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by

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MARINE TECHNOLOGY

The Practical Application of Economics to Merchant Ship Design

By Harry Benford[1]

Naval architects and marine engineers should apply practical economics to decision-making in ship design. A commercial ship is not an engineering success unless it is also a potentially profitable investment. Profitability is related to technical characteristics, and these relationships should be understood by the designer. The paper gives a brief outline of several economic methods applicable to ship design, pointing out that the choice of criterion depends on such circumstances as whether revenues are predictable or not. It continues with suggested methods for estimating weights and building costs for ships. The problems of predicting annual transport capacity and operating costs are discussed in detail. There follow several comments on the practical application of all the foregoing ideas to decision-making in ship design. Sample studies are appended. Numerical values given in the paper are only intended to indicate trends. There is no intent to present an estimating handbook; the emphasis is entirely on principles and methods of application.

Introduction

Two underlying principles that should guide every decision in ship design are:

1 *A commercial ship is an investment that earns its returns as a socially useful instrument of transport.*

2 *The best measure of engineering success is profitability; and the only meaningful measure of profitability is the returned profit (after tax) expressed as interest on the investment.*

This is not to say that profitability is the sole criterion in ship design. There are also intangibles, such as pride of owning a fine looking ship, that must also be kept in mind. Most such considerations are, however, the responsibility of business managers, not engineers. We shall next define the basic terms of this paper:

Economics is the task of allocating a finite supply of investment funds in the face of infinite possibilities.

Engineering is concerned with applying scientific knowledge to the benefit of society. In a free economy, society expresses its collective needs through its individual purchases—which places the businessman between consumer and engineer.

Engineering economics, then, is an approach to design aimed at meeting society's need with a maximum effectiveness in the use of resources: manpower, materials, and investment funds.

A common fault, both in engineering education and in engineering practice, is a failure to remember that engineers must be just as conversant with businessmen as they are with scientists. Far too few engineers take proper interest in the economic aspects of their work. Their parochialism may be permissible in pure research. In design, however, an engineer who fails to consider economics will inevitably turn out a product that is technically sophisticated but unnecessarily expensive to build. I suspect, for example, that many merchant ships have over-designed propulsion plants. I mean by this that their last few points of fuel economy can never properly repay the extra initial cost. Other examples could as well be cited. Some of this comes from outright neglect of economic considerations, the rest from the application of illogical economic criteria.

An engineer can find no better way to sell his ideas to management than to argue that his proposed design promises to be more profitable than any alternative investment. But how can the engineer be sure that his design is indeed the best? This requires a sweeping operational analysis. If the object under study is a ship, the engineer must first determine its functional requirements and operating restrictions (maximum permissible draft, and so forth). He must then methodically analyze the economics of enough hypothetical ships to find the one that promises to be the most profitable of all. He deals

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largely in imaginary ships, without benefit of detailed design. He must be able to estimate the transport potential, construction cost, and operating costs of each of these imaginary ships. This involves preliminary estimates of speed and horsepower. It also requires rough estimates of weights of the principal components of light ship: steel hull, outfitting, hull engineering, and propulsion machinery. Most practicing engineers, when confronted with such a task, are prone to lose themselves in wasteful detail. Much of the art of operational analysis involves an intelligent selection of the key factors and a strong-willed resolve to eliminate all cost issues that will have little or no effect on the final result. A related cardinal rule is this: In engineering economics, what is important is the differences between alternatives. Thus, while none of us can hope to predict accurately future cost levels, we can nevertheless reach the correct decision as long as we correctly predict relative costs. This also indicates the wisdom of omitting from consideration all factors that are common (or nearly the same) for all alternatives. These might include, for example, overhead costs. We can, and should, overlook all past costs, too, for they cannot be changed and are therefore identical for every alternative.

We have been talking about optimization studies. The same thoughts, in general, apply to feasibility studies, such as nuclear versus conventional machinery—or the merits of installing deck cranes instead of conventional mast-and-boom cargo gear.

This introduction has presented an overall view of the purpose and procedures involved in the application of engineering economics to the design of ships. The remaining sections deal with the major pertinent topics, starting with the selection of an economic criterion. The main body concludes with a section that discusses the practical application of operational analysis. The concluding pages present sample studies.

Where cost levels are cited, they are appropriate only to the United States. Physical units are generally in the British system. Supplementary values for metric units are given in cases where units are greatly different (such as in cubic feet and cubic meters). Since all weights and costs are rough, at best, the author has not converted either horsepower or long tons to their metric equivalents unless other units are simultaneously involved. (One British hp = 1.014 metric hp; one long ton = 1.016 metric tons.)

Economic Criteria

General

We must at once realize that we still have much to learn about ship economics, just as is true with the purely technical aspects of ship design. Nevertheless, the knowledge that we now have can be gainfully employed while we concurrently do the research needed to reduce the remaining areas of ignorance.

There are several valid economic criteria that let you gage the relative profitability of competing ship designs. Nearly all practical cases can be handled by one or the other of the four methods described in the following. The four criteria that we shall use here are developed at length in reference [1][2] and are presented here only in outline form. All assume uniform annual costs and revenues, although levels may vary between alternatives.

Capital Recovery Factor (CRF)

When all alternatives have equal lives and revenues are known, we can find *CRF* for each and would choose the alternative with the highest value:

$$CRF = \frac{A}{P} \qquad (1)$$

where

A = annual returns = annual revenue minus annual operating costs
P = invested cost

Returned Interest

Where revenues are known but lives differ between alternatives, *CRF* should be converted to an equivalent interest rate of return. This is most conveniently done by plotting curves of *CRF* versus interest rate for various lives. Values can be found in interest tables, or see Fig. 1 reference [1].

Average Annual Cost (AAC)

The average annual cost criterion is appropriate where revenues are unknown but the same for all alternatives. Find the alternative with lowest *AAC*.

$$AAC = Y + [CRF]P \qquad (2)$$

where

Y = annual operating costs
CRF = capital recovery factor corresponding to the life of the investment, n, and the owner's stipulated before-tax interest rate of return, i. See interest tables or use equation (3):

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (3)$$

Required Freight Rate (RFR)

When revenues are unknown but will vary between alternatives because of differences in transport capability, we merely divide *AAC* by the annual transport capacity, C, to obtain the required freight rate. The alternative with lowest *RFR* is desired.

$$RFR = \frac{AAC}{C} = \frac{Y + [CRF]P}{C} \qquad (4)$$

The capacity, C, can be in any units you desire.

[2] Numbers in brackets designate References at end of paper.

Weights

General

We must estimate light ship weights both as a step in finding cargo deadweight and in estimating costs. We need procedures that accurately reflect variations in ship size, proportions, horsepower, and any other technical parameter that might have a marked influence on the economics of our proposed ship. Our procedures usually must be applicable to imaginary ships for which we have not yet developed engineering drawings of any sort. In short, we must make use of only outline information such as the principal dimensions. And, in view of the many alternatives to be analyzed, our approach must be reasonably simple, although the proper degree will vary with circumstances, and, most importantly, the availability of a computer.

Weight values given in the following paragraphs are based largely on U.S. cargo liners built since 1960.

Schokker et al [2] present much additional weight data. Weight estimating curves for tankers and ocean ore carriers may be found in references [3] and [4]. Illies and Legrand [5] may also be consulted.

Weight Breakdown

No two shipyards or design offices seem to have exactly the same detailed system for recording weights. Where weights are cited here, they are based on Watson's breakdown [6], which is summarized under the subheads: hull structure, outfitting, hull engineering, and propulsion machinery. These make up light ship weight. Nonpayload deadweight items (such as fuel) must also be estimated, as discussed later.

Hull Structure Weight

Hull structure includes the main hull structure, superstructure, deck houses, and all internal divisional bulkheads over one-eighth inch thick. It also includes masts, king posts, and foundations.

Evans and Khoushy [7] have attempted comprehensive analyses of the structural weight of general cargo ships. Their work, in effect, stores the American Bureau of Shipping rules in a computer. The computer is programmed to estimate the midship structural weight of a ship of any reasonable combination of dimensions. Buxton of Glasgow University has done similar work on tankers. Eventually, we shall assuredly rely heavily on computer-estimated weights. I believe, however, that further developmental work remains before reliable results can be obtained. This is an important area for continuing research. As an interim contribution, computers could be used to derive polynomial equations for structural weight based on statistical analysis of existing ships. For example, equation (5), which follows, could no doubt be improved. It was derived by much guess-and-try. A computer could have sorted out the numerous variables in a quicker and more reliable way, I am sure.

