UNITED STATES ATOMIC ENERGY COMMISSION

PRELIMINARY ECONOMIC REPORT ON THE APPLICATION OF ATOMIC POWER TO MERCHANDISE SHIPS. PART II. OIL TANKER SHIPS

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Part II

Oil Tanker Ships

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REVIEWED BY M. L. Ireland, Jr. PREPARED BY W. J. Burns, Jr.

NEWPORT NEWS SHIPBUILDING AND DRY DOCK COMPANY

ATOMIC POWER DIVISION

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(b) Interim Technical Report, No. NNSD9 issued to the Atomic Energy Commission by Newport News Shipbuilding and Dry Dock Company.

(c) U. S. Merchant Marine Act, 1936 and as revised.
INTRODUCTION

This section, Part II, of the "Preliminary Economic Report on the Application of Atomic Power to Nuclear Ships" deals with ships designed to carry petroleum products in bulk. These ships are commonly called oil tankers. This section is a continuation of Part I which considered mixed dry cargo ships. Part I was forwarded to the Atomic Energy Commission on July 20, 1955, reference (a).

Scope

The study of oil tanker operations considered five classes of ships which varied from a tanker having an approximate deadweight tonnage of 19,000 tons to a tanker having an approximate deadweight tonnage of 39,000 tons. The ships were studied at various speeds and machinery was rated to correspond to the size and speed of the ship. All of the ships except the smallest were designed to carry a full load of gasoline although they normally would carry crude oil from the producing area to the refinery. Power plants for all of the ships considered used a 22,500 SHP reactor plant design as a basis, reference (b).

The oil carrying trade was investigated because it was evident that tankers can take better advantage of the inherent capabilities of a nuclear plant since their port time is very small in relation to overall voyage time. However, the fact that the cargo moves in only one direction must be considered.

Several of the major oil companies owning or chartering large tanker fleets were approached as to their willingness to supply average industry cost data on the trade routes to be selected for analysis. Each of the companies expressed a willingness to cooperate in this economic study of nuclear power.

OPERATIONS

The various oil tanker routes were examined and two routes were chosen for study. The first one was the Port Arthur - New York run which has a round trip voyage distance of 3700 miles. The second route chosen was the Delaware Bay - Persian Gulf run which has a round trip voyage distance of 17,000 miles. The shorter run (3700 miles round trip distance) is short for a nuclear powered ship and there may be, in a final weight analysis, a revenue penalty for increased weight of machinery. However, again this is the fact that the ships
would always be within the protective waters of the United States. In addition, this trade route requires by law, as do the subsidized mixed dry cargo operations, the use of U. S. flag ships manned by U. S. citizens, reference (c). All the offshore trade routes are very competitive as between U. S. flag ships and foreign owned, operated, or manned ships.

The study has been restricted to crude oil tanker operations rather than refined oil and gasoline distributing tanker operations. This results in a two port operation rather than a large number of ports of call. In oil tanker operations there are usually no charges for cargo handling as the ship absorbs the cost of pumping out as an overall ship expense. The cost of loading the oil is not charged against the ship but is absorbed by the oil terminal facility. Port charges likewise are small due to having only two ports of call. The only exceptional charges are the Suez Canal charges which are appreciable on the 17,000 mile voyage distance.

**Speed**

The speed of each ship studied was varied between 14 and 20 knots. The speed for which the ship was actually designed for, is denoted as the owner's design speed \( V_o \) and the other speeds are denoted as arbitrary design speeds \( V_a \). In all cases there is at least one arbitrary design speed above and below the owner's design speed.

**Shaft Horsepower**

For the purposes of these economic studies the average operating shaft horsepower has been defined in terms of the speed obtained at loaded draft on trial. This results in an average operating shaft horsepower lower than the normal design shaft horsepower which is confirmed by voyage log records. The normal horsepower obtained by the following formulae was used in determining the cost of machinery while the average operating shaft horsepower was used in determining the fuel oil consumption.

**Shaft Horsepower Formula:**

\[
Pt = \frac{P_m}{1.25} = \frac{P_n}{1.137}
\]

\[Pt = \text{S.H.P. on Trial at Design Speed}\]
\[P_m = \text{Maximum design S.H.P.}\]
\[P_n = \text{Normal design S.H.P.}\]

\[P = 1.02 \ Pt = 0.9 \ P_n\]

\[P = \text{Average Operating S.H.P.; in Service}\]
Deadweight and Cubic Capacity

The ship deadweight figures used in this study are based on the deadweight of each ship at loaded design draft and at owners design speed. The basic deadweight figures were adjusted as ship speed was varied from the owner's design speed due to the change in machinery plant weights. The deadweight of the ship includes cargo deadweight in tons, tons of fuel oil required for the voyage or passage, tons of fresh water required for the voyage or passage, tons of stores required for the voyage or passage and of crew and crew effects. The increase or decrease in the cargo deadweight capacity is of particular interest to the oil transportation industry.

One of the advantages hoped for from a nuclear powered ship is an increased cargo deadweight when the steaming or fueling distance is greater than the breakeven distance. The breakeven distance is defined as the distance at which the weight of machinery and shielding for the nuclear plant is equal to the weight of the oil-fired plant plus the weight of the fuel oil required to travel this distance.

The machinery weights for both nuclear and oil fired plants have been estimated for the five types of ships operating at various speeds and is shown in Table I. Reference (b) was used as the basis for estimating the machinery weights. The difference between the nuclear machinery weight and the oil-fired machinery weight is the weight of oil required to reach the breakeven distance. Beyond the breakeven distance there is a deadweight advantage which accrues to the nuclear ship over the oil-fired ship equal to the difference (expressed in tons of oil required) between the breakeven distance and any greater steaming distance. This advantage is a maximum at the steaming distance of the oil-fired ship based on full fuel oil tank capacity. The break-even distance is dependent on the method of fueling the ship and Tables II and III give the break-even distances and the maximum possible gain in deadweight tons for the various ships considered.

Using Table I, the differences in propelling plant weights have been converted into break-even distances and deadweight gains as shown in Tables II and III. On the Port Arthur - New York trade route (3700 mile round trip voyage distance) the customary method of fueling the ship is to fuel only at the cargo loading port. This method of fueling is denoted as Cond. I on Tables II and III. On the Persian Gulf - Philadelphia trade route (a 17,000 mile round trip voyage distance) the method of fueling varies. For the purpose of figuring round trip voyage distance the fueling is assumed to be done at the unloading port rather than at the loading port.
This method is denoted as Cond. II on Tables II and III.

An examination of the columns under "Round Trip Voyage Distance" -Condition I (3700 Miles) shows that, except for the two smaller ships, the break-even distance is less than the voyage distance of 3700 miles. In other words there is a deadweight advantage even though it is relatively small. The deadweight gain which results is shown under the column Deadweight Gain - Cond. I. Only at the higher speeds is this gain appreciable on the shorter trade route.

The Round Trip Voyage Distance - Condition II (17,000 miles) is based on fueling at the unloading port. The break-even distance is almost twice that for the shorter run and is due to the method of fueling plus the difference in port consumption. The deadweight gain Condition II becomes very appreciable averaging about 4.0 percent of the ship's deadweight at the owner's design speed of the vessel.

The maximum deadweight gain, based on actual bunker capacity, is a still larger amount but normally the voyage round trip distance would not be long enough to take advantage of this gain unless the ship fuels at the loading port. This is shown under Deadweight Gain - Condition III, (17,000 miles); Table III, and indicates that for certain classes of ships the deadweight gain, based on fueling at the loading port for a round trip voyage distance, exceeds the maximum possible gain. This is indicated by a figure (2) and shows that the oil-fired ship does not have sufficient fuel oil capacity to fuel on the Persian Gulf and make a round trip voyage to Philadelphia and return.

The cubic capacity of the five ships considered is not a factor to be counted as an advantage as long as the ships are in the crude oil trade. This is because the ships, except for the smallest one, were designed for carrying gasoline and when carrying crude oil they will have excess cubic capacity. Even the smallest ship will have an excess of tankage when carrying crude oil on the 17,000 mile Persian Gulf - Philadelphia run.

If it is assumed that the ship is or may be in the future carrying gasoline, the cubic gain will be the cubic volume occupied by those fuel oil tanks forward of the aft pump room and including the fuel oil wing tanks outboard of the fuel oil settlers. This is given as follows for each
of the ships considered.

