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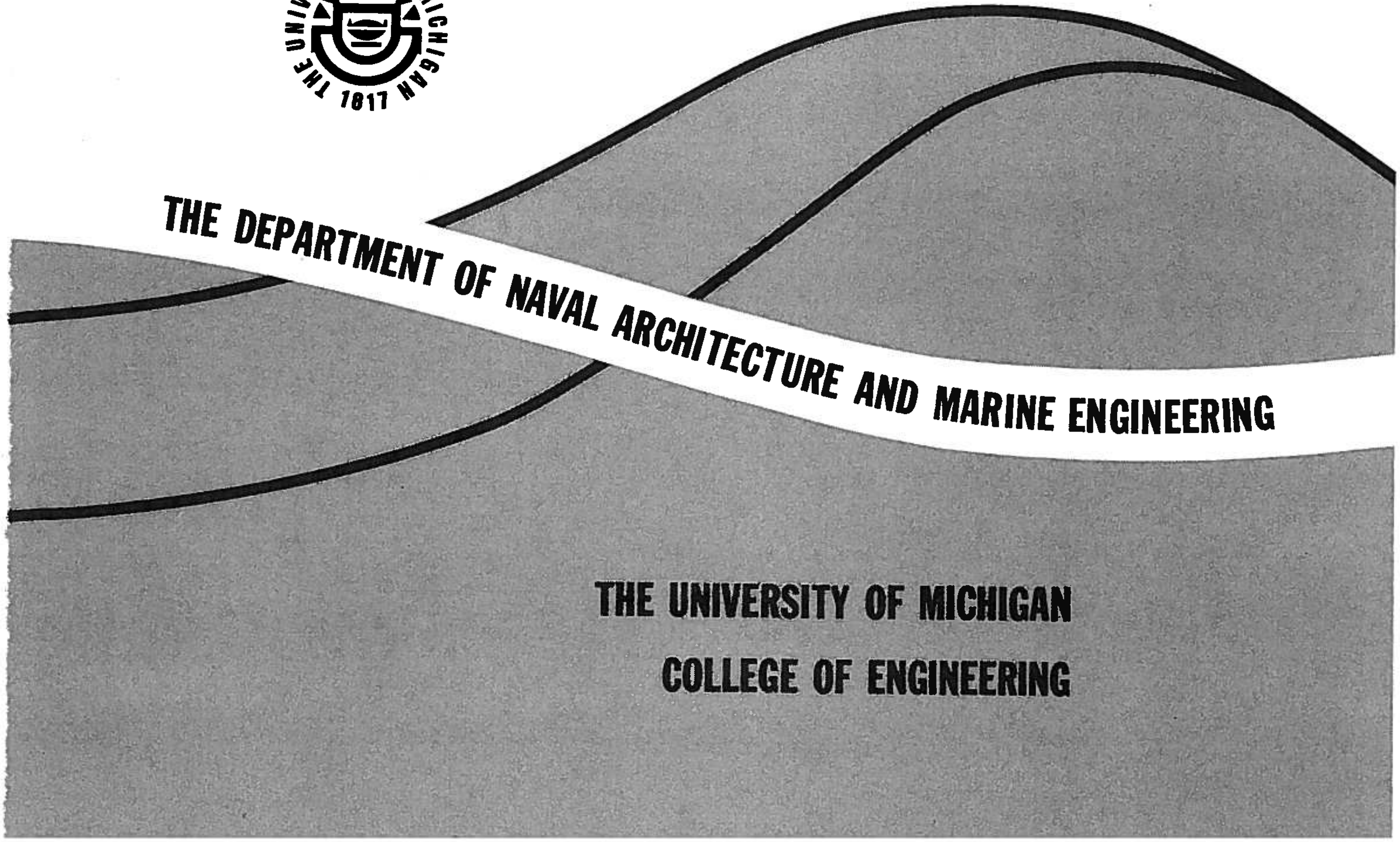

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Fresh Water Supply Aboard Ocean-Going Merchant Ships: The Economic Merit of Distillation From the Sea

By J. B. Woodward III[1]

The average annual cost of obtaining fresh water for boiler feed and domestic use by distillation from the sea is calculated for two distinct types of merchant ship, and compared to the cost of carrying purchased shore water for these uses. Results are presented as annual cost differences between the alternatives as functions of voyage length, with other significant factors as parameters. These results confirm the general belief that distillation is to be preferred, even if shore water did not typically require redistillation before use. Circumstances in which shore water might nonetheless be an attractive alternative are pointed out.

Introduction

Sea water is a satisfactory medium for flushing toilets, washing decks, transporting heat, and for a few other uses, but it is totally unsatisfactory for human consumption or for boiler feed. This elemental circumstance makes it necessary for ships to carry fresh water from shore in whatever quantity a given voyage may require, or to produce it as needed by distillation from the sea. The first method is the classical one inherited from many centuries of pre-steam sailing. The latter method has come into overwhelming favor in recent years, principally because one pound of fuel can evaporate many pounds of water, or because there may be waste heat available, as in the case of diesel propulsion. The weight and space saved by eliminating water and tanks (assuming that there is a saving) can be devoted to additional cargo, or to reducing hull dimensions and propulsive power. But a gallon of naturally fresh water purchased at the pier should cost less than one produced at sea. After all, sea-side communities produce their water supplies by distillation only when natural fresh water supply is inadequate. There thus seems to be the possibility of reliance on shore water being economically attractive in some circumstances, such as short voyages, where the amount to be carried per voyage is small.

The comparative economic merits of distillation from the sea were carefully examined in 1945 by Mark L. Ireland [1].[2] His findings generally favored this method over shore water carriage, and it is likely that his paper was influential in the subsequent increased popularity of distillation. But there are several factors of importance in the analysis of water production costs, and all may have changed since 1945. The study reported here is thus intended as a reexamination of the onboard distillation versus shore water question, making use of recent data.

A very significant change since 1945 is the advent of the digital computer for engineering and economic analyses. The calculation of costs of on-board distilled water is a lengthy one. Ireland had to rely on hand calculation, and so found it practicable to examine only a few particular cases. His general conclusions were based on these few cases, since they all showed the superiority of distillation. But some of the many cases that he did not examine might have shown the opposite results. The present study, making full use of an IBM 7090 computer, examines many thousands of individual cases, and attempts in this way to establish boundaries between alternatives, as well as to determine which is generally favored.

A second change since 1945 is the advent of large desalination plants in port areas where natural fresh water is in short supply. Since desalinated water is usually pure enough for boiler feed, whereas natural waters are not, it has a distinct advantage for the steam vessel over ordinary shore supplies. If these plants become more numerous, and their product sufficiently low in price, they can be a significant factor in the question being explored here.

The principal factors directly affecting on-board water costs are price of fuel, rate of water usage by crew and machinery, price of shore water, first costs and operating costs of water-producing and water-handling machinery, length of voyage, and costs of tankage. Secondary, but

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

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often important, factors are revenue losses from cargo deadweight usurped by water and machinery weight, or increases in hull dimensions and propulsive power needed to carry this weight. All of these are examined here in order to find the difference in average annual costs between the two competing ways of supplying the fresh water. Two distinct types of cargo ship, with different sizes, speeds, freight rates, time-at-sea percentages, and designed voyage lengths, are analyzed.