Many naval architects still rely on the most hoary of all parameters for estimating steel weights: the Cubic Number (CN) or $LBD \div 100$. They of course make corrections for block coefficient, length-depth ratio, number of decks, extent of superstructure, and so forth. The author has tried many newer ways but keeps returning to Cubic Number; it seems to be as accurate a predictor as any for notional ships—and its simplicity is hard to beat. In the case of general cargo ships, the author has found the following Cubic Number variation to be reasonably accurate and easy to use:

$$W_s = C_s \left(\frac{CN}{1000}\right)^{0.9} C_1 C_2 C_3 \qquad (5)$$

where

W_s = steel weight in long tons

$C_s \doteq 340$ (long tons per 100,000 cu ft) = 8550 (metric tons per 100,000 cu m)

$$CN = \text{Cubic Number} = \frac{LBD}{100}$$

$$C_1 = 0.675 + \frac{C_B}{2}$$

$$C_2 = 1 + 0.36\,\frac{L_S}{L}$$

$$C_3 = 0.006\left(\frac{L}{D} - 8.3\right)^{1.8} + 0.939$$

and

L = length between perpendiculars
B = beam
D = depth to uppermost continuous deck
C_B = block coefficient at design draft
L_S = length of superstructure within fore and aft perpendiculars

These figures are appropriate for hulls employing little or no special steels or aluminum alloys.

Telfer [8], Munro-Smith [9], and Watson [6] all present other, more sophisticated approaches to steel weight estimation.

Outfitting and Hull Engineering Weight

In addition to such obvious items as hull insulation and joiner bulkheads, the outfitting category includes hawse pipes, deck fittings, cargo booms, anchors, rudder and stock, galley equipment, and hatch covers (which are in this particular category for historic reasons only).

Hull engineering contains nonpropulsion mechanical equipment such as deck machinery, steering engine, generators, ventilation systems, refrigeration systems, hull piping systems and pumps, and the electrical systems.

There are pronounced variations in the weights of the categories depending on the relative degree of sophistication specified by the owners. The author has never found a completely satisfactory way to analyze these weights for preliminary design purposes. Tentatively, however, the author proposes the following for general cargo ships:

$$W_0 = C_0 \left(\frac{CN}{1000}\right)^{0.825} \quad (6)$$

and

$$W_{HE} = C_{HE} \left(\frac{CN}{1000}\right)^{0.825} \quad (7)$$

where

W_0 = weight of outfitting in long tons
W_{HE} = weight of hull engineering in long tons
C_0 = coefficient ranging from 109 (2103)[3] to 160 (3090) with an average value of 125 (2412)
C_{HE} = coefficient ranging from 53 (1023) to 82 (1583) with an average value of 62 (1196)

Propulsion Machinery Weight

The machinery category includes the propulsion system from propeller to smokestack. It also includes ladders and gratings in the machinery spaces, as well as piping, instruments, controls, and liquids in machinery.

The obvious technical parameter for estimating machinery weight is the horsepower. In the case of U.S.-built steam turbine machinery, I have found equation (8) fairly reliable:

$$W_M = C_M \left(\frac{\text{shp}}{1000}\right)^{0.5} \quad (8)$$

where

W_M = weight of propulsion machinery in long tons
shp = maximum continuous shaft horsepower
C_M = machinery weight coefficient, Table 1

Table 1 Values of Machinery Weight Coefficient, C_M

	Machinery Location Amidships	Aft
Single screw, average	235	214
Single screw, minimum	219	203

Illies [10] and Danckwardt [11] both find considerably higher weights for European-built steam turbine machinery.

Nuclear machinery apparently follows weight trends like those of oil-fired steam plants. The more optimistic forecasts are that nuclear plants will eventually weigh little, if any, more than present-day steam turbine plants.

Diesel-propulsion weight seems to vary with brake horsepower raised to a higher exponent than the 0.5 appropriate to steam plants. Values range from 0.70 to 0.82. For example, Illies [10] shows a curve that approximates the expression

$$W_M = 215 \left(\frac{\text{bhp}}{1000}\right)^{0.72} \quad (9)$$

[3] Numbers in parentheses apply to metric tons and cubic meters.

Other information on machinery weights may be found in works by Powell [12], Andreson [13], Johansen [14], Simpson [15], and White and Smith [16].

Building Costs

General

Preliminary estimation of shipbuilding costs is a subject worthy of continuing investigation. Little has been published on this topic although dependable cost estimates are highly necessary in ship design analysis. No other single input has more bearing on the final results of an economic study. The main aim is not necessarily to predict absolute cost levels, but to find how changes in the technical characteristics influence the overall cost.

Cost figures cited here are based on studies carried out in 1962, reference [17], and are appropriate to U.S. shipyards. They are given more to suggest methods of approach than to delineate quantities. Anyone who aspires to be a cost analyst must go to great lengths to collect his own data and to derive his own coefficients.

Cost Breakdown

For convenience, building costs are put into the same subdivisions used in the weight analysis. There are additional categories that involve cost but are not concerned with any weights in the finished ship. These would include engineering, staging, cleaning, launching, temporary lights, and so forth.

A second cost breakdown divides costs into material, labor, overhead, and profit. Material involves all shipyard purchases: unfinished materials, equipment, subcontracted work, outside engineering services, and so on. Labor includes wages and benefits paid to shipyard employees whose work is directly connected with a ship under contract. Overhead is the sum of all internal shipyard costs that cannot be directly attributed to any given contract. This would include officers' salaries, watchmen's pay, yard maintenance costs, taxes, fuel costs, and many others.

Hull Structure Cost

Steel material costs average $220 per long ton net weight. This includes transportation and covers special shapes, welding rods, castings, forgings, and a nominal quantity of aluminum and special steels as well as ordinary shipbuilding steel.

Hull structure man-hours for general cargo ships can be estimated as

$$MH = C \left(\frac{W_s}{1000}\right)^{0.85} \quad (10)$$

where W_s is the net weight of steel in long tons and C is a coefficient which varies from 68,000 in an efficient yard (by U.S. standards) to 140,000 in an average small and inexperienced yard. In a typical large yard, C will run around 90,000. These figures are for ships of a degree of complexity like those of recent U.S. design.

For bulk carriers, man-hours for hull structure can be estimated as:

$$\text{MH} = C\left(\frac{W_s}{1000}\right)^{0.90} \tag{11}$$

where C has average values of 70,600 for tankers and 78,500 for ocean ore carriers.

Evans and Khoushy [7] propose a unique steel cost estimating method based on an equivalent surface concept. Whether their approach is entirely practical remains to be seen.

Outfitting and Hull Engineering Costs

Outfitting and hull engineering costs are difficult to estimate. Both categories contain widely diverse components, the unit costs of which vary to an extreme. These costs are greatly in need of further study. They are large, particularly in general cargo ships; and, to the best of my knowledge, no really satisfactory preliminary estimating method exists.

Until a better approach is found, the author would estimate outfitting material costs for general cargo ships at between $720 and $1250 per long ton, net weight, with an average figure of $980. Outfitting man-hours would be approximately

$$\text{MH} = C\left(\frac{W_o}{100}\right)^{0.9} \tag{12}$$

where W_o is the net weight of outfitting in long tons and C varies from 15,000 to 27,500 with an average value of 20,000. This breakdown assumes no subcontracting of deck covering or joiner work.

For general cargo ships, the material cost for hull engineering varies between $2000 and $3400 per long ton, net weight. An average value is $2700 per ton. Man-hours can be estimated as:

$$\text{MH} = C\left(\frac{W_{HE}}{100}\right)^{0.75} \tag{13}$$

where W_{HE} is the net weight of hull engineering in long tons and C falls between 39,000 and 72,000 with an average value of 51,000.

References [3] and [4] suggest ways of estimating costs of outfitting and hull engineering for tankers and ocean ore carriers. Those figures are, however, somewhat in need of revision.

Propulsion Machinery Costs

Conventional steam turbine machinery with steam conditions of 600 psi and 850 F are discussed here. The material costs can be estimated as

$$M = \$416{,}000\left(\frac{\text{shp}}{1000}\right)^{0.6} \tag{14}$$

while man-hours can be estimated as

$$\text{MH} = 24{,}000\left(\frac{\text{shp}}{1000}\right)^{0.6} \tag{15}$$

Since both material and labor costs vary as horsepower raised to the sixth-tenths power, a simple expression for total cost of installed machinery can be derived. If we assume the overhead cost is 70 percent of labor, the average hourly labor rate is $3.20, miscellaneous costs are as later discussed, and a 5-percent profit margin is added, we have:

$$\text{Machinery cost} = \$663{,}400\left(\frac{\text{shp}}{1000}\right)^{0.6} \tag{16}$$

All of the foregoing expressions can be multiplied by about 0.91 in case machinery is located aft.

Halley [18] estimates that twin-screw steam turbine plants will cost about 13 percent more than single-screw plants. He also shows relative costs of single-screw and twin-screw diesel plants. Illies [10] shows comparative costs for steam and diesel plants, while Illies and Legrand [5] include additional material on nuclear-machinery costs. Other useful cost data may be found in publications by Andreson [13], Johansen [14], Simpson [15], and McMullen [19].