<table>
<thead>
<tr>
<th>Ship D.W.T.</th>
<th>Cubic Capacity Gain in Barrels</th>
<th>% of Ship Cubic Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>19,203</td>
<td>10,158</td>
<td>6.6</td>
</tr>
<tr>
<td>26,759</td>
<td>14,566</td>
<td>6.5</td>
</tr>
<tr>
<td>30,250</td>
<td>20,452</td>
<td>7.4</td>
</tr>
<tr>
<td>35,550</td>
<td>22,160</td>
<td>7.4</td>
</tr>
<tr>
<td>38,911</td>
<td>20,006</td>
<td>6.1</td>
</tr>
</tbody>
</table>

The figures do not include any of the following tanks: fuel oil settling, storage or center tanks aft of the after pump room.

The cubic gain shown above is appreciable and, as all the ships, except the smallest, were designed to carry gasoline if conditions warrant it, the reference design nuclear ship does have an advantage cubic wise when compared to the oil-fired ship.

**Time at Sea**

The time at sea factor is an indirect indication of where a nuclear powered ship might be applied to advantage. This is because a high time at sea factor means more fuel oil is burned per year at a given speed which in turn means an increase in the amount of money that can be saved, or capitalized, in a nuclear powered ship. For a tanker the figure is 75%-87% of the total hours per year. This is often compared to the low 50-65% figures obtained for the normal mixed dry cargo ship. However, on a revenue basis the mixed dry cargo ship is better as a tanker earns revenue only for one half of the time at sea, while the mixed dry cargo vessel is earning money the total time at sea. This is one of the reasons for the higher competitive nature of the oil tanker business.

The port time for the tankers does not vary as the ship speed is increased nor does the port time materially vary as the size of the ship is increased. The longer port time for the 17,000 mile voyage distance is the result of counting the Suez Canal passage time as port time rather than sea time. The Suez Canal passage time for Ships A and B is assumed to be 2.5 days while for Ships C, D, and E it is assumed to be 2.75 days.
The time at sea factor used in this study was based in general, on the ship being available for service 350 days per year. However, certain companies use an availability time of 345 days for the larger ships. This has resulted in an average figure of 350 days for Ships A and B and an average figure of 347.5 days for Ships C, D and E. Table IV indicates average time at sea factors for the various ships.

**Costs - General**

1. The major savings of a nuclear powered ship will be the cost of the oil burned in a conventional ship. For this reason the most attractive oil tanker for a nuclear application is the largest sized oil tanker operating at 17.5 knots - average operating shaft horsepower 17,750. The yearly fuel oil cost of running the ship is approximately 453,000 dollars on the 17,000 mile route and 374,300 dollars on the 3,700 mile route.

   On the 17,000 mile voyage, the fuel oil savings give a possible increase in first cost of approximately $6.41 \times 10^6$ dollars assuming a zero nuclear fuel cost.

2. Conventional boilers, stacks, fuel oil burning and storage facilities are not required in the nuclear ship and these savings should be deducted from the cost of the nuclear plant. This has been estimated to be about one sixth of the total oil-fired machinery cost including cargo pumping machinery but excluding hull machinery costs.

3. Wage costs for an oil tanker are normally higher than for a mixed dry cargo ship and reflect the larger fringe benefits paid by the oil companies in order to keep crews. The wage and subsistence cost for a Mariner class ship is about 472,000 dollars per year while for an oil tanker of comparable shaft horsepower the wage and subsistence cost is 480,000 dollars. For the nuclear ship the wage cost is assumed to be $25,000 per year higher than with conventional plants. This is $5,000 higher than for the mixed dry cargo ships.

   A nuclear plant requires no fireman - water tenders but would require three licensed reactor - engineer operators and one additional first assistant reactor engineer. The four men would require additional training and it is assumed that the three would be the equivalent of senior third assistant engineers while the fourth would be the equivalent of a first assistant engineer. The reactor operators, while having special training, would not be required to know reactor theory. The reactor engineer would be required to have some nuclear
engineering and reactor theory and be responsible for the maintenance and repair of the equipment within the shield.

4. Subsistence would be the same as with an oil-fired plant.

5. Under stores, supplies, equipment and maintenance, the only costs that might change are those for the Engine Department, and within this department, only steam generation maintenance. Thus the maintenance of the reactor and its equipment are to be evaluated in comparison with conventional boiler maintenance. The cost of equipment and parts replacement may be higher for a nuclear plant. However, this should be compared with the large labor cost for frequent cleaning of conventional boilers. The problem of cleaning conventional boilers is very important timewise in the oil tanker trade because of the extremely short time in port. The time from securing the boiler for cleaning to again having full steam pressure is estimated to be 24 hours. This is equal to the port time which includes the dock to sea buoy and sea buoy to dock time. If there is an abnormal amount of brick work repair, etc. to be done either the port time must be extended or the ship must leave on one boiler. The nuclear oil tanker presumably would not require cleaning time in port and preventive maintenance, an essential feature in operating a nuclear plant, is expected to keep port maintenance time within the loading and unloading time.

GENERAL RESULTS FOR OIL TANKERS

The first approach to the study of the economics of oil tanker operations was the selection of vessels covering a range of sizes. The ships selected were oil fired vessels either actually built, or proposed, by this company. These ships are denoted as follows:

- Ship A - 19,000 deadweight tons
- Ship B - 27,000 deadweight tons
- Ship C - 30,000 deadweight tons
- Ship D - 36,000 deadweight tons
- Ship E - 39,000 deadweight tons

The owner's design speed of the ships varied from sixteen to eighteen knots and each of the ships was studied using at least three other arbitrary design speeds to determine the effect of speed on operating costs and to determine minimum points. All data given for comparison purposes are on the basis of the owner's design speed of the vessel.

The information obtained from the various oil companies was usually limited to either one or two classes of
ships as none of them operated a fleet of ships which included all five classes of ships. After discussion with those who furnished the original data, the information was adjusted as required to cover the range of ships operating at the various speeds. A separate data sheet was worked up for each of the companies and the results averaged to obtain a composite picture of operating costs which we believe fairly represents the oil transportation business. This averaged data will be called the actual data or costs throughout the report as against theoretical data or costs obtained from algebraic formulae as in the Appendices.

The actual data was worked up in two ways: for use in comparing ships operating on the Port Arthur - Bayonne oil trade route; and for use in comparing ships operating in the Persian Gulf - Philadelphia oil trade route. The theoretical data used for the general equations developed in Appendices "A-l", "B-l" and "C-l" are based on the costs of the 3,700 mile Port Arthur - Bayonne run but neglecting ocean currents which actually do affect the speed of a vessel in this trade.

General Equations

Curve Sheet "A" shows a set of theoretical curves based on Ship Expense - Cost per Mile versus Round Trip Voyage Distance for each of the five ships considered. For the purposes of this study, ship expense includes the following cost accounts: wages and subsistence; insurance; stores, supplies and maintenance; total repairs; and total fuel costs. The fixed charge expense includes overhead and depreciation accounts. Voyage expense includes the port charge and canal charge accounts. The total operating cost is the sum of the ship expense, the fixed charge expense and the voyage expense. The various expenses are shown in Table V.

In addition, there has been added the actual Ship Expense Cost per Mile for the 3,700 mile voyage distance and the 17,000 mile voyage distance plus the adjusted actual Ship Expense Cost per Mile for the 17,000 mile voyage distance.

At the 17,000 mile distance three points have been plotted. The first one is a point on the theoretical curve. The second one, denoted as , is the actual data for the 17,000 mile voyage distance adjusted to eliminate the difference in fuel oil cost between the two routes and to eliminate the effect of the Suez Canal. The third point, denoted as , is the actual data for the 17,000 mile voyage distance. The actual Ship Expense Cost per Mile for a 3,700 mile distance and the adjusted actual Ship Expense Cost per Mile for a 17,000 mile voyage have been connected by a dotted line following the slope of the theoretical curve. The
actual data is connected to the adjusted actual data by a jagged line.

At the 3,700 mile distance the actual is somewhat below the theoretical due to current effect on the loaded run to Bayonne, N. J. This is approximately 0.88 of a knot gain and increases the number of voyages and the miles traveled per year which in turn decreases the cost per mile.

Considering the 17,000 mile voyage distance the theoretical ship expense cost per mile is well below the actual ship expense cost per mile. There are two reasons for the apparent discrepancy: 1. First there is a difference in the cost of fuel oil. The actual figures assumed that the ship would be fueled at the unloading port, which is Philadelphia, where the cost of fuel oil is 2.22 dollars per barrel as against 1.95 dollars per barrel if the ship is fueled at the cargo loading port, assumed to be Port Arthur; 2. The primary discrepancy, however, is due to the fact that the theoretical curve does not include any Suez Canal passage time which is normally charged against port time. This has the effect of increasing the number of voyages per year. Approximately two thirds of the discrepancy is due to the Suez Canal passage effect and one third to the difference in the cost of oil.

The ship expense cost per mile is higher as the ship size increases, which is to be expected.