The study is conducted with the intent of judging the correctness, from the cost standpoint, of the present practice of distilling water from the sea in lieu of purchasing it ashore. If on-board distilling is indeed the cheaper alternative generally, there is also the intent of finding the special circumstances under which shore water use might be favored.

Water: the Technical and Economic Problem

In discussion of fresh water for a steam vessel, two distinct supplies must be mentioned: water for human consumption, and make-up feed water for the boilers. Each has its unique quality and quantity requirements.

Potable (drinking) water is expected to meet the quality standards of the United States Public Health Service [2, 3, 4]. In addition to the obvious biological purity required, standards of color, taste, turbidity, and concentration limits on certain elements and compounds found in natural waters are specified. The details are not given here. Of special interest, however, with respect to sea service is the upper limit of 250 ppm for the chloride ion, and the limit of 500 ppm on total solids.

The Public Health Service suggests that fresh water be supplied aboard ship at the rate of 8 gpd per person for potable water, and 22 gpd per person for all other domestic uses, with a minimum storage capacity of 2 days of potable water when the water is produced aboard. The rate of supply commonly assumed in preparing marine power plant heat balances is 45 gpd per person, total of all domestic uses [5]. This figure is used as the domestic consumption rate in this paper. Storage capacities used here with the distilling plant alternative are 5-day and 10-day supplies, bases on the total (i.e. including boiler feed) needs of the ship.

Separate supplies of potable and wash water are sometimes carried aboard ship, and separate distribution systems installed. In this paper no distinction is made between potable and wash waters, since such a complication would have only a slight bearing on the economic question being studied.

The chemistry of boiler water is a lengthy and complex subject. Sludging, scaling, corrosion in the boiler, and carryover of solids to the turbines are hazards of operation chargeable to impurities in the boiler water. Here we need not explore this field, since our concern is not with the water *in* the boiler, but with the quality and quantity of the relatively small make-up stream supplied to the steam plant during operation. The standard quality specification for this water—which is also the quality specification applied to marine distiller output—is maximum total sea salt concentration of 4.3 ppm (¼ grain/gal) [6].

The amount of make-up feed required depends on the rate of loss from the machinery, and on the extent of nonreturn uses of steam such as steam atomization of the fuel, and steam soot-blowing. Recommended allowances for all of these quantities are given by the Society of Naval Architects and Marine Engineers heat-balance bulletin [5]. These recommendations are used in this study to calculate the rate of water production or amount of storage needed to maintain the make-up feed supply. The hourly feed rates used for the several machinery plants used are discussed in a later section, where they are summarized in Table 2.

A significant point in the preceding discussion is that the 4.3 ppm sea salt concentration specified for boiler is considerably less than the 250 ppm chloride maximum for drinking water. An acceptable drinking water is thus likely to be unacceptable as boiler feed. In fact, it is not only likely, but almost certainly, unacceptable. No natural fresh water, not even rain water [2], is consistently low enough in dissolved mineral matter to be used as feed in the modern boiler. Municipal water treatment plants usually improve the quality of natural water, but only with respect to biological purity, and perhaps odor, appearance, and taste. The usual source of shore water, the municipal water system of a port city, is thus not a satisfactory source of boiler feed water unless additional purification is done aboard ship. The traditional remedy for ships depending on shore water is to distill the reserve feed water as it is passed into the feed system, using a "make-up feed evaporator" installed for that purpose alone. In customary modern practice, a low-pressure distilling plant provides water from the sea for all uses, and no further treatment of this water is needed. If for any reason shore water is carried as reserve feed, it can be distilled by this plant to upgrade it to boiler feed standards.

Shore power plants must likewise upgrade their boiler feed water, but rarely use distillation, since other methods are usually cheaper for naturally fresh raw water. These other methods will not be discussed here, except to note that there are several methods in common use, and that the choice among them depends largely on the properties of the raw water to be treated [2]. The last circumstance contains the essence of an explanation why distillation alone has been favored by ships that depend on shore water sources. The ship must be prepared to accept water from many sources of diverse quality, and only distillation qualifies as a practicable universal method of treatment.

Of special interest to this study is the increasing use of distillation ("desalination") to provide fresh water for seaside communities with inadequate natural supplies [7, 8]. Although these plants are of much larger capacity than shipboard plants, the principles used are the same. Flash evaporation appears to be the most popular method in both situations. The purity of product is approximately the same in both. For

Table 1 Typical Water Prices at Selected Ports

Place	Price, $\$/10^3$ gal	Reference
New York area	1.86	12
London area	1.30	12
Abadan	1.60	12
Bergen	4.35	12
Hampton Roads	1.65	13

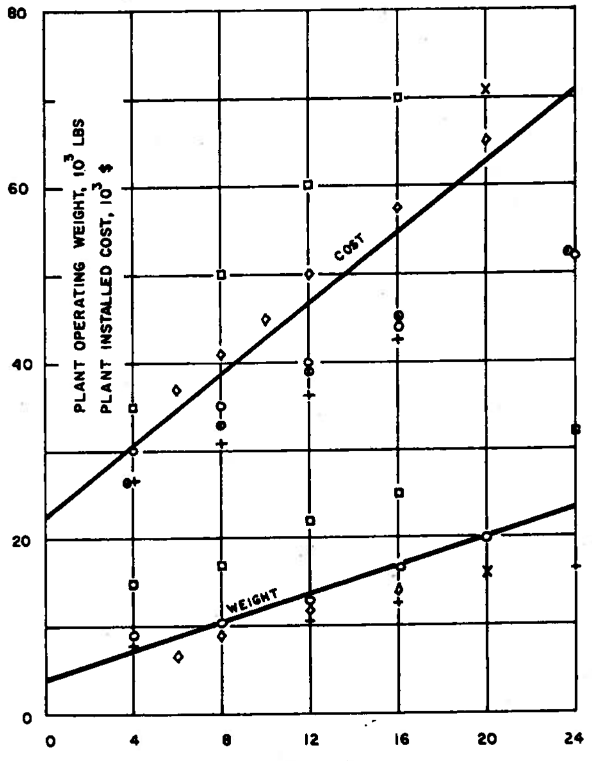

Fig. 1 Cost and weight of distilling plants

example, the plant at Aruba, Netherlands Antilles, was designed for 4 ppm total dissolved solids, and actually produced a purity of 1.2 ppm on a 500-hr performance test [9]. Where shore water is produced by these plants, they constitute a source of water acceptable for both domestic use and boiler feed without further treatment. In at least on port, such water is now being purchased by ships [10, 11]. Its availability should increase as more desalination plants are built.

Prices being paid by ships for shore water at several ports in 1967 are listed in Table 1. All of those listed are from the usual domestic-quality sources, and are not suitable for boiler feed without further treatment.

The only available data on the sale of distilled (desalinated) water to ships, at Aruba, indicates a price of about \$2.00 per 1000 gal [11, 12]. This is much higher than the published cost of the water, \$0.86 per 1000 gal [9]. This cost is not necessarily typical of desalination plants. There are too few at present to make a typical picture, for one thing. Costs as low as \$0.25 per 1000 gal have been predicted for large dual-purpose (electric power and water) plants [7]. If the same price/cost ratio now apparently in effect at Aruba holds, the price to ships at this cost would be \$0.58 per 1000 gal.