Miscellaneous Costs

All of the foregoing costs have been confined to specific parts of the ship. In addition, the miscellaneous (or nonweight) costs must also be considered. These should be kept separate since they tend to be relatively high in smaller ships, and are sensitive to unusual conditions of design or construction. As a rough indication of their magnitude, for average conditions, the subtotal of material costs for structure, outfitting, hull engineering, and machinery should be increased by about 10 percent for miscellaneous materials. Similarly, labor costs should be increased by about 33 percent for miscellaneous labor.

Overhead Costs

Estimating the cost of overhead is among the most difficult phases of cost engineering. As a rule-of-thumb, overhead is generally approximated as a percentage of labor cost, although this is not exactly a logical approach. In shipyards, the ratio of overhead to labor (including miscellaneous) generally falls between 60 and 85 percent, with 70 percent as a reasonable average. The value is particularly sensitive to the level of work in hand and to the extent of investments in laborsaving devices. In actual practice, estimating overhead cost is really a managerial, not an engineering, responsibility.

Profit

Profit is usually calculated as a percentage mark-up of the summation of all the material, labor, and overhead costs. In average times, a 5-percent mark-up is appropriate. This percentage should not, of course, be mistaken for the rate of return on the owner's investment.

Duplicate Ship Savings

The cumulative average cost ($\bar{Y}$) of identical ships, built in sequence at a shipyard, bears the following relationship to the cost of the first ship of the series:

$$\bar{Y}_x = \frac{a}{x^b} \quad (17)$$

where

x = number of identical units
a = cost of the first ship
b = exponent which varies with complexity of ship and prior experience of shipyard workers

Couch [20] derives a statistical value for b of 0.097 for general cargo ships built in U.S. shipyards. Tankers seem to follow the same trend. European and Japanese yards, however, apparently demonstrate less pronounced savings from multiple ship production. Table 2 summarizes Couch's cost relationships.

Table 2 Multiple Ship Cost Reduction Factors

Number of Ships in Contract	Ratio of Average Cost per Ship to Cost of Single Ship	Ratio of Cost of Each Additional Ship to Cost of Single Ship
1	1.000	1.000
2	0.935[a]	0.870
3	0.897	0.830
4	0.874	0.796
5	0.856	0.784
6	0.841	0.760
7	0.828	0.750
8	0.816	0.745
9	0.808	0.735
10	0.800	0.730

[a] The relative cost for each of two units is known as the cumulative average learning curve slope. This ratio holds true each time the number is doubled. For example, the cost for each of 8 ships is 93.5 percent of the cost for each of 4: (0.935 × 0.874 = 0.816).

Cost Summary

Table 3 presents a cost breakdown for a typical U.S. cargo liner as an illustration of the relationship of the cost factors previously discussed.

Table 3 Summary of Costs for Typical Cargo Liner (all in thousands)

Item	Steel	Outfitting	Hull Engineering	Machinery	Total
Material[a]	$941	$1263	$1634	$2230	$6068
(Man-hours)[a]	(380)	(243)	(244)	(156)	(1023)
Labor	$1216	$778	$781	$499	$3274
70% Overhead	$851	$545	$547	$349	$2292
Subtotal	$3008	$2586	$2962	$3078	$11,634
5% Profit	$150	$129	$148	$154	$581
Total	$3158	$2715	$3110	$3232	$12,215

[a] Including miscellaneous costs.

Owner's Costs

In addition to the shipyard bill, the shipowner is likely to have internal costs associated with new construction. These include administration and technical assistance, plan approval, inspection, legal fees, consulting fees, and interest on money paid before delivery. In one recent study, the owner's costs were found to average (as a percentage of the shipyard bill for a single ship) 3 plus 1.75 times the number of ships. This was for subsidized owners, who had used competitive bidding.

In comparative cost studies you can often omit owner's costs without materially affecting the overall results.

Accommodation Costs

The costs of building and furnishing the crew accommodations are included in the foregoing cost summaries. These assume normal complements, appropriate to nonautomated operation. Where significant crew reductions are expected, the following rough cost figures may be useful:

$$\text{Steel cost} = \$27{,}000N^{0.56}\ (+\$63{,}000) \quad (18)$$
$$\text{Outfit cost} = \$75{,}000N^{0.56}\ (+\$188{,}000) \quad (19)$$
$$\text{Hull engineering cost} = \$78{,}000N^{0.56}\ (+169{,}000) \quad (20)$$
$$\text{Total accommodation cost} = \$180{,}000N^{0.56}\ (+\$420{,}000) \quad (21)$$

where

N = number in crew, and figures in parentheses are to be added if 12 passengers are accommodated

These costs are for first-of-a-kind basis. They should be reduced for multiple ship contracts.

Transport Capacity

General

A key step in ship design is the trade route analysis that answers the following questions:

1 How much fuel should be on board at that point in the voyage where draft is most restricted? (Finding the point of limiting draft may require a separate study since displacement changes as fuel is burned.) If we have an unlimited cargo availability, the necessary weight of fuel allows calculation of the cargo deadweight. If cargo is limited in availability, the weight of fuel is used to find the required displacement.

2 What total bunker capacity is needed? Should the vessel take on round-trip bunkers at the point where fuel is cheapest, or would the overall economics be better if fuel were bought at both ends of the voyage? (In high-speed ships, the added displacement required for round-trip bunkers may be more expensive than buying half the fuel at more-than-minimum cost.)

3 How much fuel margin would be prudent?

4 What will the annual cost of fuel amount to?

5 Should the ship carry a large supply of fresh water or should evaporators be installed?

6 If the fleet is to offer fixed sailing and arrival times, what discrete speeds are appropriate?

7 How much cargo can be carried in a year—and/or how much will the probable annual revenue be?

The weight information derived from answering the foregoing questions is of course also useful in estimating stability, trim, and longitudinal bending moments in various conditions of loading.

Uncertainty

There are several phases of this work that require careful judgment and invite application of probability theory. For example, allowable drafts are seldom immutably fixed; an extra foot of draft that would cause a few hours' delay in one voyage out of twenty might be economically worthwhile. Forecasts of cargo availability and cargo mix are always questionable, as are fuel costs, and freight rates—to cite a few more examples of the need for recognizing a spectrum of future conditions. Certainly, versatility to at least some degree must be incorporated in every design.

Operating Days per Year

Many general cargo ship operators figure on 350 operating days per year, the remaining days being devoted to shipyard repairs. Ships with faster port turnaround (bulk carriers and container ships) have less time for dockside repairs and may require an additional 10 days' repair time per year.

Port and Canal Days

Port time for general cargo ships is not easily predicted and the shipowners should be consulted in this respect. For general estimates, the following may be used:

$$\text{Port days per round trip} = 10 + 1.5\,\frac{Z}{1000} \qquad (22)$$

where

Z = Round-trip distance in nautical miles.

In the case of ocean ore carriers, the total port days per round trip, including normal river transit, averages out to about 2 days plus the expression (cargo deadweight in long tons ÷ 22,000).

The Suez and Panama Canals each require about one day per passage.

Power Required for Speeds and Displacements Other Than Designed

Hadler, Stuntz, and Pien [21] present contours of speed and power for ships operating at drafts other than the designed value. Ships in the liner trade, when only partially loaded, would normally maintain speed but reduce horsepower. Bulk carriers and tramps would usually find it more economical to use full power regardless of loading condition, increasing sea speed accordingly (which fact is already implied in the nominal speed of most bulk carriers).

Fuel Rate

Average modern marine steam plants, when operated at design power, should have all-purpose fuel rates approximately equivalent to:

$$\text{Barrels per day} = 50 + 34.2\,\frac{\text{shp}}{1000} \qquad (23)$$

(There are about 6.52 barrels per metric ton of Bunker C fuel oil.)

With an average requirement for cargo refrigeration and air conditioning, another 13 barrels per day will be used. When vessels operate at reduced powers, the rate per shp will increase approximately as shown in Table 4.

Table 4 Relative Fuel Rates

Percent of maximum shp......	100	90	80	70	60	50
Relative fuel rate per shp........	1.000	1.007	1.025	1.051	1.089	1.144

Relative fuel rates for diesel plants do not rise as fast as the rates indicated above. Some engines demonstrate essentially flat fuel rates down to 70 percent of capacity, even showing a small reduction in rate between 80 and 100 percent. There are wide variations in diesel characteristics, however, and each type deserves separate investigation. See reference [17] as a start.

Port Fuel

For a first approximation, port fuel for a general cargo ship can be approximated as follows:

$$\text{Barrels per port day} = 4.5\,\frac{dwt}{1000} \qquad (24)$$

where *dwt* is the vessel's deadweight in long tons. Reference [4] shows port and canal fuel requirements for ore carriers as well as tankers.

Fresh Water

Boiler feed water is used at a rate of about 0.887 long tons per 1000 shp per day. Domestic water (potable and wash) is used at a rate of about 0.167 tons per person per day.

If evaporators are fitted, a 10-day reserve supply of fresh water is considered reasonable. Without evaporators, a 40-day water supply should be sufficient in all but the most extreme cases.

Lubricating Oil

Steam-propelled ships carry an average supply of lubricating oil weighing about 10 tons. In the case of direct-drive diesel plants, a figure of 15 tons is appropriate.