Curve Sheet B shows a set of theoretical curves based on Ship Expense Cost per Deadweight Ton versus Round Trip Voyage distance for each of the five ships considered. In addition, there has been added the actual Ship Expense Cost per Cargo Deadweight Ton for the 3,700 mile voyage distance and the 17,000 mile voyage distance which have been connected by a dotted line following the shape of the theoretical curve. At the 3,700 mile distance the actual is less than the theoretical due to the current effect which was eliminated for the theoretical curves.

On the 17,000 mile voyage distance the actual is lower than the theoretical in two ships (A and B), while it is higher on the remaining three ships (C, D and E). As on Curve Sheet A this is due to the fuel oil cost difference, the lack of Suez Canal time on the theoretical curve, plus the method of bunkering which increases the cargo deadweight tons for the actual as compared to the theoretical.

On the smaller vessels the increase in cargo
deadweight capacity for the actual data is not enough to overcome the difference in the cost of fuel oil and the increased port time due to the Suez Canal. For the larger vessels the increase in cargo deadweight capacity is enough to overcome the fuel oil cost difference and the increased port time due to the Suez Canal.

Curve Sheets C and D show Total Operating Expense per Mile and per Cargo Deadweight Ton. Total operating expense includes Fixed Expenses (depreciation and overhead) and Voyage Expense (port dues and canal dues, etc.). The depreciation was based on total cost to owner of a new ship. The new ship cost was based on normal pricing of U.S. built oil tankers for 1954-1955.

The theoretical curves assumed that fuel oil was loaded at the cargo loading port; the price of fuel oil was 1.95 dollars per barrel; there was not current effect; there was no canal passage so that the days in port were constant as compared to the actual Suez Canal passage time which was charged to port time; there were no canal charges which are substantial. In comparison the actual has a higher fuel oil cost per barrel, a higher port time and the Suez Canal charges are added into the various costs. The data for the theoretical curves is incorporated in Appendix "C-1" and the data for the actual curves appears in Table V for both the 3,700 and 17,000 mile voyages.

On Curve Sheet C - Total Operating Cost per Mile plotted against Round Trip Voyage Distance, the theoretical and the actual differ at the 3,700 mile distance due to the current effect. At the 17,000 mile distance there appears to be a wide discrepancy between the points. As explained previously, part of the discrepancy is due to the difference in fuel oil costs, the decreased time at sea due to Suez Canal passage and to the addition of Suez Canal charges to the actual costs.

The actual data for the 17,000 mile distance was adjusted to eliminate the difference in fuel oil cost, the increased port time due to the Suez Canal passage and the Suez Canal costs. The adjusted actual data agrees very well with the theoretical and a line has been drawn between the actual at 3,700 mile voyage distance and the adjusted actual data for the 17,000 mile distance. A jagged line connects the actual and the adjusted at the 17,000 mile voyage distance. The difference between the theoretical and actual at the 17,000 mile voyage distance is divided approximately as follows: 15% for the fuel oil cost, 20% for the increased port time, and 65% for the Suez Canal charges.
Curve Sheet D - Total Operating Cost per Cargo Deadweight Ton plotted against Round Trip Voyage Distance is very similar to Curve Sheet B to which is added the Fixed Expense and the Voyage Expense. In all cases the actual cost per ton at 17,000 miles is higher than the theoretical, although the difference is smaller for the smaller ships than for the larger ships.

The increase in actual cargo deadweight over the theoretical cargo deadweight, due to the method of bunkering, is not enough to compensate for the higher fuel oil charges (2.22 dollars per barrel as against 1.95 dollars per barrel), the increased port time due to the Suez Canal passage and the Suez Canal passage charges.

The actual cost per cargo deadweight and per mile at 17,000 miles shows an increasing discrepancy from the theoretical as the ship size increases from Ship A to Ship E. While part of the increase is due to the higher fuel cost, the major part is due to the very appreciable Suez Canal charges.

The major value of the Curve Sheets A through D is to give an indication of a range of costs to be expected for various voyage distances. The actual curves or actual costs will check with the theoretical if such things as current effects, fuel oil costs, and bunkering ports and canal charges can be properly factored into the formulas given in Appendices "A-1", "B-1" and "C-1". By use of the formulae a better idea can be obtained of the various operating possibilities and their effect on the main object of all economic studies - the attempt to lower the net cost of transportation.

Actual Data

This section is concerned with the interpretation of the actual data (actual obtained from the various oil companies) for the five ships considered. Each of the five ships was figured at various speeds to obtain curves of operating cost per ton, fuel oil cost per ton, cargo capacity, and permissible investment. The assumption was made that it was physically possible to run all of the ships at full load draft on both the 3,700 mile and the 17,000 mile round trip voyage distance. The resulting data was plotted against vessel speed. The results are shown on Curve Sheets E thru N. The data was also plotted against voyage distance at the owner's design speed and appears on Curve Sheets A thru D. Curve Sheet E gives the yearly cargo capacity of each of the ships operating at various speeds up to the practical limit of each. The curves are essentially straight lines up to...
the owner's design speed and then fall off due to the increased fuel needed at the higher speeds. At high speed Ship A cannot haul as much oil as the next larger ship at the slowest speed. The value of this set of curves is its use in the following curve sheets to obtain per ton figures. The various speeds indicated are the design speeds of the vessel (both owner's and arbitrary). Thus Ship A is assumed to be designed for 14, 16, 18, 19 and 20 knots for calculation purposes. The average speed of the vessel is higher due to the fact that the oil companies in general operate their vessels at the owner's design speed on the loaded passage of the voyage and on the ballast passage operate the ship at the same shaft horsepower as on the loaded passage which naturally gives an increased speed. In addition, on the 3,700 mile voyage distance there is an average current effect of plus 0.88 knots due to the Gulf Stream on the loaded passage.

Curve Sheet F - Total Operating Cost per Cargo Deadweight Ton plotted against vessel speed shows a wide discrepancy between the smallest and largest ship with Ship A costing 43% more per ton than Ship E on the 3,700 mile run at the owner's design speed and 41% more on the 17,000 mile run at the owner's design speed. On all ships on the 3,700 mile voyage, the low point of the curve occurs at the owner's design speed. On the longer run the low point occurs at a speed somewhat lower than the owner's design speed. This is due in part to the actual method of operation (constant/shaft horsepower) and to the higher time at sea per year on the longer voyage. Thus on longer voyages it is better to operate at a somewhat slower speed. Curve F is based on the machinery being sized to give the speed desired, and thus the resulting curve is somewhat different from that usually presented: which is for a given ship and machinery plant operating above and below the design speed. (The more normal way is shown as a dotted line for Ships A and E at both the 3,700 and the 17,000 mile voyage distances on Curve Sheet F). To put it another way, the curves presented are the points obtained from a series of curves (not necessarily the minimum points) of a series of ships using the same hull form but the machinery sized to obtain certain speeds. This results in a flatter curve at speeds below the owner's design speed and somewhat steeper above the owner's design speed.

Curve Sheet G gives the Total Operating Cost per Year plotted against speed. The difference between the 3,700 mile curves and the 17,000 mile curves is due to the following factors: a longer time at sea, which increases the annual fuel oil costs; the Suez Canal charges; the increased insurance costs. The 3,700 mile run has the advantage of a current effect although the wages and subsistence costs are higher on
the shorter run as are the repair costs and supplies and equipment costs. The differences on the various operating costs are shown in Table V.

Curve Sheet H - Fuel Oil Cost per Cargo Deadweight Ton plotted against speed. This set of curves gives practically a straight line up to the owner's design speed and in proportion to the deadweight of the ship. Above the owner's design speed the fuel oil cost increases markedly due to the required shaft horsepower necessary to operate at the higher speed. This has a marked effect on the total operating cost per ton (Curve Sheet F) and accounts in part for the steepness of this curve beyond the design point.

Curve Sheet J - Fuel Oil Cost per Year plotted against speed. These curves are the ones which are of vital interest nuclear-wise because it is the cost of the fuel oil per year which must pay for nuclear plant and fuel. Approximately 90-95% of the cost of the nuclear plant and fuel must come from the savings of or the elimination of the fuel oil cost. The fuel oil cost of the ships is, except for the smallest ship, about in proportion to the deadweight of the ship. On Ship A the fuel oil cost per year is higher than for the next larger sized ship, the comparison being at the owner's design speed of each. There is two knots difference in the owner's design speed of the vessels. This gives a considerably higher cost per ton for Ship A even considering the faster speed of the ship as shown on Curve Sheet H.