Calculation of Water Costs

This section summarizes the methods used to calculate water costs for both of the alternative methods of supply: shore water and distillation from the sea. Details are in the Appendix; all formulas are listed there with sources or derivations given. Numerical values are discussed in the section on scope of the study.

The differences in average annual cost between the shore-water alternative and the distillation alternative are calculated for numerous sets of input data. For the first of these alternatives, the factors considered are the cost of the water purchased, the cost of tankage needed to carry it, and secondary factors, e.g. loss of cargo revenue because of displacement given over to water carriage. For the second alternative, the factors considered are the cost of the water-producing plant, cost of associated tankage, plant operating costs, and secondary factors similar to those applying to the first alternative. Costs common to both schemes, such as the cost of distribution, are not considered.

As previously noted, the usual shore water is not suitable for boiler feed, so that the cost of on-board treatment is an appropriate burden on the shore-water alternative, unless the water be taken from a shore-side desalination plant. This suggests that there are actually three alternatives: (1) on-board distillation from the sea, (2) shore supply, with distillation of the part going to boiler feed, and (3) shore supply of sufficient purity for all uses without shipboard treatment. All three were included in the original scope of the study, but it was found that even without the burden of shipboard treatment, shore water is attractive only for relatively short voyages and low-price water. Thus the results for the second alternative listed here are superfluous, and are omitted from this report.

Installed cost as a function of rating for two-stage flash-type distilling plants, along with weight, is shown in Fig. 1. This information was kindly supplied by several American shipyards and government agencies. Since several of them asked not to be identified in the published results, the individual sets of data are not identified as to source. The contributors are listed, however, in the acknowledgments.

Cost of tankage is calculated from an estimate of the amount of structure needed to hold the required water, with cost estimates based on references [14] and [15]. The amount of water to be carried in the shore-water alternative is calculated from the rate of consumption and the length of voyage, including a margin. With a distilling plant, a reserve of water for a number of days is assumed to be carried at all times.

Fuel costs and maintenance costs are assumed to be the significant operating costs for the distilling plant. Labor costs for normal operation are assumed to be negligible.

Fuel costs cannot be calculated directly, since distilling plants do not themselves consume fuel, but are integrated into the power plant, and usually use bleed steam as their source of heat. It is necessary to take the difference of the total fuel consumptions found by two plant heat balances, one with the distilling plant producing at a certain rate, and the other with it secured.

Maintenance costs typical of distilling plants are difficult to determine. The annual maintenance cost used here is based on sketchy data, and must be regarded as an approximation only. Fortunately, it is but a small part of the total annual cost. Sources of information are references [6] and [14].

The secondary cost factors are calculated in different ways for the two distinct ship types studied. The first of these is a bulk carrier with assumed unlimited cargo available. Total displacement is taken to be the same for both water supply alternatives, so that the difference in weight between them is a difference in cargo deadweight. To account for the difference, weight of machinery, tanks, and water at the beginning of a voyage is calculated for each alternative. This weight, multiplied by a freight rate appropriate to the ship and to the voyage length, is revenue lost, and is charged as a cost against water supply.

The second type of ship is a container ship. In this case, the ship is assumed to be designed for a particular voyage and a particular number of containers. Revenue is not affected by the choice of water supply, but weights of machinery and water influence weight of structure and propulsion power. Thus the secondary factor is the increase in first cost of ship hull structure and power plant, and increased fuel cost because of the greater power, caused by the excess weight of one alternative over the other. These things cannot be calculated exactly in a general study such as this, but estimates can be made from published information. The source used here is a study by Giblon and Rohlih [17].

All costs are combined into an average annual cost by the formula

$$\mathrm{AAC} = \mathrm{CRF}\cdot P + Y \qquad (1)$$

For the bulk ship, this becomes:

$$\mathrm{AAC(distill)} = \mathrm{CRF}\cdot\ (P_d + P_t) + C_f + C_m \quad \$/\mathrm{yr} \qquad (2)$$

$$\mathrm{AAC(shore)} = \mathrm{CRF}\cdot\ (P_t) + C_L + C_w \quad \$/\mathrm{yr} \qquad (3)$$

For the container ship:

$$\mathrm{AAC(distill)} = \mathrm{CRF}\cdot(P_d + P_t) + C_f + C_m \quad \$/\mathrm{yr} \qquad (4)$$

$$\mathrm{AAC(shore)} = \mathrm{CRF}\cdot(P_t + P_h\, P_m) + C_w + C_{fl} \quad \$/\mathrm{yr} \qquad (5)$$

For container ships, the secondary factors are calculated as part of the shore water costs, based on the difference in weight between the two alternatives. The difference and resulting cost are negative when the shore-water option has the lesser total weight. It is immaterial which alternative is charged with this item, since results are to be given as differences in average annual cost.

Scope of Study

Power Plant, and Rate of Water Use

Rates of make-up feed to the power plant are calculated for three cases: (1) to replace nominal leakage, (2) to replace nominal leakage plus steam used for fuel

Nomenclature

AAC = average annual cost, \$/year
A_t = tank surface area, sq ft
a = coefficient in equation for freight rate
C_B = block coefficient
C_f = annual fuel cost, \$/year
C_{fl} = extra fuel cost due to increment in SHP, \$/year
C_L = lost annual revenue, \$/year
C_m = annual maintenance cost, \$/year
CN = cubic number
CRF = capital recovery factor
C_w = annual shore water cost, \$/year
D = supply of reserve water, days
D = hull depth, ft
D_w = domestic water use rate, lb/hr
D_v = length of round trip voyage, days
dwt = deadweight tonnage
L = length between perpendiculars, ft
L_1 = length of one-way voyage, days
L_r = length of round-trip voyage, nmiles
L_s = length of superstructure, ft
MUF = make-up feed rate, lb/hr
N = number of voyages per year
P = initial cost, \$
P_d = initial cost of distilling plant, installed, \$
P_H = base cost of hull, \$
P_h = increment in hull cost, \$
P_L = initial cost contributed by labor, \$
P_m = increment in machinery cost, \$
P_t = cost of tankage, \$
p_f = price of fuel oil, \$/bbl
p_w = price of water, ¢/1000 gal
R_d = rating of distilling plant, gpd
R_f = freight rate, \$/ton
SHP = shaft horsepower
Δ SHP = increment in SHP
U = percent time at sea
V = tank volume, cu ft
V_k = ship speed, knots
W_f = fuel carried for distilling plant, tons
W_H = hull weight, tons
ΔW_H = increment in hull weight, tons
W_M = machinery weight, tons
W_d = weight of distilling plant, tons
W_r = weight of reserve water carried, tons
W_t = weight of tanks, tons
W_w = weight of water carried, tons
W_x = excess weight of shore water alternative, tons
w_e = increment in water production rate to supply later needs in port, lb/hr
w_f = rate of fuel use chargeable to distilling plant, lb/hr
w_{fl} = increment in fuel consumption because of Δ SHP
w_w = water use rate, lb/hr
w_{24w} = water use rate, gpd
Y = sum of annual operating costs, \$/year

Table 2 Water Consumption Rates and Corresponding Increments in Fuel Consumption (both in lb/hr)