Provisions and Stores

The necessary weight of provisions and stores hinges principally on the ship's complement and days between replenishment. The weight is not large and allowance for the complete round trip is reasonable. A figure of 0.01 ton per person per day may be used.

Passengers, Crew, and Effects

The weight of the people on board plus their personal belongings may be estimated on a basis of one-sixth of a long ton per person.

Table 5 Relative Operating Costs (Northern European and U.S. shipowners on same trade route)

Item	Ratio to U.S. Owner's Cost
Total wages	0.25
Subsistence	0.85
Stores and supplies	0.80
Maintenance and repair	0.70
Hull and machinery insurance	0.40
Protection and indemnity insurance	0.30
Overhead and miscellaneous	0.55
Fuel	1.00
Port and canal	1.00
Cargo handling	1.00

Dunnage

The final item to be considered under the category of nonproductive deadweight is the weight of dunnage. In a general cargo ship, this usually runs from 1.5 to 2 percent of the cargo carried.

Annual Transport Capacity

All of the foregoing weight and scheduling factors can be combined to provide an estimate of the ship's annual transport capacity. In general-cargo ships there are usually partial-loading complications that must not be overlooked. In triangular or more complex trade routes, the simple concept of cargo tons per year is not altogether meaningful. Tons-per-year on each leg of the voyage is more significant. Also, mixed cargoes carried at different freight rates require the immediate conversion of tons per leg to revenue per leg.

Operating Costs

General

Books could be written about each of the principal categories that make up the total cost of operating a ship. For engineering economy purposes, relatively simple approaches are usually sufficient. The important aim should be to find the trends in cost as influenced by changes in the technical parameters. Experience has shown that in typical optimization studies you can ignore all annual costs, except that for fuel, without making any appreciable difference in the selection of conditions. Of course, when alternative designs imply appreciable differences in operating costs (additional crew members for example) you must carefully evaluate such differences.

A good general reference on the subject of operating costs is that by Walton [22].

Cost Levels

Where cost figures are given, they are based on recent U.S. levels. Table 5 shows factors that may be used to convert U.S. costs to approximate costs for northern Europe. Needless to say, such double approximations are risky. But, again, my aim is to illustrate methods of analysis, and to indicate trends rather than absolutes.

Inflation can be ignored in most engineering economy studies (except as it influences stipulated interest rates) as long as all costs rise more or less together. If crew wages, however, rise faster than general inflation, you should try to predict their relative level at perhaps mid-life and use that figure in your analysis.

Wages

The crew complement for a general cargo liner, without passengers, can be estimated on the following basis:

$$N_C = C_{ST}\left[C_{DK}\left(\frac{CN}{1000}\right)^{1/6} + C_{ENG}\left(\frac{\text{shp}}{1000}\right)^{1/5} + \textit{cadets}\right] \tag{25}$$

where

N_C = total complement
C_{ST} = coefficient for steward's department
C_{DK} = coefficient for deck department
C_{ENG} = coefficient for engine department
(see Table 6)
CN = cubic number = $\frac{LBD}{100}$
shp = shaft horsepower

If 12 passengers are carried, add two in steward's department. Table 6 lists appropriate values for the various coefficients.

Crew complements on U.S. flag bulk carriers tend to be smaller by about a dozen men than on general cargo ships of comparable size.

Table 6 Crew Complement Coefficients (nonautomated)

Item	Notes	Min.	Aver.	Max.
C_{ST}	Steward's department	1.20	1.25	1.33
C_{DK}	Deck department	11.5(13.6)[a]	13(15.4)	14.5(17.1)
C_{ENG}	Engine department: Steam turbine, single screw	11	12	15
	Steam turbine, twin screw	13.5	15	16
	Diesel, single screw[b]	8.5	10	11

[a] Numbers in parentheses apply to $\frac{CN}{1000}$ in metric units.

[b] For diesel plants, substitute for the second term within the parentheses in equation (25):

$$C_{ENG}\left(\frac{\text{bhp}}{1000}\right)^{1/3}$$

At the present time, the average annual crew cost, including benefits, is about $12,500. If current trends continue, the midlife level for a new ship would be about $16,000, when corrected for overall inflation.

Figures cited here and in the following paragraphs are from reference [17] and are based on cost data supplied by nine owners of general cargo ships. Similar cost information for bulk carriers may be found in references [3] and [4]. Illies and Legrand [5] may be consulted for a comprehensive summary of European ship operating costs.

Wage Levels Under Automation

As automation is introduced, it will primarily replace men at the lower end of the wage scale. A flat rate per man would then lead to distortion. Instead, the following relationship may be used:

$$\text{Total annual crew cost} = \$27{,}000(N_c)^{1/3} \quad (26)$$

Subsistence

An average figure for annual subsistence costs is $770 per person.

Fuel

Average figures for Bunker C fuel oil, including barging, are $2.15 per barrel in eastern U.S. ports and $1.79 per barrel in northern Europe. Costs vary in different parts of the world and this cost item deserves special attention in actual trade-route studies.

Maintenance and Repair

Costs of maintenance and repair are among the most difficult to estimate. Actual costs vary widely and are influenced by such diverse factors as trade-route weather conditions, bow shape, owner's standards, and initial extra costs for reliability. Variation also arises in that many owners assign much maintenance work to the crew, and thereby disguise that cost under such headings as wages, subsistence, and supplies.

Perhaps computers may lead the way to more reliable predictions of maintenance and repair costs. In the meantime I propose for steam-powered general cargo ship mid-life averages:

$$\text{Annual cost of hull M \& R} = \$10{,}000\left(\frac{CN}{1000}\right)^{2/3} \quad (27)$$

and

$$\text{Annual cost of machinery M \& R} = \$4500\left(\frac{\text{shp}}{1000}\right)^{2/3} \quad (28)$$

For metric units, substitute $108,000 for $10,000 in equation (27).

Stores and Supplies

The category of stores and supplies comprises paint, cleaning materials, and lubricating oil. Most of these items are used for shipboard maintenance and are applied by the crew. Hence the annual cost is largely a function of the crew complement, N_C. Here is a rough approximation:

For crews of 50 men or fewer:

$$\text{Annual cost of stores and supplies} = \$80\left(\frac{N_C}{10}\right)^4 \quad (29)$$

For crews of more than 50:

$$\text{Annual cost of stores and supplies} = \$50{,}000 + \$4{,}000(N_C - 50) \quad (30)$$

Protection and Indemnity Insurance

Protection and indemnity insurance protects the owner against lawsuits, most of which arise from his own crew. Although rates are quoted on a gross tonnage basis, there is logic in estimating protection and indemnity insurance costs in terms of crew complement:

$$\text{Annual cost of protection and indemnity insurance} = \$965\, N_C \quad (31)$$

Hull and Machinery Insurance

The cost of insuring the ship against damage or loss varies with the owner's past record. An average figure may be estimated as follows:

$$\text{Annual cost of hull and machinery insurance} = \$10{,}000 + 0.007\ (\text{invested cost}) \quad (32)$$

War-Risk Insurance

The annual cost of war-risk insurance is about 0.1 percent of the invested cost.

Overhead and Miscellaneous

Overhead and miscellaneous costs include fleet management, communications, crew transportation, survey fees, and so forth. The amounts, which vary widely, are hardly susceptible to scientific analysis. One rule-of-thumb estimate for annual cost of overhead and miscellaneous is $\$65{,}000 + \$2(CN)$, where CN is the cubic number $LBD/100$ in foot units. For metric units, substitute $70 for $2.

Port Expenses

Port costs include pilotage, cutoms fees, tonnage tax, tug service, and line handling. Cargo-handling and terminal-use charges are excluded. Walton [22] shows curves that fit the following compound expression, which may be used when actual charges are not known:

$$\text{Port expenses per call} = \$233 + \$19.25\,\frac{CN}{1000} \quad (33)$$

(in metric units, $19.25 becomes $680)

plus

$$\text{Port expenses per day} = \$20 + \$8.20\,\frac{CN}{1000} \quad (34)$$

(in metric units, $8.20 becomes $290).

Canal Fees

Reference [4] contains a convenient summary of canal charges. These fees may change periodically because of statutory modification or reinterpretation of the rules.

Cargo Handling Costs

In most ship cost studies, cargo handling costs will be the same for all alternatives. When this is true, you should specificially omit these costs from your analysis. Cargo revenue can then be treated as though the shipper were paying the shipowner only for transportation, not stevedoring.

Walton [22] and McMillan and Westfall [23] are standard references for cargo handling costs. Reference [17] summarizes these publications and others.

Application of Engineering Economy to Ship Design

General

The preceding sections outline the building blocks; now how do we put them together? Our purpose is to find the most profitable of all possible designs that fit the shipowner's functional needs. How we approach the task depends in part on the owner's commercial environment. For example, cargo availability in the bulk trades may be practically unlimited, and ship size restrictions are set only by physical conditions such as harbor depth and drydock facilities. General cargo liners, on the other hand, are more likely to have their size determined by forecasts of cargo availability. We can at once, then, divide all ships into two broad categories: those whose size is limited by physical environment and those whose size is limited by cargo availability.