From the values of the fuel costs per year as plotted against speed (Curve Sheet J) it is possible to calculate the ratio of permissible nuclear machinery cost to estimated oil-fired machinery costs using various nuclear fuel costs. The assumption is made that the gross profit of the oil-fired ship will be equal to the gross profit of the nuclear powered ship or in other words the total yearly operating cost of the oil-fired ship plus the revenue gain due to the increased cargo capacity of the nuclear ship is equal to the total yearly operating cost of the nuclear ship. This is expressed by the following formulae:

\[ R_0 - C_0 = R_N - C_N \]
\[ R_N = R_0 + R_n \]
\[ C_N = C_0 + R_n \]
\[ R_0 = \text{Gross Revenue of oil-fired ship} \]
\[ R_N = \text{Gross Revenue of nuclear powered ship} \]
\[ R_n = \text{Gross Revenue due to increased cargo capacity of nuclear powered ship.} \]
\[ C_o = \text{Total yearly operating cost of oil-fired ship.} \]

\[ C_N = \text{Total yearly operating cost of a nuclear powered ship.} \]

The ratio of machinery cost (nuclear to oil-fired) has two limits. The first is when the nuclear fuel cost is zero so that the entire fuel oil savings plus the additional cargo revenues are applied to possible increases in nuclear machinery costs plus possible increases in wages, stores and repairs. The machinery cost ratio is maximized under this condition. When the nuclear fuel cost is zero the possible increase in nuclear machinery cost over the oil-fired machinery cost can be expressed as follows:

\[ M_N = \frac{C_F + R_n - .1C_S - .1C_M - 25,000}{C_C} \]

\[ M_N = \text{Possible increase in machinery cost over the oil-fired machinery cost.} \]

\[ C_F = \text{Yearly fuel oil cost of an oil-fired ship} \]

\[ R_n = \text{Yearly revenue gain due to the increase in the cargo capacity of the nuclear powered ship.} \]

\[ C_S = \text{Yearly cost of stores supplies and equipment for the oil-fired ship. This cost for the nuclear ship is assumed to be 10 percent higher.} \]

\[ C_M = \text{Yearly cost of repairs for the oil-fired ship. This cost for the nuclear ship is assumed to be 10 percent higher.} \]

\[ $25,000 = \text{Yearly wage increase for the nuclear ship.} \]

\[ C_C = \text{Rate of capitalization.} \]

The ratio of machinery cost thus becomes:

\[ \text{Ratio} = \frac{M_o + M_n}{M_o} = \frac{M_N}{M_o} \]

\[ M_o = \text{Owners cost of oil-fired machinery plant.} \]

\[ M_n = \text{Possible increase in machinery cost over the oil-fired machinery cost.} \]

\[ M_N = \text{Possible owner's cost of nuclear machinery.} \]
The second limit for the ratio of machinery cost will be when the ratio is one, i.e. the cost of the nuclear machinery plant is equal to the cost of the oil-fired machinery plant. In this case the possible cost of the nuclear fuel is maximized. The possible nuclear fuel cost is given by the following formula:

\[ C_N = C_F + R_N - .1C_S - .1C_M - 25,000 \]

\[ C_N = \text{Yearly nuclear fuel cost} \]

Both limits have been determined for the five classes of ships at the owner's design speed and for the 17,000 mile voyage distance. The limits have been plotted against possible nuclear fuel costs and are shown on Curve Sheet K. In addition, on Curve Sheet L, are shown the machinery cost ratios versus the possible nuclear fuel cost for Ship E at 17, 17.5, 16 and 14 knots. Other than the two ratio limits, the most important point on the various lines is the point where the possible cost of nuclear fuel is equal to one half the cost of the oil fuel. This point is indicated both on Curve Sheets K and L.

An examination of Curve Sheet K shows that the machinery cost ratio reflects the speed and size of the ship. Ship A has higher machinery cost ratio than Ship B due to its considerably higher speed and shaft horsepower which in turn gives a higher yearly fuel oil cost. Ship E being the largest ship and the second fastest ship has the largest yearly fuel oil cost and thus, the highest possible machinery cost ratio. For this reason Ship E was chosen for examination at speeds other than the owner's design speed which are shown on Curve Sheet L.

Ship E has the largest fuel oil costs and also the largest gain in cargo capacity. This results in the largest maximum machinery cost ratio (when the nuclear fuel cost is zero) and also the highest ratio when the nuclear fuel cost is assumed equal to one half the oil fuel cost. The machinery cost ratios at 17.5 and at 18 knots (the nuclear fuel cost being one half the fuel oil costs) are fairly substantial.

Curve Sheet M is a cross-plot of Curve Sheet L, the machinery cost ratio being plotted against speed rather than possible nuclear fuel costs. Three curves are shown: the upper limit curve of maximum machinery cost ratios (nuclear fuel cost equals zero); the lower limit curve of minimum machinery cost ratios (ratio equals one); and the more realistic curve of machinery cost ratios (nuclear fuel cost equals one half of the fuel oil cost. The curve resulting from \( C_N = \frac{C_F}{2} \) indicates that as speed is increased the possibilities of nuclear power increase proportionately faster than the speed increases.

In order to compare the machinery cost ratios of the five classes of ships, the machinery cost ratios, with the
nuclear fuel cost equal to one half the fuel oil cost, were plotted not against speed but against normal shaft horsepower. The results are shown on Curve Sheet N and give almost a straight line plot. Due to the fact that the assumed increases in cost of supplies, cost of repairs and wage costs are fairly constant they have a greater effect at the lower shaft horsepowers than at the higher shaft horsepowers. This has a tendency to make the curve shown on Curve Sheet N drop off somewhat as the shaft horsepower increases. If all the cost increases of a nuclear powered ship over the oil-fired ship were a function of shaft horsepower a straight line would result as a plot of machinery cost ratios versus normal shaft horsepower.

Curve Sheet N also indicates that each ship will have a set of machinery cost ratios versus nuclear fuel cost curves, very similar to that shown for Ship E on Curve Sheets L and M.
CONCLUSIONS

1. Oil tankers have an inherent advantage over the mixed dry cargo vessels in providing investment possibilities for a nuclear plant due to the larger yearly fuel oil cost.

2. There is economy in size and speed if the ship is designed for such conditions.

3. Terminal facilities often dictates vessel size.

4. Properly used, the theoretical curves give very good results in predicting costs per ton.

5. The possible additional investment is considerable, being 7.25 million dollars or 70% of the total cost to the owner for the largest oil-fired ship.

6. The possible permissible investment for coastwise ships is also considerable being approximately 4.5 million dollars of the latest super-tankers.

7. All trends point to larger tankers and as the tanker size increases the possibilities for nuclear power increase.

8. The use of nuclear power for any particular ship does not change the most economical speed as determined for an oil-fired ship.
APPENDIX "A-1"

Theoretical Curve for Ship Expense per mile - Oil Tankers.

I Ship Expense per year
\[
C_c = C_w + C_s + C_m + C_r + C_f
\]
\[
C_w = \text{Wages and subsistence cost per year which are considered to be the same in port and at sea.}
\]
\[
C_s = \text{Stores, Supplies and Equipment cost per year.}
\]
\[
C_m = \text{Maintenance and Repair Cost per year.}
\]
\[
C_r = \text{Insurance cost per year.}
\]
\[
C_f = \text{Fuel Oil cost per year.}
\]

(a) Values for each of the costs are given in the Appendix A-1 Data Sheet.

(b) The port time has been held constant for each ship for all theoretical curves.

(c) The number of miles travelled per year is
\[
MN = \frac{350}{D_p + \frac{1}{24V}}
\]
\[
D_p = \text{Days in port per voyage}
\]
\[
V = \text{Average Speed of the Vessel - S.H.P. Constant}
\]
\[
M = \text{Miles travelled per round trip}
\]
\[
N = \text{Number of voyages per year}
\]
350 = The number of days per year that ship is available for cargo.
350 - used for ships A and B
347.5 - used for ships C, D and E

II Ship Expense per Mile:
\[
\frac{C_c}{MN} = \left(\frac{C_w + C_s + C_m + C_r}{350}\right) \left(\frac{D_p}{M} + \frac{1}{24V}\right) + \frac{C_f}{MN}
\]
\[
C_f = \left(\frac{C_w + C_s + C_m}{N}\right) \left(\frac{D_p}{M} + \frac{1}{24V}\right) + \frac{D_u}{C_u}
\]
\[
C_p = \text{Cost of Fuel Oil per day in port}
\]
\[
C_s = \text{Cost of Fuel Oil per day at sea}
\]
\[
D_u = \text{Days that ship is unavailable for cargo}
\]
\[
C_u = \text{Cost of Fuel Oil per day that ship is unavailable}
\]
\[
\frac{C_c}{MN} = \frac{(C_u + C_s + C_m + C_r + Du + Cu)D_p + C_u + C_s + C_m + C_r + Du + Cu}{350 \times 24V} + \frac{C_sD_p + C_sD_q}{M}
\]

\[
\frac{C_c}{MN} = \frac{(C_u + C_s + C_m + C_r + Du + Cu + 350C_p)}{350M}D_p + \frac{C_u + C_s + C_m + C_r + Du + Cu}{350 \times 24V} + \frac{C_s}{24V}
\]

2. \[
A = \frac{C_c}{MN} = \frac{(C_u + C_s + C_m + C_r + Du + Cu + 350C_p)}{350M}D_p + \frac{C_u + C_s + C_m + C_r + Du + Cu + 350C_s}{350 \times 24V}
\]

Denoting all constant terms for any one ship by K values the equation becomes

2A. \[
A = \frac{C_c}{MN} = \frac{K_1}{M} + K_2
\]

Therefore the cost per mile should be a hyperbolic curve approaching a limit equal to K2 as M approaches infinity.
Appendix "A-1"

The table below shows the values used in determining the theoretical curve shown as ship expense per mile plotted against voyage distance in miles.