SHP	Use	Soot Blow	Stm Atom	Crew	MUF	DW	w_w	w_f
10000	A			0	378	0	378	20.0
	B			20	378	312	690	23.7
	C	yes	yes	20	1308	312	1620	34.8
	D	yes	yes	50	1308	780	2088	40.1
20000	A			0	724	0	724	23.9
	B			20	724	312	1036	27.3
	C	yes	yes	20	2343	312	2655	46.0
	D	yes	yes	50	2343	780	3123	51.2
30000	A			0	1058	0	1058	27.5
	B			20	1058	312	1370	30.9
	C	yes	yes	20	3344	312	3656	56.9
	D	yes	yes	50	3344	780	4124	62.1
40000	A			0	1391	0	1391	31.4
	B			20	1391	312	1703	34.9
	C	yes	yes	20	4243	312	4655	68.7
	D	yes	yes	50	4243	780	5123	74.0

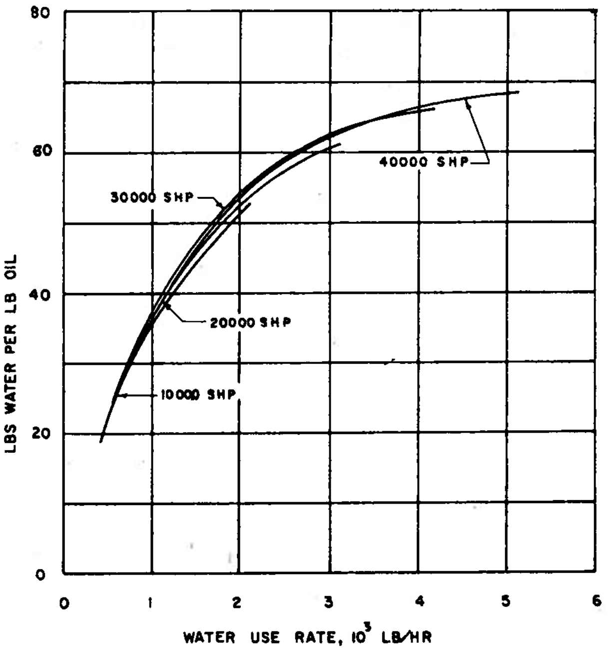

Fig. 2 Pounds of water produced per pound of oil

atomization, and (3) to replace nominal leakage, atomization steam, and soot-blowing steam. For each case, the additional water required for domestic use is calculated for crews of 0 (complete automation!), 20, and 50 men. For each category of use, the allowances recommended by reference [5] are used. Heat balances were made for each of the nine combinations, with and without distilling plant in operation, to determine the amount of fuel chargeable to water production. The four cases discussed in this paper are summarized in Table 2.

Power rating of the propulsion plant affects the rate of water use, since the nonreturn uses and leakage are taken to be fixed percentages of the total flow rate through the plant. Ratings used are 10,000, 20,000, 30,000, and 40,000 SHP. The resulting water consumption rates, including domestic use, are listed in Table 2, along with the extra fuel consumption found by heat balance. The same water consumption rates are used to calculate the amount of water that must be purchased for the shore-water alternative.

Such distinguishing characteristics of steam power plants as steam conditions and number of stages of feed heating may also affect the amount of fuel chargeable to distillation. To test this possibility, the heat balances were repeated for the following conditions: (1) 600 psi, 865 F steam, both two and four stages of feed heating, (2) 600 psi, 950 F steam, both two and four stages of feed heating, (3) 1200 psi, 950 F steam, both two and four stages of feed heating, and (4) 1400 psi, 950 F steam, with five stages of feed heating. Several of these were also calculated with the alternatives of either sea-water-cooled distillers or main-condensate-cooled distillers. Among all of these, however, the amounts of fuel chargeable to distillation turned out to be so nearly the same that the differences appeared to be insignificant. Thus effect of steam conditions and cycle arrangement are not considered.

As a matter of interest, the ratio of water produced to oil burned is shown in Fig. 2.

The rating of a shipboard distilling plant typically falls between two and three times the average water use rate shown on design heat balances. The factor used for the results to be presented here is two; the rating in each case is thus $2.0 \cdot w_{w'}$ converted to gpd. Values of w_w are listed in Table 2. The effect of varying this factor up to three is also explored.

Water storage capacities of five and ten days, for holding reserve distiller product, are used.

Prices and Other Direct Economic Factors

Fuel price used is $1.50, $2.00, and $2.50 per barrel.

Shore water prices used are $0.50. $1.00, and $1.50 per 1000 gal. A look back at Table 1 shows that the first two of these are optimistic.

Capital recovery factors used are 0.10, 0.15 and 0.20 before tax. These are assumed to include all fixed annual costs, such as insurance, in addition to actual capital recovery.

Voyage length is an important consideration since it determines the amount of water and tankage that must be aboard; 2000 through, 32,000 miles are analyzed.

Secondary Factors

The discussion just above applies equally to both the bulk ships and the container ships. The secondary cost factors are, however, quite different for the two ships.

Four bulk carriers are studied. All are taken to have a 17-knot average sea speed, to be in service 350 days a year, and to have a short (2.8 days per voyage) time in port. Since speed is fixed, power is assumed to determine a deadweight tonnage for the ship. Thus the four powers result in four ships of different deadweight. A relation derived by Benford [17] between SHP and deadweight is used to give a unique connection between these two parameters. The deadweights used are 15,000, 58,000, 101,000, and 144,000, corresponding to 10,000, 20,000, 30,000, and 40,000 SHP, respectively.

Freight rates are based on length of voyage and dwt of ship, following Benford in reference [11]. The rates are arbitrarily varied through a factor of two to test the sensitivity of the results to this factor. See equation (6) in the Appendix.

Eight container ships are studied. These are derived from the four values of SHP and sea speeds of 16, 20, and 24 knots. A displacement for each combination of SHP and speed is chosen to give a reasonable combination of these three parameters, using curves of reference [14] as guide. The combinations are listed in Table 3. They are eight in number rather than twelve, because four of the combinations fell outside the reasonable range of practice. (Size of ship is needed in calculating the increment in hull cost caused by weight of the water system.)

The container ships are also assumed to be in service 350 days per year, but with at-sea times of 40, 60, and 80 percent of the 350 days.

Summary

The parameters varied independently are SHP, CRF, rate of water use, fuel price, water price, rating ratio of the distilling plants, length of voyage, freight rate (bulk ship only), sea speed (container ship only), and percent item at sea (container ship only). Input information used, but not varied independently, can be found in the formulas listed in the Appendix.

Table 3 Distinguishing Characteristics of Container Ships

SHP	Speed, knots	Displacement
10 000	16	26 000
10 000	20	7 000
20 000	16	70 000
20 000	20	23 000
20 000	24	7 800
30 000	20	43 000
30 000	24	15 500
40 000	24	26 000

Results

It is impracticable to present all of the results generated in this study; there are just too many combinations of the variables, and dimensionless combinations of them don't produce enough correlations to be helpful. The compromise with completeness adopted here is to present results for a representative combination of variables, then use this as a base from which to show the effects of variations that are significant.

Bulk Ships

The representative combination for the bulk ships is the 20000 SHP/58000 dwt ship, with water use rate C (Table 2), and CRF of 0.15. The results are shown in Fig. 3 in the form of differences in average annual cost between the alternatives as a function of round-trip voyage distance, with freight rate and water price as parameters. Figs. 4, 5 and 6 indicate the influences of difference in CRF, power and size of ship, and water use rate, respectively.