Another factor influencing our method of analysis is the question of whether we are comparing technologies (such as steam versus diesel) or seeking the ideal design of any one technology. These are called feasibility studies and optimization studies, respectively. In practice we have to mix feasibility and optimization; often we cannot be sure that one technology is better than another until we have found the economically optimum design and mode of operation for each. The following paragraphs explain how these considerations influence our approach to decision-making in ship design. The final paragraphs deal with the selection of propulsion machinery.

Feasibility Studies

Feasibility studies involve at least two alternatives, one normally being in the role of the challenger, the other the defender. These studies are used to weigh the economic feasibility of possible innovations: aluminum versus steel hulls, mechanical hatch covers versus manual covers, containers versus break-bulk cargo, nuclear propulsion versus steam or diesel, and so forth.

The question may involve only a relatively small subsystem of the ship (such as mechanical versus manual hatch covers). You may then be safe in assuming that the decision will not involve any other parts of the ship design, schedule of operation, or annual revenue. When that is the case, you need only find whether the extra first cost of the innovation is more than repaid by the probable future savings. This is most conveniently handled through an average annual cost approach:

$$NAS = (Y_D - Y_C) - CRF(P_C - P_D) \qquad (35)$$

where

NAS = net annual saving

Y_D = annual operating cost of defender

Y_C = annual operating cost of challenger

CRF = ship's overall before-tax capital recovery factor

P_C = invested cost of challenger

P_D = invested cost of defender

Many feasibility studies cannot be isolated as in the paragraph above. The introduction of nuclear propulsion, as one example, would dictate changes in many phases of the ship's design and operation. Under those conditions, you should make comprehensive economic analyses of both challenger and defender. In the preliminary stages you may well select as defender a conventional ship for which you already have a breakdown of weights and costs. You can then estimate the corresponding weights and costs for the challenger and arrive at a comparative figure either for required freight rate or interest rate of return, depending on whether income is predictable. Sample Study No. 1 illustrates this approach. What use you make of the results will require judgment and will be influenced by the confidence you can place in your estimates. You must remember that you have been a little unfair to the challenger in that you have presumably met the defender on his own grounds: a long-developed, probably optimized, design. Further refinement would benefit the challenger more than the defender. You should also consider other types of ships for application of the new technology, seeking that type that would best exploit the challenger's unique advantages.

Proposed innovations frequently involve differences in weight. How these are handled depends on whether the ship's size is limited by cargo availability or by physical environment. Where cargo is unlimited, any change in weight of the ship should logically cause an equal and opposite change in weight of cargo. On the other hand, when cargo is limited, a change in weight of any component will change the required displacement, which will trigger a series of spiraling interactions, requiring a redesign of the entire ship. How this complication is handled depends in turn on such questions as whether design speed is fixed or variable. Obviously, judgment is required in these matters, and you should try to put the challenger in its best light without, however, departing from reality in your approach.

Not surprisingly, most feasiblity studies are made by advocates of the innovation. Their computed results almost invariably seem to favor the challenger. The prudent observer must therefore base his own conclusion, not on the results, but on the assumptions and economic criterion used.

Optimization

James Napier [24], who was perhaps the father of ship economics, set up a cost equation which he differentiated to find the optimum speed. That approach, while valid, is perhaps less satisfactory than the iterative procedures used today. Iteration is more versatile; it requires fewer simplifying assumptions, and it shows the penalties involved in departing from optimum conditions. The last factor is important. Moderate departures from the point of maximum profitability seldom cause any pronounced drop in profitability itself. A quantitative understanding of this is desirable when weighing the intangibles.

The drawback to the iterative procedure is the bulk of work involved. We cannot be sure we have found the best design until we have analyzed a good many candidates. Even when helped by a computer, we must limit ourselves to some reasonable number. We must therefore crop out the less promising alternatives and analyze the rest in a methodical way. But we must be careful not to overdo the cropping out. Potentially valuable possibilities are often overlooked solely because we uncritically accept outmoded dogma. Progress requires skepticism of all past practice and a willingness to consider the freaks.

Optimization With Unlimited Cargo

Naval architects have long known that, when cargo is unlimited, big ships and big profits go hand in hand. Most bulk carriers, such as tankers, find few practical limitations on the availability of cargo. They should, therefore, be made as large as their physical environment will allow. If they must use specific canals, the authorities will dictate certain maximum dimensions and those are what should be used. Other practical limitations may be set by shoreside cargo gear, turning basins, shipyard facilities, and so forth. Such limitations, if they are indeed immutably fixed, simplify the naval architect's task by making many key decisions for him. Let us look, however, at the more complicated case where harbor depth is the only direct restriction. The question then is this: Given a maximum operating draft, how big can we make the ship and what is its most economical speed?

Our ship size now becomes a function of the draft because excessive proportions must eventually result in uneconomical design. Admittedly, the proper degree of extremity is not as clear cut as tradition would have us believe. But assume that for any given draft there is indeed some fixed upper limit on length and beam. Reference [4] shows that the optimum bulk carrier is the one designed around a draft somewhat (usually about 10 percent) greater than the maximum operating draft. This is because the correspondingly greater length and beam result in a larger, hence more profitable, ship even when operating at the specified draft. The proper degree of oversizing is found by iteration.

Let us next assume that we are going to select the maximum length and beam for a design draft (d_D) somewhat greater than the limited operating draft (d_0). How large can we make the beam? Few seagoing ships have beam-draft ratios larger than 3.0, presumably because more extreme proportions lead to problems of excess stability. We can tentatively accept that criterion, perhaps cheating to the extent of using d_D rather than d_0 in the calculation. This upper limit, incidentally, is less firmly fixed than ever, now that flume stabilizers are proving successful.

If we assume next that our bulk carrier should have minimum tanker freeboard (based on d_D) we can readily determine depth (D). This is another assumption that deserves further study; using a somewhat greater freeboard may prove profitable because it would allow a longer ship. It might permit elimination of the forecastle and ease ballasting problems as well. In any event, for a given depth, we assume the maximum permissible length will be about 14 times as great. Again, future studies should treat that dictum to economic analysis.

Having estimated the maximum practical set of dimensions, the last remaining way to enlarge the ship is to make the block coefficient as great as we dare. There is still more art than science in this step and the actual decision can only be made on the drawing board. Tentatively, we can accept a value of 0.83 as an upper limit for a bulk carrier of the proportions just described and intended for operation in moderate seas.

The next step is to find the ideal speed. We take the hull selected above and repeatedly analyze the overall economics with propulsion plants of various powers, each of which would drive the hull at some determinable speed. If we knew more about the relationship between hull form and propeller vibrations we could consider the influence of shp on maximum permissible block coefficient. Little is known here, however. We can say therefore that the optimum hull form is virtually the same regardless of speed. In short, Alexander's formula, which relates block coefficient and speed-length ratio, has no place in bulk-carrier design.

The final aim in our optimization study should be to find the most profitable design as indicated by one of the economic criteria discussed earlier. Do not be satisfied to find the ship of maximum deadweight coefficient or other strictly technical parameter.

Since so many of our decisions hinge on the allowable draft, that particular restriction deserves the most careful scrutiny. Once again, a probabilistic approach may be desirable.

Sample Study No. 2 illustrates a few of the ideas outlined in the foregoing.

Optimization With Limited Cargo

Consider next the case of the general cargo liner. Here is a design problem that is as complex as anything in the field of engineering. Speed must be selected to suit some reasonable schedule; cargo must be taken on and discharged at several ports; the cargo mix will vary on different legs of the voyage, with widely differing densities and all manner of stowage requirements. Operation at a range of partial drafts is the general rule, and the availability of cargo is subject to continuous fluctuation. We are a long way from having developed a completely rational approach to such designs.

Even if we were sure of our liner's functional requirements, we would still have trouble finding the really best of all possible combinations of dimensions, hull form, and power. This is perhaps not too serious, for studies such as Appendix II of reference [3] show that, having chosen a cargo deadweight and sea speed, almost any reasonable combination of proportions and hull form will produce about the same overall economic result. As Basingstoke [25] remarks, it's pretty hard to design a really bad cargo liner, although some apparently try.

The important aims in cargo-liner design are to choose the optimum ship size and speed. The selection of speed is apparently less a question of engineering than of business management. Owing to the peculiarities of the conference system, quick delivery has an exaggerated role in attracting cargo. There is no economically optimum speed; you merely want to go somewhat faster than your competitor. Thus, until the conferences get around to adopting a speed-adjusted freight scale, the choice of liner sea speed will fall outside the realm of engineering economy. The choice of ship size, however, is more readily adaptable to engineering analysis. The naval architect should start with the manager's forecast of future cargo availabilities, which will presumably have long-range trends up or down, complicated by fluctuating short-term characteristics. Given an assumed cargo availability curve and an assigned sea speed, a little trial-and-error will lead to the most profitable ship size. If the long-range trends are up or down, due regard must be paid to the time value of money. That is, far-future incomes will have less influence than those closer at hand. Computer techniques can easily handle the thousands of possible variations in cargo mix and availability, each weighted by its estimated probability of occurrence.