<table>
<thead>
<tr>
<th>SHIP</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>$/yr.</td>
<td>374.3</td>
<td>393.6</td>
<td>441.5</td>
<td>454.0</td>
<td>466.5</td>
</tr>
<tr>
<td>$/yr.</td>
<td>33.0</td>
<td>34.2</td>
<td>34.9</td>
<td>35.6</td>
<td>36.1</td>
</tr>
<tr>
<td>$/yr.</td>
<td>95.4</td>
<td>114.1</td>
<td>123.1</td>
<td>134.9</td>
<td>141.9</td>
</tr>
<tr>
<td>$/yr.</td>
<td>97.0</td>
<td>99.4</td>
<td>113.0</td>
<td>124.8</td>
<td>129.7</td>
</tr>
</tbody>
</table>

| Cw/1000 | $/day | 334.0 | 334.0 | 509.0 | 509.0 | 509.0 |
|Cs/1000 | $/day | 819.0 | 755.0 | 922.0 | 975.0 | 1220.0 |
| Dp      | days   | 2.0   | 2.0   | 2.25  | 2.25  | 2.25  |
| Dw      | days   | 15.0  | 15.0  | 17.5  | 17.5  | 17.5  |
| F.O. Cons/V. Day | $/day | 133.0 | 133.0 | 133.0 | 133.0 | 133.0 |
| V       | Knots  | 18.80 | 16.5  | 16.93 | 16.83 | 17.78 |

<table>
<thead>
<tr>
<th>$/Mile</th>
<th>4160.0</th>
<th>4344.0</th>
<th>5741.0</th>
<th>5977.1</th>
<th>6137.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.72</td>
<td>6.55</td>
<td>7.29</td>
<td>7.73</td>
<td>8.07</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ans</th>
<th>3700 Miles</th>
<th>$/Mile</th>
<th>6.83</th>
<th>7.72</th>
<th>8.84</th>
<th>9.35</th>
<th>9.73</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5000 Miles</td>
<td>$/Mile</td>
<td>6.54</td>
<td>7.42</td>
<td>8.44</td>
<td>8.93</td>
<td>9.30</td>
<td></td>
</tr>
<tr>
<td>-10000 Miles</td>
<td>$/Mile</td>
<td>6.13</td>
<td>6.98</td>
<td>7.86</td>
<td>8.33</td>
<td>8.68</td>
<td></td>
</tr>
<tr>
<td>-15000 Miles</td>
<td>$/Mile</td>
<td>5.99</td>
<td>6.84</td>
<td>7.67</td>
<td>8.13</td>
<td>8.48</td>
<td></td>
</tr>
<tr>
<td>-17000 Miles</td>
<td>$/Mile</td>
<td>5.96</td>
<td>6.81</td>
<td>7.63</td>
<td>8.08</td>
<td>8.43</td>
<td></td>
</tr>
<tr>
<td>-20000 Miles</td>
<td>$/Mile</td>
<td>5.93</td>
<td>6.77</td>
<td>7.58</td>
<td>8.03</td>
<td>8.38</td>
<td></td>
</tr>
<tr>
<td>-25000 Miles</td>
<td>$/Mile</td>
<td>5.88</td>
<td>6.72</td>
<td>7.52</td>
<td>7.97</td>
<td>8.32</td>
<td></td>
</tr>
</tbody>
</table>

APPENDIX "B-1"

Theoretical Curve for Ship Expense per ton - Oil Tankers.

I Ship Expense per year

1. \[ C_c = C_w + C_s + C_m + C_i + C_f \]

II Deadweight available for cargo per voyage

3. \[ \Delta_c = \Delta_w - (D_s \Delta_s + D_p \Delta_p)^{1.2} - D_r (S_\Delta + W_\Delta) - M_\Delta \]

Equation No. 3 is the general equation for oil tanker operations. It is developed into two equations, Nos. 4 and 4a, which differ due to the difference in the assumed method of fueling. Equation No. 4 assumes the ship is fueled and watered at the cargo loading port while equation 4a assumes that the ship takes on fuel and water at the unloading port.

Equation 4.

\[ B = \Delta_c = \Delta_w - (D_s \Delta_s + D_p \Delta_p)^{1.2} - D_r (S_\Delta + W_\Delta) - M_\Delta \]

Equation 4a.

\[ B = \Delta_c = \Delta_w - 0.5 (D_s \Delta_s + D_p \Delta_p)^{1.2} - 0.5 D_r (S_\Delta + W_\Delta) - M_\Delta \]

\[ \Delta_c = \text{Carage carried per voyage - tons} \]

\[ \Delta_w = \text{Ships deadweight - tons} \]

\[ D_s = \text{Days at Sea per voyage} \]

\[ D_p = \text{Days in Port per voyage} \]

\[ D_r = D_s + D_p = \text{Total days per voyage} \]

\[ \Delta_s = \text{Fuel Oil consumption per day at sea - tons/D} \]

\[ \Delta_p = \text{Fuel Oil consumption per day in port - tons/D} \]

\[ S_\Delta = \text{Consumable Stores used per day - tons/D} \]

\[ W_\Delta = \text{Fresh Water Consumed per day - tons/D} \]

\[ M_\Delta = \text{Crew and effects - tcns} \]

All values are constant except \( D_s \)

Equations No. 4 and 4a are valid for any voyage distance in which the fuel oil consumed and the fresh water consumed does not exceed the fuel oil and fresh water tank capacity. Beyond this refueling and the filling of water tanks must be factored in.

III Ship Expense per Deadweight Ton (using Equation 4)
Only variables are \( C_r, N, \ell, D \); \( D = \frac{M}{24V} \)

\[
C_F = C_p + C_s + C_u = N(C_p D_p + C_s D_s) + D_u C_u
\]

\[
= N(C_p D_p + C_s \frac{M}{24V}) + D_u C_u
\]

\[
\begin{align*}
C_p &= \text{Cost of Fuel Oil consumed in port per day} \\
C_s &= \text{Cost of Fuel Oil consumed at sea per day} \\
D_p &= \text{Days in port per voyage} \\
D_s &= \text{Days at sea per voyage} \\
N &= \text{Number of voyages per year} \\
M &= \text{Miles per voyage} \\
D_u &= \text{Days that ship is unavailable for cargo} \\
C_u &= \text{Cost of Fuel Oil per day that ship is unavailable}
\end{align*}
\]

\[
\frac{C_c}{N \Delta c} = \frac{C_w + C_s + C_M + C_x + D_u C_u + N(C_p D_p + C_s \frac{M}{24V})}{\Delta c}
\]

\[
N = \frac{350}{D_s + D_p} = \frac{350}{\frac{M}{24V} + D_p}
\]

\[
\begin{align*}
C &= \frac{C_c}{N \Delta c} = \frac{(D_p + \frac{M}{24V})(\frac{C_w + C_s + C_M + C_x + D_u C_u}{350}) + C_p D_p + C_s \frac{M}{24V}}{\Delta c - \frac{M}{24V} (D_s + D_p)} \Delta c - (D_p + \frac{M}{24V})(S_a + W_a) - M_a
\end{align*}
\]

Denoting all constant terms for any one ship by \( K \) values the equation becomes

\[
\begin{align*}
C &= \frac{C_c}{N \Delta c} = \frac{(C_w + C_s + C_M + C_x + D_u C_u + 350 C_p) D_p + (C_w + C_s + C_M + C_x + D_u C_u + 350 C_s) M}{350} \frac{350}{\Delta c}
\end{align*}
\]

\[
C = \frac{C_c}{N \Delta c} = \frac{K_1 + K_2 + M}{\Delta c}
\]

-26-
Appendix "B-1"

The Table below shows the values used in determining the theoretical curve shown as Ship Expense over cargo deadweight ton plotted against voyage distance in miles.