The difference in AAC used in all of these figures is the AAC for the shore-water alternative less that of the distilling-plant alternative. Where this difference is positive, the distilling plant is thus the cheaper.

The difference between annual costs of the alternatives is a strong function of voyage length, since the cargo revenue loss counted as a cost is proportional to the amount of water that must be loaded. Water price is a factor of comparable effect; in Fig. 3 only the $0.50 price shows any favorable opportunity for shore-water use. Freight rate is also obviously important because of its direct contribution to lost cargo revenue. High freight rate favors the alternative that is lightest on leaving port, and so favors the distilling plant for long voyages, and shore water for short ones.

An increase in CRF favors the shore-water alternative since it has the smaller initial investment.

Fig. 5 indicates that the economic advantage of the distilling plant is greater on the larger ships.

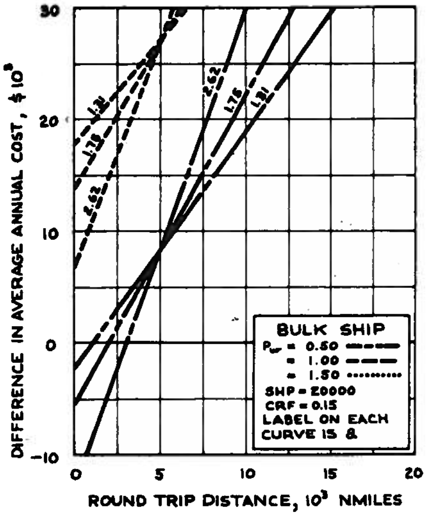

Fig. 3 For *bulk ships:* Differences in average annual costs of the alternatives as function of voyage length. Water price and freight rate are the parameters

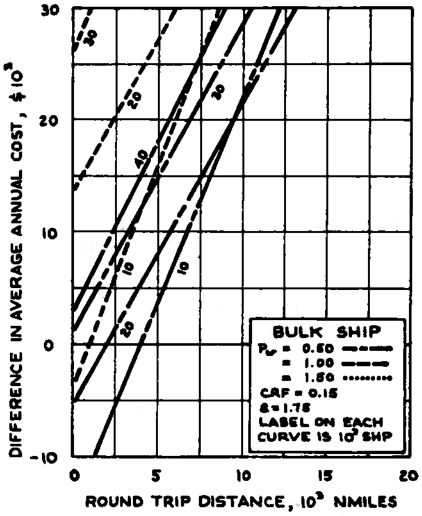

Fig. 5 For *bulk ships:* Differences in average annual costs of the alternatives as function of voyage length, showing influence of ship size

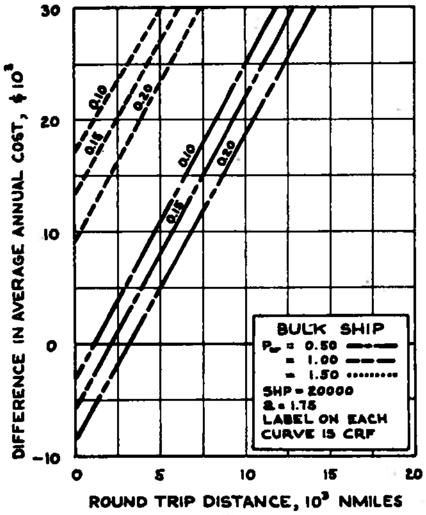

Fig. 4 For *bulk ships:* Differences in average annual costs of the alternatives as function of voyage length, showing influence of CRF

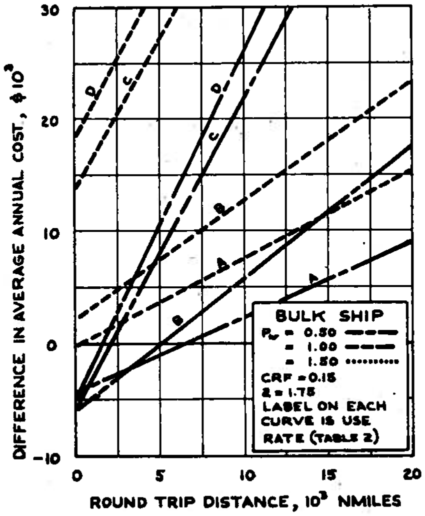

Fig. 6 For *bulk ships:* Differences in average annual costs of the alternatives as function of voyage length, showing influence of water use rate

Higher water use rates favor the distilling-plant alternative, except for very short voyages in which the amount of water carried at any rate would be negligible.

Higher fuel prices obviously tend to favor the carrying of shore water; but the effect is small for reasonable variations in price, because fuel cost is a relatively minor item. No fuel price variation is included in the results here; all figures are for a $2.00 per barrel price.

The effect of variation in distilling-plant first cost might well be questioned, especially since Fig. 1 shows a sizable scatter in the price estimates. Although this point is not explicitly covered, Fig. 4 indicates quite well the effect of first cost, since a change in first cost has the same effect as a change in CRF. (The cost of tankage is approximately the same for both alternatives, except at very long voyages, so that the variation between lines in Fig. 4 is due principally to variation in the product CRF$\cdot P_d$.) For example, doubling the price of the distilling plant has about the same effect as increasing CRF from 0.10 to 0.20 in Fig. 4.

Table 4 Cost Breakdown for Bulk Ships, for SHP = 20,000, CRF = 0.15, *pw* = 1.00

		Distilling Plant					Shore Water		
a	L_R	$CRF \cdot P_d$	C_L	C_f	C_m	$CRF \cdot P_t$	C_L	$CRF \cdot P_t$	C_w
1.31	2000	8038	12445	2236	564	1715	11446	1652	37037
	10000	8038	17887	2236	564	1715	51793	3645	37037
	18000	8038	19081	2236	564	1715	91324	5182	37037
	26000	8038	19785	2236	564	1715	130650	6516	37037
1.75	2000	8038	16607	2236	564	1715	15261	1652	37037
	10000	8038	23849	2236	564	1715	69057	3645	37037
	18000	8038	24441	2236	564	1715	121765	5182	37037
	26000	8038	26381	2236	564	1715	174200	6516	37037
2.62	2000	8038	24910	2236	564	1715	22892	1652	37037
	10000	8038	35774	2236	564	1715	103586	3645	37037
	18000	8038	38163	2236	564	1715	182648	5182	37037
	26000	8038	39510	2236	564	1715	261299	6516	37037

Table 4 is a tabulation of the individual cost categories for a few combinations of variables. It is included to give the reader an idea of the relative importance of the categories, and to enable him to make his own estimates with different input data. The most noticeable thing in this tabulation is the dominant influence of the lost-revenue category.

Increasing the distilling plant rating for a given water use rate (e.g. adding a standby unit) makes this alternative cost more, but an increase in rating might logically be coupled with a reduction in the reserve water carried. In analyses made with a ratio of gal/day rating to gal/day use of 3.0 and a 5.0 day reserve supply (in place of 2.0 and 10.0, respectively), the reduction in reserve water allowed enough extra cargo revenue to just about offset the increased investment in the distilling plant, except for very short voyages.

The results show overall that the economic position of the distilling plant is unassailable. The shore-water alternative appears attractive only for water prices (i.e. $0.50) that are far below contemporary prices, or perhaps for rates of water use that are unrealistically low. Although fuel price, value of CRF, freight rate, and first cost of distilling plants are significant factors, and in actuality may vary beyond the ranges used here, no variation that seems reasonable can reverse the picture.

