THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

NUCLEAR TANKER ECONOMICS

Harry Benford

July, 1957

IP-228

ACKNOWLEDGEMENTS

I wish to make known my grateful appreciation for the expert assistance, generously given, by the following members of the faculty and staff of the University of Michigan:

Hobart Coffey, Professor of Law

John G. Lewis, Associate Research Engineer

Thomas Sawyer, Assistant Professor of English

Marx E. Weech, Research Engineer

George L. West, Jr., Assistant Professor of Naval Architecture and Marine Engineering.

Opinions expressed in the paper are strictly my own, and are frequently at odds with the thinking of one or more of the above-mentioned gentlemen. In addition, the following students of the University of Michigan's Department of Naval Architecture and Marine Engineering willingly assisted in the calculations:

Messrs:

George Antoniou
M. Balanda
James Barden
Nedret Basar
Tarik Batur
Zakir Coskuner
Stephen Ho
Wei-Fang Huang
Muhammad Husain
Charles Kahlke
John Montgomery
Thomas Page
Ilmar Palm-Leis
Herbert Pollock
Tøger Teilman
Paul Van Mater
Howard Youngclaus

Harry Benford

TABLE OF CONTENTS

LIST OF FIGURES

SUMMARY

This study deals with the economics of nuclear tankers, with emphasis on the probable future. There are two main aims: 1) to give nuclear engineers the tools with which to make their own cost studies, and 2) to show the cost reductions which must be made if nuclear power is to become commercially competitive with existing marine plants.

The intent of this study, then, is to be of service to the profession through the presentation of useful information relative to nuclear tanker costs. Government restrictions on the publication of certain elements of nuclear fuel costs, plus lack of reliable capital cost estimates, preclude any definitive work on nuclear economics at this time. Nevertheless, a number of general conclusions are reached and these may be of interest. For example, it is shown that: 1) nuclear power cannot possibly compete commercially until its machinery costs are reduced to less than two or possibly three times those of conventional type; 2) on the other hand, if a greatly reduced--but still reasonable--return on investment is acceptable, nuclear fuel and machinery cost ratios may each exceed their conventional counterparts by as much as four-to-one and still prove acceptable. (The last statement presupposes optimum application.); 3) nuclear power can be used most advantageously in large ships on long voyages; 4) it is more important to reduce the cost than the weight of nuclear machinery; 5) finally, the commercial advantages of foreign costs apply to nuclear as well as conventional ships.

A large share of the paper is devoted to the estimation of probable upper and lower limits for the various operating costs such as crew wages, repairs, and insurance.

Typical calculations, presented in detail, show methods by which the data can be put to use in nuclear tanker cost studies.

A. INTRODUCTION

For some time it has been recognized that if nuclear energy looks good for stationary power plants, it should look even better for merchant ships where the reduction in fuel weight could be turned to economic advantage through increased payload capacity. For example, a large conventionally-powered ship on a long voyage may carry over 4,000 tons of fuel oil which amounts to roughly four times the weight of the propulsion machinery itself. (This and other factors favorable to shipboard use of nuclear energy are discussed in some detail in References 1 and 2.) The economic gain resulting from the elimination of great weights of fuel is, however, more than offset by the high capital costs associated with atomic machinery. Its most enthusiastic advocates concede that capital costs for nuclear plants will continue to be inherently greater than conventional plants of equal power, this despite drastic reductions expected in present nuclear construction costs. Thus, it is clear that if shipboard nuclear propulsion is to become competitive, it must offer other advantages, principally the reduction of fuel costs below those attainable with fossil fuels.

When nuclear fuel becomes cheap, the best application for shipboard use should be in a vessel with a large annual power utilization. It is generally recognized that a big tanker engaged in a long ocean haul would very likely use nuclear power to best advantage. (Reference 1 goes into this at some length.) Ore carriers, trailerships and passenger ships are also worthy of consideration. The present study is confined to tankers in the belief that this type is most likely to lead the way in the application of atomic energy to merchant ships.

The experts are agreed that nuclear power for ship propulsion is technically feasible (see References 1, 2, and 3). The burning issues concern the questions of economic feasibility. For example, according to Reference 1, high-ranking officials of the federal government make contrasting claims as to the probable costs of building and operating a proposed 20,000 shaft horsepower nuclear tanker. One official cites bid prices for a nuclear plant at a figure very little more than three times the cost of a conventional plant. He estimates that nuclear fuel costs will be almost low enough, within five years, to make the nuclear tanker commercially competitive, despite the higher capital cost.

The other official states that the construction cost ratio is in the neighborhood of seven rather than three and that nuclear fuel which now costs fifty times as much as fuel oil will probably still cost fifteen to twenty times as much as fuel oil five years hence.