<table>
<thead>
<tr>
<th>SHIP</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta s) - F.O. Consumption/Sea day tons</td>
<td>63.4</td>
<td>58.4</td>
<td>71.4</td>
<td>75.4</td>
<td>94.5</td>
</tr>
<tr>
<td>(\Delta p) - F.O. Consumption/Port day tons</td>
<td>26.1</td>
<td>26.1</td>
<td>39.4</td>
<td>39.4</td>
<td>39.4</td>
</tr>
<tr>
<td>Days in Port</td>
<td>2.0</td>
<td>2.0</td>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>Days at Sea - 3700 Miles</td>
<td>8.2</td>
<td>9.34</td>
<td>9.11</td>
<td>9.16</td>
<td>8.67</td>
</tr>
<tr>
<td>5000 Miles</td>
<td>11.08</td>
<td>12.63</td>
<td>12.31</td>
<td>12.38</td>
<td>11.72</td>
</tr>
<tr>
<td>10000 Miles</td>
<td>22.16</td>
<td>25.25</td>
<td>24.61</td>
<td>24.76</td>
<td>23.43</td>
</tr>
<tr>
<td>15000 Miles</td>
<td>33.24</td>
<td>37.88</td>
<td>36.92</td>
<td>37.14</td>
<td>35.15</td>
</tr>
<tr>
<td>17000 Miles</td>
<td>37.68</td>
<td>42.93</td>
<td>41.84</td>
<td>42.09</td>
<td>39.84</td>
</tr>
<tr>
<td>20000 Miles</td>
<td>44.33</td>
<td>50.51</td>
<td>49.22</td>
<td>49.51</td>
<td>46.86</td>
</tr>
<tr>
<td>25000 Miles</td>
<td>55.41</td>
<td>63.13</td>
<td>61.53</td>
<td>61.89</td>
<td>58.59</td>
</tr>
</tbody>
</table>

| S | Stores Consumption/day - tons | 2.0 | 2.5 |
| W | Water Consumption/day - tons | 10 up to 147 | 12 up to 165 |
| M | Crew and Effects - tons | 35 | 40 |

| \(\Delta c\) - 1000 Cargo Deadweight Available |
|---|---|---|---|---|---|
| 3700 Miles | 18.31 | 25.84 | 29.16 | 34.41 | 37.61 |
| 5000 Miles | 18.09 | 25.60 | 28.85 | 34.08 | 37.24 |
| 10000 Miles | 17.21 | 24.69 | 27.76 | 32.93 | 35.88 |
| 15000 Miles | 16.35 | 23.78 | 26.68 | 31.78 | 34.52 |
| 17000 Miles | 16.00 | 23.42 | 26.24 | 31.32 | 33.98 |
| 20000 Miles | 15.48 | 22.87 | 25.59 | 30.63 | 33.16 |
| 25000 Miles | 14.62 | 22.27 | 24.50 | 29.48 | 31.80 |

Equation

\[
C = \frac{K_1 + K_2 M}{\Delta c}
\]

K1 same as in App. "A-1" 4160.0 4344.0 5741.0 5977.1 6137.2
K2 same as in App. "B-1" 5.72 6.55 7.29 7.73 8.07
Appendix "B-1" (continued)

<table>
<thead>
<tr>
<th>SHIP</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ans.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3700 miles</td>
<td>1.38</td>
<td>1.10</td>
<td>1.12</td>
<td>1.00</td>
<td>.96</td>
</tr>
<tr>
<td>5000 miles</td>
<td>1.81</td>
<td>1.45</td>
<td>1.46</td>
<td>1.31</td>
<td>1.25</td>
</tr>
<tr>
<td>10000 miles</td>
<td>3.62</td>
<td>2.82</td>
<td>2.84</td>
<td>2.53</td>
<td>2.42</td>
</tr>
<tr>
<td>15000 miles</td>
<td>5.49</td>
<td>4.32</td>
<td>4.31</td>
<td>3.84</td>
<td>3.69</td>
</tr>
<tr>
<td>17000 miles</td>
<td>6.20</td>
<td>4.93</td>
<td>4.94</td>
<td>4.38</td>
<td>4.22</td>
</tr>
<tr>
<td>20000 miles</td>
<td>7.67</td>
<td>5.91</td>
<td>5.93</td>
<td>5.23</td>
<td>5.04</td>
</tr>
<tr>
<td>25000 miles</td>
<td>10.06</td>
<td>7.55</td>
<td>7.66</td>
<td>6.74</td>
<td>6.53</td>
</tr>
</tbody>
</table>

Data Sheet
APPENDIX "C-1"

Theoretical Curves for Total Ship Expenses per Mile or per Ton - Oil Tankers

The basic data for these curves was developed in Appendices "A" and "B". Only the equations will be given in this section together with an explanation of any new symbols or constants.

I Total Expenses per Year

Total Expenses = Ship Expenses + Voyage Expenses + Fixed Charges

\[ C_T = (C_w + C_3 + C_{at} + C_{fl}) + C_v + C_o \]

Voyage Expense = Cargo Expense = Ship Handling Expense

For oil tanker operations the cargo expenses are divided between the ship and the terminal and as far as the ship is concerned they are not separated out of the general ship's expenses. Therefore, for the purposes of this study they are considered to be zero.

An oil tanker in the crude oil trade is normally either loaded or in ballast. For this reason the ship's handling expenses per year vary only as the number of voyages.

\[ \text{Voyage Expenses} = N(k + \Delta A \Delta c) \]

\[ = N \Delta c \text{ for a tanker full one way - in ballast the other way} \]

\[ C_v = N \Delta c \]

\[ k = \text{Minimum cost of Port Charges per voyage} \]

\[ \Delta A = \text{Cost per ton for Port Charges per voyage above the minimum cost} \]

\[ \Delta c = \text{Cargo tons per voyage} \]

\[ C_u = \text{Port charges per voyage for a tanker loaded one way and in ballast one way} \]

\[ C_v = \text{Voyage expense per year} \]

\[ C_o = \text{Fixed changes per year including depreciation, overhead and interest for a new ship.} \]
8. \( C_r = C_w + C_s + C_m + C_r + C_o + D_u \Delta_c + N(C_P D_P + C_s \frac{M}{24V}) + N(K + C_A \Delta_c) \)

8A. \( C_r = C_w + C_s + C_m + C_r + C_o + D_u \Delta_c + N(C_P D_P + C_s \frac{M}{24V}) + N(C_w) \)

Equation 8A will be used as theoretical curve assumes a tanker loaded one way and in ballast on return passage.

II Total expenses per mile

\[
D = \frac{C_r}{N M} = \frac{C_w + C_s + C_m + C_r + C_o + D_u \Delta_c + N(C_P D_P + C_s \frac{M}{24V}) + N N C_w}{N M}
\]

9. \( D = \frac{C_r}{N M} = \frac{(C_w + C_s + C_m + C_r + C_o + D_u \Delta_c + 350 C_o) D_p + (C_w + C_s + C_m + C_r + C_o + D_u \Delta_c + 350 C_s) \frac{C_n}{350 \times 24V}}{N M} \)

All terms are constant except \( M \). Denoting all constant terms by \( K \) values the equation becomes.

9A. \( D = \frac{C_r}{N M} = \frac{K_1^' \frac{K_2}{M} + K_3}{M} \)

The cost per mile should approximate a hyperbolic curve approaching a limit equal to \( K_2 \) as \( M \) approaches infinity.

III Total Expenses per Deadweight Ton

\[
E = \frac{C_r}{N \Delta_c} = \frac{C_w + C_s + C_m + C_r + C_o + D_u \Delta_c + N(C_P D_P + D_s C_s) + N N C_w}{N \Delta_c}
\]

\[
E = \frac{C_r}{N \Delta_c} = \frac{(D_p \frac{M}{24V})(C_w + C_s + C_m + C_r + C_o + D_u \Delta_c) + C_P D_P + C_s \frac{M}{24V} + C_n}{\Delta_c}
\]

10. \( E = \frac{C_r}{N \Delta_c} = (\frac{(C_w + C_s + C_m + C_r + C_o + D_u \Delta_c + 350 C_e) D_p + (C_w + C_s + C_m + C_r + C_o + D_u \Delta_c + 350 C_s) \frac{M + C_n}{350 \times 24V}}{\Delta_c} \)
Denoting all constant terms for any one ship by the equation becomes

\[ E = \frac{C_r}{N\Delta_c} = \frac{K_1' + K_2'M + K_3'}{\Delta_c} \]
The table below shows the values used in determining the theoretical curves shown as total ship operating cost per mile and per deadweight cargo tons plotted against voyage distance in miles. The values for $\Delta_c$ were taken from Appendix "B-1".