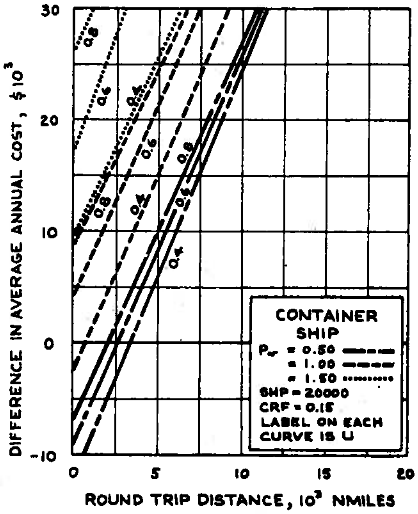

Fig. 7 For *container ships:* Differences in average annual costs of the alternatives as function of voyage length. Water price and time-at-sea are the parameters.

Container Ships

The representative combination for container ships is the 20,000 SHP/20 knot ship with water use rate C and CRF of 0.15. The results are shown in Fig. 7 in the same format that is used for the bulk ships. Figs. 8 and 9 indicate the influences of differences in CRF and water use rate, respectively.

The difference in annual cost between the alternatives is a strong function of voyage length in these ships also, and also because of the influence of the secondary costs. The increasing weight of water and tankage with lengthening voyage means increasing hull weight, SHP, and fuel consumption, and these are the burdens of a ship relying on shore water. Water price has its obvious direct influence on costs, but CRF is a more complex influence than in the bulk ships. For long voyages, high CRF favors the distilling-plant alternative because the large tonnage of shore water needed for the other alternative causes a significant increase in first cost of hull and machinery. For short voyages, the distilling plant is the principal investment item, so that high CRF favors shore water. The net result could be said to be favorable to the use of shore water, since the breakeven distances (distances for zero difference in annual cost) is generally increased. The complex influence of CRF makes it impossible to use the CRF data to estimate the effect of variations in distilling-plant price, as was

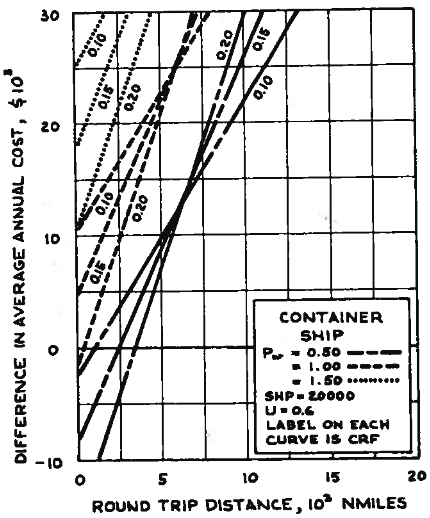

Fig. 8 For *container ships:* Differences in average annual costs of the alternatives as function of voyage length, showing influence of CRF

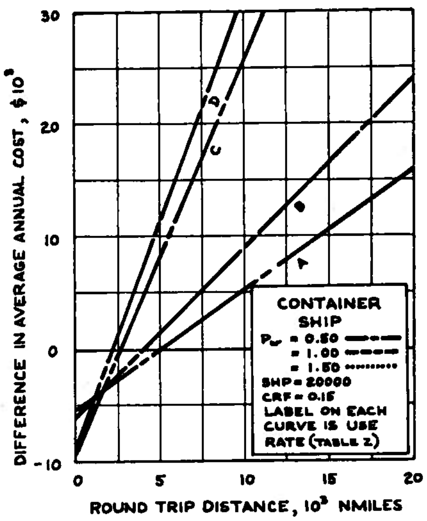

Fig. 9 For *container ships:* Differences in average annual costs of the alternatives as function of voyage length, showing influence of water use rate

Table 5 Cost Breakdown for Container Ships, for SHP = 20,000, CRF = 0.15, pw = 1.00

		Distilling Plant				Shore Water				
U	L_R	$CRF \cdot P_d$	C_f	C_m	$CRF \cdot P_t$	$CRF \cdot P_m$	$CRF \cdot P_h$	C_{fl}	$CRF \cdot P_t$	C_w
0.40	2000	9630	1202	564	3440	-638	-1783	-327	2865	20350
	8000	9630	1202	564	3440	3535	10005	1774	6600	20350
	14000	9630	1202	564	3440	8222	22952	3948	7328	20350
	20000	9630	1202	564	3440	13250	35610	5656	11975	20350
0.60	2000	9070	1640	564	3440	-856	-2278	-654	2662	27177
	8000	9070	1640	564	3440	3160	8395	2345	6102	27177
	14000	9070	1640	564	3440	7338	19520	5391	6730	27177
	20000	9070	1640	564	3440	11842	31105	8215	11040	27177
0.80	2000	8465	1967	564	3440	-1070	-2802	-1080	2517	33313
	8000	8465	1967	564	3440	2783	6555	2594	5724	33313
	14000	8465	1967	564	3440	6467	16617	6408	6005	33313
	20000	8465	1967	564	3440	10430	26610	9715	10232	33313

suggested for the bulk ships. However, this estimate still can be made by changing the applicable cost category in Table 5, then summing to get the difference between the two alternatives. Table 5 is similar to Table 4 in that it is a tabulation of individual cost categories for several combinations of variables.

Higher percentage time at sea generally favors the distilling-plant alternative. Higher time at sea means more water purchased in a year for one alternative, and more fuel burned for the other, since water is used at a greater rate at sea than in port. But the distilling plant can be smaller, since less time in port means less extra water to be made at sea for later use in port when the plant is secured.

Low water use rates favor the shore-water alternative, as Fig. 9 shows. You will note, however, that this figure is plotted for the lowest ($0.50) water price, and that even with this price and the lowest use rate, shore water appears to be favored for voyages of only modest round-trip length.

Results are given for only one of the eight ships for which the analysis was made. The reason for this omission is that there is no significant difference among them, although there is a slight tendency for the shore-water alternative to look better in the smaller, slower, ships.

Loading water at both ends of the voyage improves the competitive position of the shore-water alternative, since it approximately halves the weight chargeable to it. The improvement is indicated in Fig. 10. How-

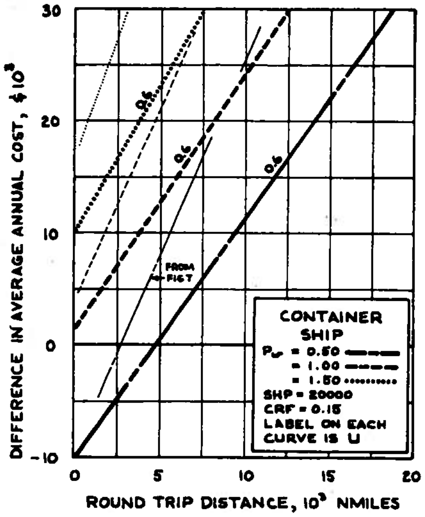

Fig. 10 For *container ships:* Differences in average annual costs of the alternatives as function of voyage length. Similar to Fig. 7, but with water loaded at both ends of voyage

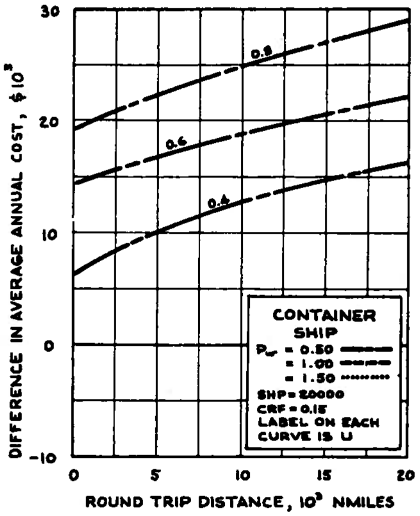

Fig. 11 For *container ships:* Differences in average annual costs of the alternatives as function of voyage length. No secondary costs (extra hull and machinery costs chargeable to water system)

ever, the improvement is not enough to reverse the advantage of the distilling plant, except at the lowest water price.