Where combinations of size and speed are analyzed, you must think of the entire fleet operation rather than the single ship. In the cargo-restricted trades, frequency of service will influence the availability of cargo. Again, this is a matter of business judgment rather than engineering.

Limited-Cargo Bulk Carriers

We have so far discussed unlimited-cargo carriers and cargo liners. There are also two important classes of ships designed to carry limited quantities of bulk cargo. One is the tramp ship; the other is the petroleum-product carrier.

The tramp ship has the most unpredictable functional demands of all; its cargoes are of the bulk variety most of the time, but not always. Cargo availability will fluctuate. Large capacity may be a blessing one day, but deep draft a curse the next. High sea speed is seldom important except, at times, to reach a port in time to capture a cargo. In conclusion, you can design a tramp ship on a purely intuitive basis. Or you can apply your intuition instead to estimating the probability of future demands, putting these figures into the computer, then applying the Monte Carlo probability technique to large numbers of alternative designs on hundreds of imaginary voyages.

Petroleum-product carriers present another family of problems. Functionally, they are required to provide a given level of annual transport capability. Further, they are limited in size by shoreside tankage. They are best analyzed on a fleet-wide basis. Usually the biggest source of error is the cargo forecast, so a probabilistic approach should be used in studying the economics of many alternative designs.

Optimization of Machinery

Let us assume that the owner has decided on steam turbine machinery for his new ship. Our problem is to select the most economical set of steam conditions and cycle arrangements. Put in another way, we must find the most profitable balance between capital costs and operating costs (principally for fuel).

Giblon and Stott [26] have used a computer to make heat balances on some 25 combinations of cycle and steam conditions, each over a wide range of horsepowers. They present curves of specific fuel consumption, providing the key to further analysis. Given these fuel rates, plus your best estimates of initial costs for machinery, your battle is half won. The proper economic criterion will probably be the average annual cost:

$$AAC = [CRF]P + F + Y \qquad (36)$$

where

CRF = capital recovery factor (before tax) appropriate to the ship, based either on its predicted returns or on the owner's stipulated rate of interest before tax
P = invested cost of the installed machinery
F = annual cost of fuel
Y = net sum of all other annual costs that are a function of the plant selected

The last factor, Y, will include, as a minimum, insurance costs (about $0.01P$) and maintenance and repair costs (about $0.02P$). It begins to get complicated if differences in fuel weight between the various alternative plants are great enough to affect significantly the cargo deadweight or necessary displacement. Other complications ensue if some of the alternatives imply additions to the crew. As discussed earlier, this requires estimates of accommodation costs, and so forth. As in any other study, the inputs will require judgment and will vary with the type of ship and its operating conditions.

The average annual cost approach is also convenient for selecting machinery components that have identical operating costs (or none at all) but differing lives:

$$AAC = [CRF]P \qquad (37)$$

where CRF is based on the before-tax interest rate appropriate to the ship itself but to a life appropriate to the particular component. See equation (3).

Sample Study 1. Nuclear Power for Merchant Ships

The following hypothetical studies are presented, not to prove or disprove the feasibility of nuclear ship propulsion, but to illustrate a method of analysis. A secondary objective is to give at least a rough idea of where nuclear ship costs may gain most from improvement.

Ship Types

Two contrasting ship types are taken: a 20-knot cargo liner designed for a 6000-mile round-trip voyage, and a 16-knot bulk-cargo ship (representative of tankers, ore carriers, and so forth) suitable for a 24,000-mile round-trip voyage. The cargo liner is designed around a cargo capacity of 8000 long tons, whereas the bulk carrier is simply designed to carry as much cargo as possible on a draft of 34.2 ft. The fuel weight-saving potential of nuclear power is exploited in the first case by reducing the overall size of ship and horsepower. In the bulk carrier, the lessened weight of fuel is converted directly to increased cargo deadweight. The bulk carrier is assumed to sail with full deadweight in one direction and return in ballast. The cargo liner sails with an average cargo deadweight of 75 percent of the maximum (6000/8000).

Power Plants

Each of the two types of ships is analyzed with three different power plants:

1 conventional, oil-fired steam turbine
2 nuclear air-cooled reactor (ACR)
3 nuclear pressurized water reactor (PWR)

Both nuclear plants are of advanced, compact design.

Machinery Weights

Weights of the conventional plant and both nuclear plants are assumed to be the same for a given shp and machinery location. They are based on average values from equation (8).

Technical Summary and Weight Breakdown

The major technical characteristics of the proposed designs are shown in Table 7, while Table 8 summarizes weights.

Cost Levels

In the case of the nuclear ships I have tried to predict reasonably optimistic cost levels attainable within the next ten years. Developmental costs are specifically excluded, and multiple cost-saving factors apply to each of ten identical reactors. Ship hull and conventional machinery costs are on an each-of-five basis, with a reduction factor of 0.851. U.S. building and operating costs are used, with some allowance for future increases in wages.

Fuel Costs and Bunkering

The conventional cargo liner is assumed to take on bunkers at each end of the voyage: $2.15 per barrel at one end, $1.79 per barrel at the other. The conventional bulk carrier takes on bunkers for a round trip at the unloading port at a cost of $2.15 per barrel.

The conventionally powered cargo liner is assumed to use bunker oil at a rate of (63 + 0.342 shp) barrels per day at sea, which allows 13 barrels per day for refrigerated cargo and air conditioning. The conventionally powered bulk carrier is assumed to use bunker oil at a rate of (50 +.0 342 shp) barrels per day at sea. Allowances are made for port fuel in each case.

Table 7 Technical Characteristics

Ship Type Propulsion	Cargo Liner Conv.	Cargo Liner Nucl.[a]	Bulk Carrier Conv.	Bulk Carrier Nucl.[a]
Speed, knots	20	20	16	16
Displacement, tons	15800	14245	53100	53100
SHP	16000	15000	17000	17000
Crew	51	49	45	45
Specific fuel consumption; grams per shp-hr.	245	—	238	—
Pounds per shp-hr.	0.54	—	0.525	—
Fuel oil cost per barrel[b]	$1.97	—	$2.15	—
Nuclear fuel, mills per shp-hr[c]		ACR: 3.20 PWR: 2.73		ACR: 3.20 PWR: 2.70
Operating days per year	350	340	340	330
Sea days per round trip	12.5	12.5	62.5	62.5
Port days per round trip	19.0	19.0	3.6	3.6
Round trips per year	11.11	10.80	5.145	5.00

Notes

[a] Characteristics are appropriate to both types of reactor except as noted.
[b] There are about 6.52 barrels per metric ton.
[c] A mill is 0.10 cent.

Table 8 Weight Summary

Ship Type Propulsion	Cargo Liner Conv.	Cargo Liner Nucl.[a]	Bulk Carrier Conv.	Bulk Carrier Nucl.[a]
	Long Tons			
SHP	16000	15000	17000	17000
Structure	3620	3565[b]	10600	10800[b]
Outfit	1080	1000		
Hull engineering	540	500	1678	1678
Machinery	940	910	882	882
Light ship	6180	5975	13160	13360
Cargo	8000	8000	36220	39470
Fuel	1350	0	3450	0
Lube oil	15	15	15	15
Crew, effects	9	9	8	8
Provisions, stores	16	16	21	21
Feed water	145	145	151	151
Domestic water	85	85	75	75
Deadweight	9620	8270	39940	39740
Displacement	15800	14245	53100	53100
Cargo per year	133320[c]	129600[c]	186400[d]	197100[d]

Notes

[a] Nuclear weights are appropriate to both types of reactors.
[b] Includes 200 tons of protective structure.
[c] At 75 percent capacity each way.
[d] Fully loaded one way, return in ballast.

Annual Costs of Capital Recovery

Annual costs of capital recovery are based on the assumptions shown in Table 9.

The financing figures in Table 9 are, I believe, realistic. The bulk carrier is assumed to be part of a captive fleet owned by a corporation with little need for bank loans. As part of a captive fleet it has a relatively assured income, and appropriate interest rates of return are there-

Table 9 Capital Costs Factors

Ship	Cargo Liner	Bulk Carrier
Life, years	25	25
After-tax interest rate (based on overall returns after tax related to total investment)	12.5%	10%
Owner's equity as percent of total investment	50	100
Bank loan as percent of total investment	50	0
Bank interest rate	5%	—
Bank loan period, years	25	—
Tax rate	48%	48%
Resulting *CRF* (before tax)	0.2027	0.1750

fore somewhat lower than those required by investors in a common carrier.

Building Costs

The total installed cost of conventional machinery, including profit, is estimated on this basis:

$$\text{Cost} = \$647{,}000 \left(\frac{\text{shp}}{1000}\right)^{0.6} \tag{38}$$

For machinery aft, the cost is multiplied by a factor of 0.91. These figures are before reduction for building five identical units.