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F.D.Cons/Port Day $/day 334.0  334.0  509.0  509.0  509.0
F.O.Cons/Sea Day $/day 819.0  755.0  922.0  975.0  1220.0
days in port 2.0  2.0  2.25  2.25  2.25
days unavailable 15.0  15.0  17.5  17.5  17.5
F.O.Cons/Unavail. day $/day 133.0  133.0  133.0  133.0  133.0
Port Charges/Voy. $/Voy. 2020.0  2618.0  3228.6  3503.9  3695.2

Equation No. 9A+10A

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<td></td>
<td>17.5</td>
<td>17,750</td>
<td>94.4</td>
<td>3,218</td>
<td>3,095</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>19,900</td>
<td>105.6</td>
<td>3,152</td>
<td>3,038</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cond. I - Bunkers Loaded at Cargo Loading Port - 3700 mile voyage distance
Cond. II - Bunkers loaded at Cargo unloading Port - 17,000 mile voyage distance
(1) Fuel Oil Margin & Port Time Included
<table>
<thead>
<tr>
<th>SHIP D.W.T.</th>
<th>SPEED KNOTS</th>
<th>DEADWEIGHT GAIN - TONS</th>
<th>MAX. D.W.T. GAIN</th>
<th>MAX. GAIN AS A % OF SHIP D.W.T.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 19,562</td>
<td>14</td>
<td>-58</td>
<td>1,053</td>
<td>1,484</td>
</tr>
<tr>
<td>19,393</td>
<td>16</td>
<td>-74</td>
<td>1,341</td>
<td>1,364</td>
</tr>
<tr>
<td>19,203</td>
<td>18</td>
<td>-89</td>
<td>1,760</td>
<td>1,200</td>
</tr>
<tr>
<td>19,105</td>
<td>19</td>
<td>-82</td>
<td>2,100 (2)</td>
<td>1,093</td>
</tr>
<tr>
<td>19,033</td>
<td>20</td>
<td>-21</td>
<td>1,336 (2)</td>
<td>955</td>
</tr>
<tr>
<td>B 26,960</td>
<td>14</td>
<td>-36</td>
<td>1,428</td>
<td>3,436</td>
</tr>
<tr>
<td>26,879</td>
<td>16</td>
<td>-30</td>
<td>1,928</td>
<td>3,279</td>
</tr>
<tr>
<td>26,661</td>
<td>16.3</td>
<td>-24</td>
<td>2,014</td>
<td>3,244</td>
</tr>
<tr>
<td>26,621</td>
<td>17.4</td>
<td>-4</td>
<td>2,487</td>
<td>3,112</td>
</tr>
<tr>
<td>26,559</td>
<td>18.5</td>
<td>+84</td>
<td>3,376</td>
<td>2,930</td>
</tr>
<tr>
<td>C 30,482</td>
<td>14</td>
<td>42</td>
<td>1,691</td>
<td>4,038</td>
</tr>
<tr>
<td>30,303</td>
<td>16</td>
<td>48</td>
<td>1,072</td>
<td>2,201</td>
</tr>
<tr>
<td>30,250</td>
<td>16.5</td>
<td>43</td>
<td>1,158</td>
<td>2,387</td>
</tr>
<tr>
<td>30,110</td>
<td>18</td>
<td>158</td>
<td>1,642</td>
<td>3,290</td>
</tr>
<tr>
<td>30,130</td>
<td>19</td>
<td>163</td>
<td>1,984</td>
<td>4,028</td>
</tr>
<tr>
<td>D 35,770</td>
<td>14</td>
<td>52</td>
<td>1,743</td>
<td>4,174</td>
</tr>
<tr>
<td>35,570</td>
<td>16</td>
<td>49</td>
<td>1,188</td>
<td>2,418</td>
</tr>
<tr>
<td>35,550</td>
<td>16.3</td>
<td>48</td>
<td>1,236</td>
<td>2,528</td>
</tr>
<tr>
<td>35,446</td>
<td>17.4</td>
<td>140</td>
<td>1,589</td>
<td>3,175</td>
</tr>
<tr>
<td>35,441</td>
<td>18</td>
<td>185</td>
<td>1,953</td>
<td>3,613</td>
</tr>
<tr>
<td>E 39,238</td>
<td>14</td>
<td>41</td>
<td>1,877</td>
<td>7,037</td>
</tr>
<tr>
<td>39,024</td>
<td>16</td>
<td>79</td>
<td>1,198</td>
<td>2,505</td>
</tr>
<tr>
<td>38,911</td>
<td>17.5</td>
<td>126</td>
<td>1,498</td>
<td>3,077</td>
</tr>
<tr>
<td>38,895</td>
<td>18</td>
<td>156</td>
<td>1,640</td>
<td>3,344</td>
</tr>
</tbody>
</table>

Cond. I - Bunkers loaded at cargo loading port - 3,700 Mile Voyage
Cond. II - Bunkers loaded at cargo unloading port - 17,000 Mile Voyage
Cond. III Bunkers loaded at cargo loading port - 17,000 mile Voyage
(2) - Indicates Ship does not have sufficient F.O. capacity for maximum gain under Cond. III method of loading.
**TABLE IV**  
Percent Time at Sea  
(Based on Owner's Design Speed)

<table>
<thead>
<tr>
<th>Ship</th>
<th>Percent per Voyage</th>
<th>Percent per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3700 Miles</td>
<td>17000 Miles</td>
</tr>
<tr>
<td>Ship A</td>
<td>80.0</td>
<td>89.3</td>
</tr>
<tr>
<td>Ship B</td>
<td>82.0</td>
<td>90.6</td>
</tr>
<tr>
<td>Ship C</td>
<td>82.0</td>
<td>89.3</td>
</tr>
<tr>
<td>Ship D</td>
<td>80.0</td>
<td>89.4</td>
</tr>
<tr>
<td>Ship E</td>
<td>79.0</td>
<td>88.7</td>
</tr>
</tbody>
</table>
Table V (a)

Average Cost and Operating Data at Owner's Design Speed
3700 Mile Round Trip Voyage Distance

<table>
<thead>
<tr>
<th>SHIP</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHIP EXPENSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insurance</td>
<td>97.0</td>
<td>99.4</td>
<td>113.0</td>
<td>124.8</td>
<td>129.7</td>
</tr>
<tr>
<td>Wages, Subst., Cabin Crew</td>
<td>374.3</td>
<td>393.6</td>
<td>441.5</td>
<td>454.0</td>
<td>466.5</td>
</tr>
<tr>
<td>Stores, Supplies, Maint.</td>
<td>33.0</td>
<td>34.2</td>
<td>34.9</td>
<td>35.6</td>
<td>36.1</td>
</tr>
<tr>
<td>Total Repairs</td>
<td>95.4</td>
<td>114.1</td>
<td>123.1</td>
<td>134.9</td>
<td>141.9</td>
</tr>
<tr>
<td>Sub Total</td>
<td>599.7</td>
<td>641.3</td>
<td>712.5</td>
<td>749.3</td>
<td>774.2</td>
</tr>
<tr>
<td>Total Fuel Cost D.D.+ .002</td>
<td>254.2</td>
<td>239.5</td>
<td>281.2</td>
<td>306.8</td>
<td>374.3</td>
</tr>
<tr>
<td>TOTAL</td>
<td>853.9</td>
<td>880.8</td>
<td>993.7</td>
<td>1056.1</td>
<td>1148.5</td>
</tr>
</tbody>
</table>

| FIXED CHARGE EXPENSE |     |     |     |     |     |
| Depreciation | 95.5 | 95.5 | 105.3 | 105.3 | 105.3 |
| Overhead | 445.8 | 454.6 | 490.9 | 535.2 | 566.8 |
| TOTAL | 541.3 | 550.1 | 595.2 | 640.5 | 671.1 |

| VOYAGE EXPENSEES |     |     |     |     |     |
| Port Charges | 70.6 | 82.6 | 99.5 | 109.8 | 121.2 |
| Suez Charges | 70.6 | 82.6 | 99.5 | 109.8 | 121.2 |
| TOTAL | 1370.3 | 1418.0 | 1585.1 | 1701.1 | 1836.5 |