The results for the container ships are generally the same for the bulk ships: shore water can be made attractive only at unrealistically low water prices and use rates.

Without Secondary Costs

The secondary costs, lost cargo revenue in the case of bulk ships, and increments in hull and power costs in the case of container ships, are perhaps the most uncertain of the cost categories used, since they are not so firmly seated in confirmable data as the others. A reader who has good sources of information for a case of interest to him may wish to improve on these estimates; the cost breakdowns in Tables 4 and 5 enable this to be done for some cases. But also suppose that secondary factors be neglected altogether, as might be reasonable for a ship whose cargo revenue was not to be affected, and whose hull dimensions and power had already been fixed. The result of neglecting these factors is generally unfavorable to the shore-water alternative. Although this alternative gains for the long voyages where it is otherwise heavily penalized by high weight, it loses for short voyages where the distilling-plant alternative is heavier. The net change is a flattening of the curves of annual cost difference versus voyage length, with the breakeven distance decreasing or vanishing. Such curves are shown by Fig. 11, and should be compared to the curves for $P_w = 0.50$ in Fig. 7. The results for a similar treatment of the bulk ship are about the same. The 80-percent time-at-sea curve of Fig. 11 corresponds approximately to the bulk case.

Conclusions

The economic merit of supplying fresh water by distillation of sea water is confirmed. When realistic water use rates and shore water prices are used, the shore-water alternative is attractive only for the shortest voyages, and only then on the assumption that the water require no treatment before use.

Variations in CRF, freight rate, fuel price, and ship size and power affect the comparison, but not enough to alter the general conclusion.

The results do suggest that the shore water supply would be competitive for voyages of reasonable length (e.g. North Atlantic round trip) if reductions occur in either use rate or water price. Either reduction would have to be a major one, however. The only such reduction that can be surmised from discussions in this paper is a drop in price of desalinated water. If some of the published predictions of low water costs from future large multi-purpose plants are accomplished, there may indeed be sources of cheap, boiler-feed-quality water that will make dependence on shore water the attractive alternative for some services. But this is largely speculation.

No mention has been made of the intangible advantages of distilling plants, since their position seems to be well fixed by tangible figures. But perhaps a parting note should at least mention the most obvious of intangible advantages; namely, the independence of shore supply that the distilling plant conveys. A ship might well be designed for a special service where suitable shore water was the preferred choice, but the life of a ship is of such length that it may be shifted to runs in later life that its designers never planned for. My advice is to always at least leave room in the machinery space for later addition of the distiller.

Acknowledgments

Cost information on installed distilling plants was supplied by several organizations, and this key contribution is gratefully acknowledged. These organizations are United States Maritime Administration, Newport News Shipbuilding, Litton Industries, New York Shipbuilding, Bath Iron Works, and Sun Shipbuilding.

Bryant Hilliard of Esso International was also of considerable help in answering numerous questions on prices and availability of shore water, as experienced by the Esso fleet.

Professor Harry Benford of the University of Michigan was also a generous contributor by his help in getting cost data, and by his original suggestions that such a study be made.

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Appendix

Formulas and Their Derivation

Formulas Used for the Bulk Ships

1 Average Annual Cost

$$\text{AAC} = (\text{CRF})\cdot P + Y \qquad \$/\text{yr}$$

2 Annual Maintenance Cost

$$C_m = (0.017)\ (4500)\ (\text{SHP}/1000)^{2/3} \qquad \$/\text{yr}$$

or 1.7 percent of total machinery maintenance cost, after [18] with total maintenance cost estimated from [14]

3 Relationship Between dwt and SHP for 17-knot Average Sea Speed

$$\text{dwt} = (\text{SHP} - 6500)/0.2325 \qquad \text{tons}$$

From [19], Fig. 4, for 17-knot tankers

4 Length of One-Way Voyage

$$L_1 = \tfrac{1}{2}\left[\frac{L_r}{(17)\ (24)} + 2.8\right] \qquad \text{days}$$

for assumed 2.8 days in port per voyage

5 Number of One-Way Voyages per Year

$$N = 350/L_1 = 285{,}500/(L_r + 1142)$$

6 Freight Rate

$$R_f = \text{a}\ (L_r/1000)/(\text{DWT}/10000)^{0.623} \qquad \$/\text{ton}$$

From Fig. 2 of [18]. Value of *a* from this figure is 1.31; values of 1.75 and 2.62 are also used here.

7 Annual Cost of Water Purchased

$$C_w = 13.95\ (p_w)\ (w_w) \qquad \$/\text{yr}$$

8 Annual Cost of Fuel Chargeable to Distilling Plant

$$C_f = \frac{24w_f\ (L_r + 1142)\ (285{,}500)p_f}{2240\ (816)\ (L_r + 1142)} \qquad \$/\text{yr}$$

$$= 24.3\ (p_f)\ (w_f) \qquad \text{for } p_f \text{ in } \$/\text{bbl}$$

9 Rating of Distilling Plant

$$R_d = (2.0)\ (2.88)\ w_w \qquad \text{gpd, for } w_w \text{ in lb/hr}$$

10 Installed Cost of Distilling Plant

$$P_d = 23000 + (2.0)\ R_d \qquad \$$$

See Fig. 1.

11 Weight of Distilling Plant

$$W_d = \frac{4000 + (0.8)R_d}{2240} \qquad \text{tons}$$

12 Total Extra Fuel Carried for Distilling Plant Operation

$$W_f = \left[\frac{(1.2)\ (24)\ (L_r + 1142)}{816} + 24\right]\frac{w_f}{2240} \quad \text{tons/voyage}$$

using advice of [14] for margin of one day's consumption plus one-fifth total sea consumption. Fuel assumed to be loaded at both ends of voyage.

$$= 0.0353\ \frac{(L_r + 1822)w_f}{2240}$$

If fuel is loaded at one end of the voyage for the entire trip, then

$$= 0.0647\ \frac{(L_r + 1513)w_f}{2240}$$

13 Weight of Water, Leaving Port, Shore Water Alternative

Use w_w in place of w_f in formulas of paragraph 12 to find W_w

14 Weight of Reserve Water, Distilling Plant Alternative

$$W_R = (24/2240)D \cdot w_w$$

15 Structural Weight of Water Tanks

$$V = (2240/62.3)W_w \quad (\text{or } W_R) \qquad \text{cu ft}$$

$$A_t = 6 \cdot V^{2/3} = 65.4 \cdot W_w^{2/3} \qquad \text{sq ft}$$

Assume tank is a cube of 3/4 in. equivalent thickness [15] steel @ 480 lb/ft^3

$$W_t = 0.876 \cdot W_w^{2/3}$$

16 Cost of Tank Structure

For labor cost, follow method of [15], using an equivalent surface to be twice actual surface, 0.4 manhours per ton, $3.50 per hour rate, 70 percent overhead, and 5 percent profit:

$$P_L = (2)\ (65 \cdot 4W_w^{2/3})\ (0.4)\ (1.70)\ (3.50)\ (1.05)$$

$$= 327W_w^{2/3} \qquad \$$$

For material cost, follow [14], using $220 per ton, so that total cost is

$$P_t = 327W_w^{2/3} + (1.05)\ (220)\ (0.876W_w^{2/3})$$

$$= 529W_w^{2/3}$$

Note that in the following calculations, only ½ of P_t is used, it being assumed that only ½ of the tank is actually extra structure.