The installed costs of the nuclear plant are estimated in two steps. In the case of the air-cooled reactor, the total cost (including profit) but exclusive of the purchase price of the reactor, is estimated as follows:

$$\text{Cost} = \$635{,}000 \left(\frac{\text{shp}}{1000}\right)^{0.6} \tag{39}$$

For machinery aft, use 91 percent of foregoing.

The purchase price plus shipyard profit for each of ten reactors is estimated as follows, whether of air-cooled or pressurized water variety:

$$\text{Cost} = \$740{,}000 \left(\frac{\text{shp}}{1000}\right)^{0.4} \tag{40}$$

Equation (40) is based on published costs in reference [27] for non-nuclear machinery, with intuitive corrections for the special requirements of reactor technology. The equation is probably somewhat optimistic.

Since installation of the pressurized water reactors would require considerably more man-hours, total cost figures for the reactor arrived at above are arbitrarily increased by $875,000 to $900,000.

Table 10 summarizes the estimated construction costs.

Operating Costs

Table 11 shows the assumed relationships between operating costs of nuclear and conventional ships.

Economic Analysis

Table 12 shows the summary of all the preceding technical and economic factors, using required freight rate (*RFR*) as the measure of merit. Cargo handling costs are excluded in both cases.

Table 10 Summary of Building Costs

Ship Type / Machinery	Costs in $1000 Cargo Liner Conv.	Cargo Liner Nucl.	Bulk Carrier Conv.	Bulk Carrier Nucl.
Costs for one unit[a]				
Structure	2962	2928	6978	7105
Outfitting	2402	2235	6074	6074
Hull engineering	3058	2857		
Machinery[b]	3416	3250	3227	3170
Total for one unit	11838	11270	16279	16349
Total for each of five	10074	9591	13853	13912
Reactor	—	2190	—	2300
Total for each of five with ACR	—	11781	—	16212
Adjustment for PWR	—	875	—	900
Total for each of five with PWR	—	12656	—	17112

Notes

[a] Costs include shipyard profit and overhead.

[b] Nuclear machinery costs shown in this line are exclusive of purchase price of reactor, and are appropriate only to installation of air-cooled reactor.

Table 11 Nuclear Versus Conventional Ship Operating Costs

Cost Category	Relative Cost for Nuclear Plant
Wages	Crew numbers would be the same for a given hull size and horsepower, but average wage per man would be 5 percent higher.
Subsistence	Same cost per man.
Maintenance and repair	Same proportion of initial investment.
Stores and supplies	Same cost per man.
P & I insurance[a]	50 percent more per man.
H & M insurance[b]	$10,000 plus same proportion of initial investment.
Other insurance	Same
Overhead & misc.	Same
Port expense	Same cost per port-day.
Operating days per year	10 fewer in recognition of down time for refueling and more stringent restrictions on operation.

Notes

[a] P & I: Protection and indemnity insurance (backed by Price-Anderson Act).

[b] H & M: Hull and machinery insurance.

Conclusions

As stressed in the beginning, this analysis has not been intended as a definitive investigation into the economic feasibility of nuclear ships. While the author has leaned toward optimistic nuclear cost levels, he has not sought the ideal hull for the nuclear plants. In his judgment you will have trouble finding an economically competitive nuclear ship attainable within the next decade, but you have some tools here to find out for yourself.

The contrasting annual costs of fuel and capital recovery make it evident that commercial feasibility of nuclear power can best be attained through efforts to lower the initial costs of reactor plants.

Sample Study 2. Economical Speed for a Bulk Carrier

This study illustrates the application of economics to optimization of ship design. The object of this particular analysis is to find the most economical design speed for an ocean ore carrier. As our starting point, we shall

Table 12 Economic Analysis: Required Freight Rate (all costs are in $1000, except *RFR*)

Ship Type / Machinery	Cargo Liner Conv.	Cargo Liner ACR	Cargo Liner PWR	Bulk Carrier Conv.	Bulk Carrier ACR	Bulk Carrier PWR
Invested cost	10074	11781	12656	13853	16212	17112
Operating cost (per year)						
Wages	638	644	644	562	580	580
Subsistence	39	37	37	35	35	35
Maint. & repair	79	92	99	178	208	219
Stores & supplies	54	52	52	33	33	33
P & I insurance	49	71	71	43	65	65
H & M insurance	82	94	100	109	126	132
Other insurance	10	10	10	14	14	14
Overhead & misc.	93	93	93	129	129	129
Port expenses	59	57	57	27	27	27
Subtotal	1103	1150	1163	1130	1217	1234
Fuel	185	174	148	444	412	348
Total operating costs	1288	1324	1311	1574	1629	1582
CRF[a]	0.2027	0.2027	0.2027	0.1750	0.1750	0.1750
Capital recovery costs	2042	2388	2565	2424	2837	2995
Average annual cost excl. cargo handling	3330	3712	3878	3998	4466	4577
Tons of cargo per year	133320	129600	129600	186400	197100	197100
RFR[b] excl. cargo handling	$24.98	$28.64	$29.92	$21.45	$22.66	$23.22
Ratio: nuclear to conventional	1.00	1.15	1.20	1.00	1.06	1.08

[a] Capital Recovery Factor
[b] Required Freight Rate

Table 13 Principal Characteristics of Ore Carrier

Length between perpendiculars	735 ft (223 m)
Limiting operating draft	34 ft (10.4 m)
Design draft	37.5 ft (11.4 m)
Beam	93.75 ft (28.5 m)
Block coefficient at design draft	0.80
Beam-draft ratio at design draft	2.5
Displacement at design draft	59,100 long tons
Displacement at operating draft	53,500 long tons
Machinery	Single screw, steam turbine
SHP	To be optimized
Sea speed	To be optimized

assume that the technical characteristics presented in Table 13 are already established. The ship is intended to carry iron ore over a distance of 12,000 miles, and to return in ballast.

Fuel oil for the round trip is taken aboard at the cargo discharge port. The point of limiting draft, 34 ft, is the loading port. (The voyage is the same as that of the bulk carrier analyzed in the preceding feasibility study.)

Table 14*a* shows how the required freight rate, *RFR*, is computed for different arbitrary values of installed shp and corresponding speed. Capital costs are based on an owner's stipulated after-tax interest rate of return of 12 percent, a 48-percent corporate profits tax, a life of 20 years, and an all-equity investment. Table 14*b* is a re-analysis of 14*a*, but with an assumed revenue of $26 per long ton. The capital recovery factor, *CRF*, is the criterion used in 14*b*. Table 15 explains the steps shown in Tables 14*a* and 14*b*.

In Tables 14*a* and 14*b*, the basic variable is shaft horsepower rather than speed because most of our cost and weight estimates are based on power, not speed.

An examination of the tables shows that the optimum speed is 15.7 knots in each case. If, in Table 14*a*, the assumed interest rate had been considerably higher, the indicated optimum speed would also have been higher. Similarly, a large increase in the assumed freight rate in Table 14*b* would have indicated a higher desirable sea speed.

In these tables we have indicated the most promising discrete value of horsepower and speed. The exact optimum can be found by curve plots like Fig. 33 in reference [4]. Other design drafts could be investigated through repetition of Tables 14*a* and 14*b*. See Fig. 32, reference [4] for an example of the results of such a study.

Sample Study 3. Feasibility Study for Great Lakes Ore Carriers

This is not a typical feasibility study but serves to illustrate how one or more potential innovations may be compared, using a recently built conventional ship as a standard.

The Great Lakes iron ore shipping industry has been depressed in recent years. The high-grade Lake Superior district ores are about gone, and foreign ores are being imported increasingly. Hope for a revival on the Great Lakes stems from the commercially successful development of low-grade ore beneficiation (pelletizing) and the construction of a new lock at Sault Ste. Marie, which will admit ships 1000 ft by 100 ft, overall.

In our search for more economical Great Lakes ore carriers, we have proposed several innovations. Each could be given separate analysis. We have chosen, however, to be somewhat less rigorous; we show a defender and only two proposed challengers, each one of which embodies several departures from current standards. The summary is tabulated in enough detail so that any one proposed change can be singled out for analysis if you so desire.

