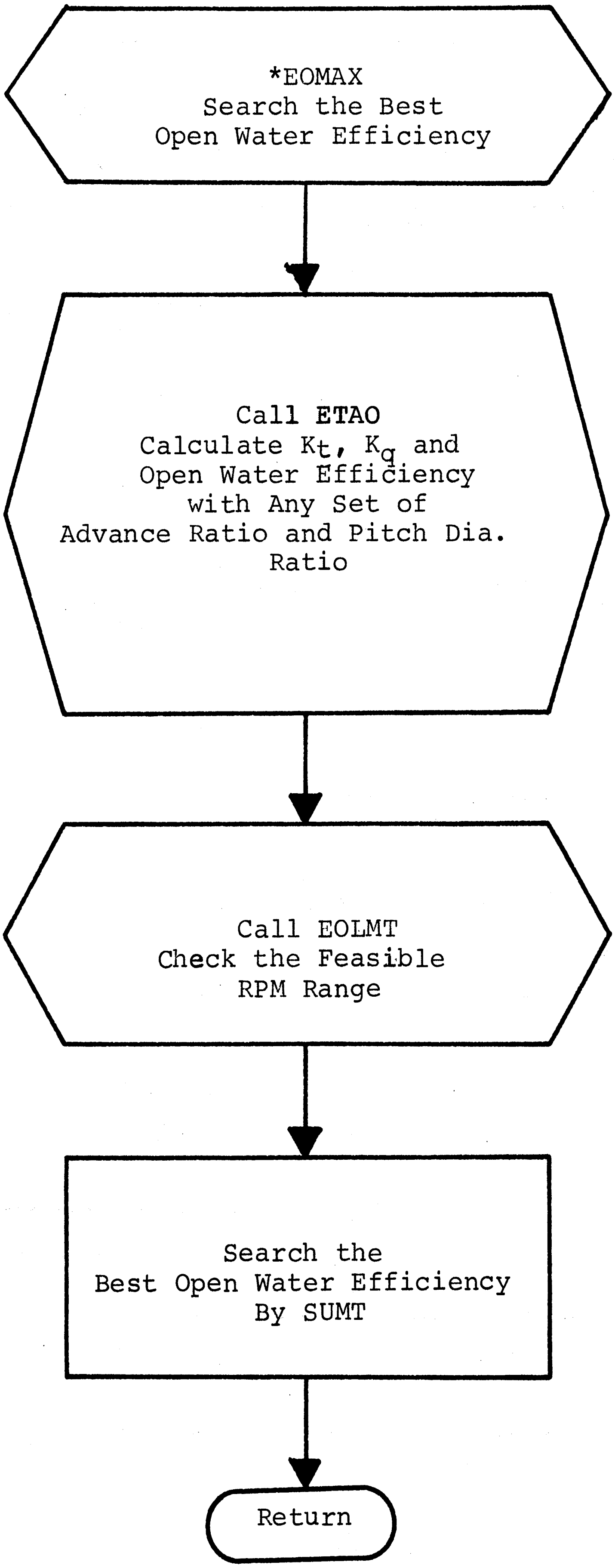

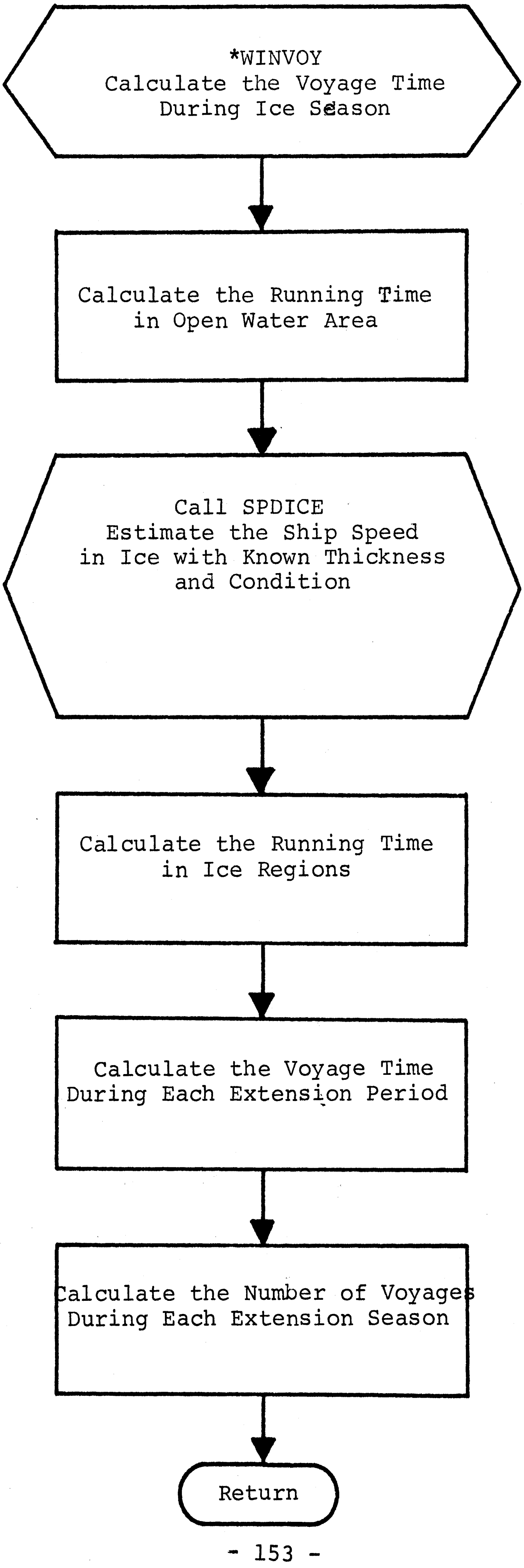
*WINVOY
Calculate the Voyage Time During Ice Season
Calculate the Running Time in Open Water Area
Call SPDICE
Estimate the Ship Speed in Ice with Known Thickness and Condition
Calculate the Running Time in Ice Regions
Calculate the Voyage Time During Each Extension Period
Calculate the Number of Voyages During Each Extension Season
Return

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