<p>|   | Days in Port | 2.0   | 2.0   | 2.25  | 2.25  | 2.25  |
|   | Days at Sea  | 8.0   | 9.09  | 8.88  | 8.93  | 8.47  |
|   | Days per Voyage | 10.0  | 11.09 | 11.38 | 11.18 | 10.72 |
|   | Voyages per Year | 34.95 | 31.55 | 31.22 | 31.08 | 32.42 |
|   | Time at Sea Factor | 420.0 | 387.0 | 473.0 | 500.0 | 626.0 |
|   | Fuel Oil Consumption-Bbls/day | 18.33 | 25.86 | 29.18 | 34.44 | 37.64 |
| Cargo Tons per Voyage |</p>
<table>
<thead>
<tr>
<th>SHIP</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>COST PER MILE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ship Expense $/M</td>
<td>6.60</td>
<td>7.55</td>
<td>8.60</td>
<td>9.18</td>
<td>9.57</td>
</tr>
<tr>
<td>Total Operating Expense</td>
<td>10.58</td>
<td>12.15</td>
<td>13.72</td>
<td>14.78</td>
<td>15.29</td>
</tr>
</tbody>
</table>

| COST PER CARGO DWT-TON |     |     |     |     |     |
| Ship Expense $/Ton | 1.33 | 1.08 | 1.09 | 0.99 | 0.94 |
| Total Operating Expense $/Ton | 2.14 | 1.74 | 1.74 | 1.59 | 1.50 |
### Table V (b)

**Average Cost and Operating Data at Owner's Design Speed**  
17,000 Mile Round Trip Voyage Distance

<table>
<thead>
<tr>
<th>SHIP</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHIP EXPENSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insurance</td>
<td>109.3</td>
<td>111.8</td>
<td>126.5</td>
<td>139.3</td>
<td>144.6</td>
</tr>
<tr>
<td>Wages, Subst., Cabin Crew</td>
<td>367.3</td>
<td>389.9</td>
<td>433.0</td>
<td>442.0</td>
<td>451.5</td>
</tr>
<tr>
<td>Stores, Supplies, Maint.</td>
<td>25.0</td>
<td>25.0</td>
<td>25.8</td>
<td>26.5</td>
<td>27.0</td>
</tr>
<tr>
<td>Total Repairs</td>
<td>95.4</td>
<td>114.1</td>
<td>123.1</td>
<td>134.9</td>
<td>141.9</td>
</tr>
<tr>
<td>Sub Total</td>
<td>597.0</td>
<td>640.8</td>
<td>708.4</td>
<td>742.7</td>
<td>765.0</td>
</tr>
<tr>
<td>Total Fuel Cost D.D.+.002</td>
<td>307.5</td>
<td>284.9</td>
<td>346.9</td>
<td>365.4</td>
<td>454.0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>902.5</td>
<td>925.7</td>
<td>1055.3</td>
<td>1108.1</td>
<td>1219.0</td>
</tr>
<tr>
<td>FIXED CHARGE EXPENSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depreciation</td>
<td>95.5</td>
<td>95.5</td>
<td>105.3</td>
<td>105.3</td>
<td>105.3</td>
</tr>
<tr>
<td>Overhead</td>
<td>445.8</td>
<td>454.6</td>
<td>491.0</td>
<td>535.2</td>
<td>566.8</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOYAGE EXPENSES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port Charges</td>
<td>16.75</td>
<td>21.15</td>
<td>26.61</td>
<td>28.47</td>
<td>31.21</td>
</tr>
<tr>
<td>Suez Charges</td>
<td>111.4</td>
<td>145.6</td>
<td>161.4</td>
<td>193.2</td>
<td>216.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>128.6</td>
<td>166.7</td>
<td>188.0</td>
<td>221.7</td>
<td>247.3</td>
</tr>
<tr>
<td>Total Operating Expense</td>
<td>1478.5</td>
<td>1547.0</td>
<td>1734.3</td>
<td>1864.0</td>
<td>2033.1</td>
</tr>
<tr>
<td>Days in Port</td>
<td>4.5</td>
<td>4.5</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Days at Sea</td>
<td>37.7</td>
<td>43.2</td>
<td>41.9</td>
<td>42.1</td>
<td>39.9</td>
</tr>
<tr>
<td>Days per Voyage</td>
<td>42.2</td>
<td>47.7</td>
<td>46.9</td>
<td>47.1</td>
<td>44.9</td>
</tr>
<tr>
<td>Voyages per Year</td>
<td>8.3</td>
<td>7.34</td>
<td>7.41</td>
<td>7.38</td>
<td>7.74</td>
</tr>
<tr>
<td>Time at Sea Factor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Oil Consumption-Bbls/day</td>
<td>420.0</td>
<td>387.0</td>
<td>473.0</td>
<td>500.0</td>
<td>626.0</td>
</tr>
<tr>
<td>Cargo Tons per Voyage</td>
<td>17.38</td>
<td>24.86</td>
<td>27.98</td>
<td>33.16</td>
<td>36.18</td>
</tr>
</tbody>
</table>
### Table V (b) (Cont'd)

<table>
<thead>
<tr>
<th>SHIP</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COST PER MILE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ship Expense $/M</td>
<td>6.40</td>
<td>7.42</td>
<td>8.38</td>
<td>8.82</td>
<td>9.27</td>
</tr>
<tr>
<td>Total Operating Expense</td>
<td>10.47</td>
<td>12.40</td>
<td>13.76</td>
<td>14.85</td>
<td>15.45</td>
</tr>
<tr>
<td><strong>COST PER CARGO DWT-TON</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ship Expense $/Ton</td>
<td>6.27</td>
<td>5.07</td>
<td>5.09</td>
<td>4.53</td>
<td>4.35</td>
</tr>
<tr>
<td>Total Operating Expense $/Ton</td>
<td>10.23</td>
<td>8.47</td>
<td>8.37</td>
<td>7.62</td>
<td>7.26</td>
</tr>
</tbody>
</table>
LIST OF CURVE SHEETS

A- Ship Expense - Cost per Mile vs Round Trip Voyage Distance

B- Ship Expense per Cargo D.W.T. - Ton vs Round Trip Voyage Distance

C- Total Operating Cost per Mile vs Round Trip Voyage Distance

D- Total Operating Cost $/Cargo D.W.T. - Ton vs Round Trip Voyage Distance

E- Annual Cargo Capacity - Tons vs Speed

F- Total Operating Cost - $/Ton vs Speed

G- Total Operating Cost per Year vs Speed

H- Fuel Oil Cost - $/Ton vs Speed

J- Total Fuel Oil Cost - vs Speed

K- Ratio of Machinery Cost - vs Nuclear Fuel Cost

L- Ratio of Machinery Cost - vs Nuclear Fuel Cost (Ship E at various speeds).

M- Ratio of Machinery Cost - vs Speed (Ship E only)

N- Ratio of Machinery Cost - vs Normal Shaft Horsepower
THEORETICAL CURVES

ACTUAL DATA CURVES AT 3 TOP & 12000 MILES

SHIPEXPENSE - DWT TON

ROUND TRIP VOYAGE DISTANCE - MILES

NEWPORT NEWS SHIPBUILDING AND DRY DOCK COMPANY
ATOMIC POWER DESIGN DIVISION
SHIP EXPENSE PER CARGO DWT TON
VS
ROUND TRIP VOYAGE DISTANCE
AT OWNER DESIGN SPEED

FTR 7-28-65
NEWPORT NEWS SHIPBUILDING & DRY DOCK CO
ATOMIC POWER DESIGN DIVISION
TOTAL OPERATING COST $/CARGO WATERTON
VS.
ROUND TRIP VOYAGE DISTANCE

THEORETICAL CURVES

ACTUAL DATA CURVES AT 3,700 $/1,000 MILES

ROUND TRIP VOYAGE DISTANCE - MILES

REF. 7-28-68
NEWPORT NEWS SHIPBUILDING & DRY DOCK CO.
ATOMIC POWER DESIGN DIVISION

RATIO OF MACHINERY COST - \( \frac{M_u}{M_o} \)

- V$ -
NUCLEAR FUEL COST

SHIPS A' THRU E' @ OWNER'S DESIGN SPEED

> INDICATES \( c_n = \frac{c}{2} \)

A' - 18 KNOTS; B' - 16 KNOTS; C' - 16.5 KNOTS
D' - 16.5 KNOTS; E' - 16.5 KNOTS

\( c \) = YEARLY NUCLEAR FUEL COST
\( c_u \) = YEARLY FUEL OIL COST

10,000 MILE VOYAGE DISTANCE

YEARLY NUCLEAR FUEL COST \( \times 10^4 \)

-55-
NEWPORT NEWS SHIPBUILDING & DRY DOCK Co.
ATOMIC POWER DESIGN DIVISION

RATIO OF MACHINERY COST $M_a$
$M_o$

$\psi_S +$
NUCLEAR FUEL COST
SHIP "E" ONLY AT VARIOUS SPEEDS.
$\rightarrow$ INDICATES $C_m = \frac{C_o}{e}$

$C_m = $ YEARLY NUCLEAR FUEL COST
$C_o = $ YEARLY FUEL OIL COST

RATIO OF MACHINERY COST $M_a$

7,000 MILE VOYAGE DISTANCE

YEARLY NUCLEAR FUEL COST $\times 10^9$