17 Lost Revenue from Weight of Machinery, Fuel, Water, and Tankage Weights

$$C_L = \tfrac{1}{2}\left[\frac{285{,}500}{L_r + 1142}\right] (\text{freight rate})\ (W)$$

$$= \tfrac{1}{2} \cdot N \cdot R_f \cdot W \qquad \$/\text{yr}$$

where $W = W_d + W_R + \tfrac{1}{2}W_t + W_f$

for the distiller alternative.

$$= W_w + \tfrac{1}{2}W_t$$

for shore water alternative.

18 Average Annual Cost of Distiller Alternative

$$\text{AAC} = (\text{CRF}) \cdot (P_d + P_t) + C_f + C_m + C_L \qquad \$/\text{yr}$$

19 Average Annual Cost of Shore-Water Alternative

$$\text{AAC} = \text{CRF} \cdot P_t + C_L + C_w \qquad \$/\text{yr}$$

Formulas Used for the Container Ships

1 Formulas 1, 2, 7, 9, 10, 11, 14, 15, 16 from the bulk-ship listing also apply to the container ships.

2 Length of Round Trip Voyage

$$D_v = L_r/(24 \cdot V_k \cdot U) \qquad \text{days}$$

3 Number of Voyages per Year

$$N = 350/D_v$$

4 Fuel Rate Chargeable to Distilling Plant Operation

$$w_f = w_f\left[w_w + w_e\,\frac{1 - U}{0.1}\right]/w_w \qquad \text{lb/hr}$$

The meaning is that w_f determined from the at-sea heat balances is corrected by a factor to allow for port-use water being made at sea. The rate of water use in port, based on time-at-sea, is

w_e for 10 percent time in port, hence this factor is also corrected by $(1 - U)/0.1$

5 Annual Fuel Cost Chargeable to Distilling Plant

$$C_f = 24p_f \cdot w_f \cdot 350U/2240 \qquad \$/\text{yr}$$
$$= 24.3p_f \cdot w_f \cdot U \qquad \text{for } p_f \text{ in } \$/\text{bbl}$$

6 Weight of Extra Fuel per Voyage for the Distilling Plant Alternative

$$W_f = \frac{24w_f}{2240}\left[1 + (1 + 0.2/2)\,\frac{L_r}{24V_k}\right]$$
$$= 0.0107w_f\left[1 + 0.0458\,\frac{L_r}{V_k}\right] \qquad \text{tons}$$

for fuel loaded for entire voyage, but with margin as in paragraph 12 for bulk ships, based on one-way voyage length.

7 Weight of Water, Leaving Port, Shore Water Alternative

$$W_w = 0.0107\left[w_w + \frac{1 - U}{0.1}\,w_e\right]\left[1 + 0.0458\,\frac{L_r}{V_k}\right] \qquad \text{tons}$$

using same margin as for fuel.

8 Excess Weight of the Shore Water Alternative

$$W_x = W_w + W_{t1} - (W_d + W_f + W_R + W_{t2}) \qquad \text{tons}$$

where the extra subscripts, 1 and 2, on W_t refer to tanks associated with shore water and distilling plant, respectively.

9 Machinery Weight

$$W_M = 247\left[\frac{\text{SHP}}{1000}\right]^{1/2} \qquad \text{tons}$$

from [14].

10 Rating of Distilling Plant

$$R_d = (2.0)\,(2.88)\left(w_w + w_e\frac{1 - U}{0.1}\right) \quad \text{gpd for } w_w \text{ in lb/hr}$$

11 Increase in SHP Because of Extra Weight

$\text{SHP} = 250W_x/W_M$ for 16-knot ship
$\text{SHP} = 450W_x/W_M$ for 20-knot ship
$\text{SHP} = 820W_x/W_M$ for 24-knot ship

estimated from Fig. 3 of [17].

12 Increase in Hull Weight Because of Δ SHP

$$W_H = 0.46\,\Delta\,\text{SHP} \qquad \text{tons}$$

estimated from Fig. 4 of [17].

13 Cost of Δ SHP

$$P_m = \Delta\,\text{SHP}\,\frac{d(690{,}000\ \text{SHP}^{0.6})}{d(\Delta\,\text{SHP})}$$
$$= 6580\ (\Delta\,\text{SHP})\ (\text{SHP}^{-0.4}) \qquad \$$$

where the base cost of machinery, $690{,}000\ \text{SHP}^{0.6}$, is taken from [14].

14 Base Weight of Hull

The steel hull weight is estimated by equations 20–23 of [14], which give this weight in terms of the ratios C_B, L_s/L, and L/D, and cubic number. The proportions of the Mariner-class ships are used here for the ratios. CN is estimated from displacement by equation 13 of [14]. The result is the following simple formula for steel weight in terms of displacement:

$$W_H = 320\ (\Delta/1000)^{0.9} \qquad \text{tons}$$

15 Base Cost of Hull

$$P_H = 1.05\left[(1.1)\ (220)W_H + (1.70)\ (3.50)\ (1.33)\ (90{,}000)\left(\frac{W_H}{1000}\right)^{0.85}\right]$$
$$= \left[0.254\,\frac{W_H}{1000} + 0.748\,\frac{W_H}{1000}^{0.85}\right]\cdot 10^6 \qquad \$$$

The contribution of labor manhours,

$$90{,}00_0\left(\frac{W_H}{1000}\right)^{0.85},$$

is from [14]. The formula here is developed in similar fashion to formula 16 for the bulk ships. Additions here are margins for material (1.1) and indirect labor (1.33)

16 Cost of Extra Hull Weight

$$P_h = \Delta\,W_H\,\frac{d(P_H)}{d(\Delta\,W_H)}$$
$$= \left[\Delta\,W_H\,0.254 + 0.636\left(\frac{W_H}{1000}\right)^{0.15}\right]\cdot 10^6 \qquad \$$$

17 Extra Fuel Cost Because of Δ SHP

$$w_{fl} = 0.5(\Delta\,\text{SHP})$$
$$C_{fl} = 24.3p_f \cdot w_{fl} \cdot U \qquad \$/\text{yr}$$

similar to formula 5.

18 Average Annual Cost of Distiller Alternative

$$\text{AAC} = \text{CRF} \cdot (P_d + P_t) + C_f + C_m \qquad \$/\text{yr}$$

19 Average Annual Cost of Shore-Water Alternative

$$\text{AAC} = \text{CRF} \cdot (P_t + P_h + P_m) + C_w + C_{fl} \qquad \$/\text{yr}$$