The defender is representative of the most modern existing Great Lakes ore carriers. The first challenger is one of a fleet incorporating the following innovations:

1 Ships will be foreign-built (which limits their size to

Table 14a Required Freight Rate Versus Horsepower and Speed

1. SHP/1000	5	10	15	20	25	30
2. C_{DWT}	0.764	0.761	0.758	0.755	0.753	0.751
3. Design *DWT*	45.2	45.0	44.8	44.6	44.5	44.4
4. Oper. *DWT*	39.6	39.4	39.2	39.0	38.9	38.8
Investment (costs in $1000)						
5. $ per ton displacement	252	263	274	283	294	305
6. Shipyard bill	14900	15540	16190	16720	17390	18030
7. Misc. expense	574	583	592	601	610	624
8. Inv. Cost	15474	16123	16782	17321	18000	18654
Schedule						
9. Design speed	11.2	14.1	15.6	16.6	17.3	17.8
10. Oper. speed	11.3	14.2	15.7	16.7	17.4	17.9
11. Sea days/RT	88.5	70.4	63.7	59.9	57.5	55.8
12. Port days/RT	3.7	3.7	3.6	3.6	3.6	3.5
13. Total days/RT	92.2	74.1	67.3	63.3	61.1	59.3
14. RT/year	3.69	4.58	5.06	5.35	5.56	5.74
Weights (tons)						
15. Fuel tons/day	33.8	59.8	84.4	109.6	135.0	160.3
16. Fuel *DWT*	1720	2421	3200	3770	4470	5160
17. Misc. *DWT*	232	242	252	262	272	282
18. Cargo/RT	37648	36737	35748	34968	34158	33358
Fuel (tons)						
19. Fuel tons/day	33.8	59.8	84.4	109.6	135.0	160.3
20. Sea fuel/RT	2990	4210	5380	6560	7760	8960
21. Port fuel/RT	89	89	89	89	89	89
22. Productive fuel/RT	3079	4299	5469	6649	7849	9049
23. Productive fuel tons/year	11340	19670	27650	35520	43600	51900
24. Idle fuel/year	293	293	293	293	293	293
25. Total fuel/year	11633	19963	27943	35813	43893	52193
Port & Canal Costs						
26. Port costs/RT	5.7	5.7	5.7	5.7	5.7	5.7
27. Bunker cost/RT	2.0	2.0	2.0	2.0	2.0	2.0
28. Total/RT	7.7	7.7	7.7	7.7	7.7	7.7
Annual Costs & Summary (costs in $1000)						
29. Port & canal	28	35	39	41	43	44
30. Crew wages	414	425	432	437	441	444
31. OH & misc	51	51	51	51	51	51
32. Maint. & Repair	160	170	178	185	191	196
33. Stores and supplies	21	24	25	27	28	29
34. Subsistence	39	40	41	41	41	42
35. Insurance	195	199	207	213	221	229
36. Sub total	908	944	973	995	1016	1035
37. F.O.	162	278	388	498	611	727
38. Annual oper. costs	1070	1222	1361	1493	1627	1762
39. Annual cost cap. recov	3273	3410	3549	3663	3807	3945
40. *AAC*[a] ($/1000)	4343	4632	4910	5156	5434	5707
41. Cargo/yr (1000 LT)	138.9	168.3	180.9	187.1	189.9	191.5
42. *RFR*	$31.27	$27.53	$27.14	$27.56	$28.60	$29.80
10. Oper. speed	11.3	14.2	15.7 (opt.)	16.7	17.4	17.9

[a] Average annual cost

Table 14b Capital Recovery Factor Versus Horsepower and Speed
(A reanalysis of the final steps in Table 14a, based on a predicted revenue of $26 per ton.)
Annual costs and revenues are in $1000

1. SHP/1000	5	10	15	20	25	30
10. Operating speed	11.3	14.2	15.7	16.7	17.4	17.9
41. Cargo per year	138.9	168.3	180.9	187.1	189.9	191.5
43. Annual revenue	3611	4376	4703	4865	4937	4979
38. Annual oper. costs	1070	1222	1361	1493	1627	1762
44. Annual return	2541	3154	3342	3372	3310	3217
8. Invested cost	15474	16123	16782	17321	18000	18654
45. *CRF*	0.1642	0.1956	0.1991 (opt.)	0.1947	0.1839	0.1725

that of the defender since the St. Lawrence Seaway would have to be traversed in delivery).

2 Ships are automated and carry crews of 14 men.

3 The operating season is extended to 11 months and ships are suitably ice-strengthened.

4 A tax write-off period of 10 years is used (rather than the standard 50 years).

5 The design aims for austerity in nonessentials.

6 The ships are built under long-term contract for several identical units.

The second challenger represents a fleet of U.S.-built ships of maximum size for the new lock at Sault Ste. Marie. It also incorporates innovations 2–6 in the foregoing.

Table 15 Notes on Tables 14a and 14b
Figure numbers referenced are in reference [4]

Line in Tables 14*a* and 14*b*	Notes
1	Arbitrary values of shp
2	Ratio of deadweight to displacement, Fig. 13
3	Line 2 × design displacement
4	Line 3 − (design displ. − oper. displ.)
5	Fig. 20
6	Line 5 × design displacement
7	$350,000 + 1.5 percent Line 6
8	Line 6 + Line 7
9	Speed in knots, Fig. 8
10	Line 9 × 1.007
11	24000 ÷ (24 × Line 10); RT: round trip
12	2 + (cargo deadweight ÷ 22,000)
13	Line 11 + Line 12
14	340 operating days per year
15	8 + 5.18 (shp ÷ 1000)
16	Line 15 × Line 11 × 1.15 × 0.5 (The 1.15 is for margin; the 0.5 for one-way bunkers.)
17	Fig. 27
18	Line 4 − Line 16 − Line 17
19	Same as Line 15
20	Line 19 × Line 11
21	Fig. 26. Assume port and canal fuel needs are nil.
22	Line 20 + Line 21
23	Line 22 × Line 14
24	Table 7 of reference [4]
25	Line 23 + Line 24
26	$1000 + $80 (design displ. ÷ 1000)
27	$2000 ~~per year~~ for bunkering stops
28	Line 26 + Line 27
29	Line 28 × Line 14
30	Fig. 28
31	$50,000 + $12 (design displ. ÷ 1000)
32	Fig. 30
33	Fig. 31
34	9.4% Line 30
35	$5000 + 1.2% Line 8
36	Summation Lines 29–35
37	$2.10 × 6.63 × Line 25 ($2.10 per barrel, 6.63 barrels per ton)
38	Line 36 + Line 37
39	*CRF* × invested cost = 0.2115 × Line 8
40	Line 38 + Line 39
41	Line 18 × Line 14(÷1000)
42	Line 40 ÷ Line 41
43	$26 × Line 41
44	Line 43 − Line 38 (This is return before tax)
45	Line 44 ÷ Line 8 (This is capital recovery factor before tax.)

For both challengers, numbers to be built are based on an anticipated traffic of 25 million long tons per year. Duplicate cost savings for foreign construction are assumed to be at only half the rate expected in a U.S. yard.

Table 16 develops the relative economics of the defender and both challengers. Crew wages are arbitrarily set 60 percent above current levels in recognition of the trend. Capital recovery costs are based on a 10-percent after-tax interest rate of return. All ships are single screw with steam propulsion.

You can readily conclude from the final figures in the table that both challengers are economically feasible. Whether they are politically feasible is another matter.

Table 16 Feasibility of Two Innovative Ships in the Great Lakes Iron Ore Trade

Alternative Assumptions	Defender	Challenger 1	Challenger 2
Crew complement	37	14	14
Operating season, months	7	11	11
Tax depr. period, years	50	10	10
Specification	normal	austere	austere
Building yard	U.S.	foreign	U.S.
Limiting length overall, ft	730	730	1000
Limiting beam, ft	75	75	100
Technical Characteristics			
LBP, ft	712	712	970
Beam, ft	75	75	100
Draft, ft	25.5	25.5	25.5
Displacement, LTFW	32800	32800	60000
Light weight, LT	8038	8038	15235
Deadweight, LT	24762	24762	44765
Fuel, water, stores, LT	602	602	900
Cargo capacity, LT	24160	24160	43865
Speed, loaded, mph	16.7	16.7	16.7
Shaft horsepower, normal	9000	9000	14000
Ships Required			
Round trips per year	42	62.5	62.5
Cargo per year per ship, 10^6 LT	1.015	1.51	2.74
Ships Required for 25 × 10^6 LT	24.65	16.55	9.12
Ships per contract	1	2 × 8	9
Invested Costs ($1000)			
Basic ship (U.S.-built)	9335	9335	15600
Automation features		+200	+200
Added reliability		+500	+500
Fewer accommodations		−600	−600
Winter oper. features		+600	+600
Austere design		−500	−500
Cost for one U.S.-built ship	9335	9535	15800
Ships per contract	1	8	9
Factor for duplication	—	0.906	0.802
Factor for foreign-built	—	0.50	—
Capital cost per ship	9335	4227	12670
Annual Costs per Ship ($1000) and Summary			
Wages	371	336	341
Subsistence	15	10	10
P & I insurance	5	5	5
Stores & supplies	13	17	17
H & M insurance	75	52	171
Maintenance & repair	135	239	490
Fuel	172	271	422
Towing	26	50	63
Winter surveillance	3	0	0
Overhead & misc	79	92	92
Total Annual Oper. Costs	894	1072	1611
Capital Costs (tax rate: 48%)	1639	578	1734
Average annual cost	2533	1650	3345
Required freight rate, per LT	$2.50	$1.09	$1.22
RFR ratio to defender	1	0.44	0.49

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