It is not the intent of this paper to prove either of these gentlemen right or wrong. The aim, rather, is to show how the various technical factors affect the overall economy of tankers. The material is presented in such a way that nuclear engineers can fill in the missing parts to suit their own expert judgment and then fit the pieces together to come up with a reasonable economic analysis. This approach may be particularly valuable in pin-pointing those areas most in need of improvement and thus hasten the day when nuclear marine power will become truly competitive. The paper may also be put to use in weighing the commercial benefits of extra money spent for reductions in machinery weight, increases in thermal efficiency, reductions in crew requirements, etc. The figures of Reference 4, which deals with the economics of conventional tankers, are used as bases for estimating weights and costs of nuclear tankers. In order to make any real use of the present paper, Reference 4 should also be at hand.

In those areas where it makes a difference, costs are based on nuclear ships built no sooner than ten years from now. This is done to make valid the comparison with conventional power. It is assumed that in the normal course of events it will take at least ten years to gain the experience necessary to eliminate most of those high costs brought on solely by ignorance of nuclear engineering.

B. ECONOMIC CRITERIA

Before further discussion, it seems desirable to explain the interpretation placed on the phrase "economically feasible" or its synonyms, "commercially feasible" or "commercially competitive." When, in this paper, you meet any of the above terms applied to nuclear tankers, they are meant to imply that such a ship represents as good an investment as a conventionally-powered ship of the same size in the same trade. By this definition, an atomic ship--to be considered "commercially feasible"-- must do more than simply earn a reasonable profit. It must earn an annual profit large enough to repay the initial investment just as rapidly as would be the case with the cheaper-to-build conventional ship.

Stating the above in another way, the commercial success or failure of a nuclear vessel is measured in terms of its comparison with its conventional counterpart. If potential rates of return on investment (or pay-off periods, or capital recovery factors) are equal in each case, the nuclear ship can be said to be "economically feasible." If the rate of return cannot be shown to measure up in this way, people will have little incentive to risk their spare money on such a venture. Under normal free enterprise conditions such a ship would, therefore, never get beyond the planning stage.

Aside from questions of first cost, this assumes equal "risks" in each case. For example, if the proposed nuclear ship is more likely to be destroyed for one reason or another, then proportionately greater rates of return would be required.

It must also be pointed out that our yardstick is by no means a perfect measuring device. Changing cost of bunker oil, in particular, makes our criterion anything but an eternal, carved-in-granite, basic reference. Conclusions reached today may require re-evaluation tomorrow. This weakness, unfortunately, is common, in one degree or another, to almost any sort of investment cost study you care to make.

In line with the foregoing arguments and for reasons advanced in Reference 4, the current study makes use of the capital recovery factor (C.R.F.) as the standard basis for comparison:

$$\text{C.R.F.} = \frac{\text{Annual Profit}}{\text{Invested Cost}}$$

or

$$\text{Years to Repay Investment} = \frac{1}{\text{C.R.F.}}$$

(C.R.F. may be converted to actual rate of return on investment by use of Figure 24 in Reference 4.)

A great deal of debate has been directed towards the proper definition of "annual profit" as used in the numerator of the expression for C.R.F. The bone of contention is whether depreciation and/or interest should be included as annual costs to be subtracted from annual income. The debate is a bit academic because, while the quantitative results depend on which system is used, the qualitative results do not. For example, if optimum power--and thus speed--are to be determined by calculation of maximum C.R.F., the same optimum power and speed will be indicated whether depreciation and/or interest are included or not. The table on the following page illustrates this point.

The optimum powers and speeds may be found graphically as shown in Figure 1. The curves show clearly that the optimum power (and speed) is exactly the same in each case.

TABLE I

OPTIMUM SPEED INVESTIGATION

(Costs are in $÷1000)

Ship	A	B	C	D	E
Shaft horsepower (normal)	10,000	15,000	20,000	25,000	30,000
Nominal sea speed	12.83	14.57	15.90	16.93	17.81
Invested cost	13,425	14,010	14,511	14,977	15,404
Annual income	5,384	5,986	6,404	6,710	6,956
Crew wages, insurance, fuel, repairs, etc.	1,264	1,444	1,610	1,770	1,925
Profit before depreciation and interest	4,120	4,542	4,794	4,940	5,031
Corresponding C.R.F.(%)	30.7	32.4	33.0	33.0	32.7
3% interest charge	403	421	436	450	462
Profit before depreciation	3,717	4,121	4,358	4,490	4,569
Corresponding C.R.F.(%)	27.7	29.4	30.0	30.0	29.7
5% depreciation charge	672	701	726	749	771
Profit	3,045	3,420	3,632	3,741	3,798
Corresponding C.R.F. (%)	22.7	24.4	25.0	25.0	24.7

(Results plotted in Figure 1)

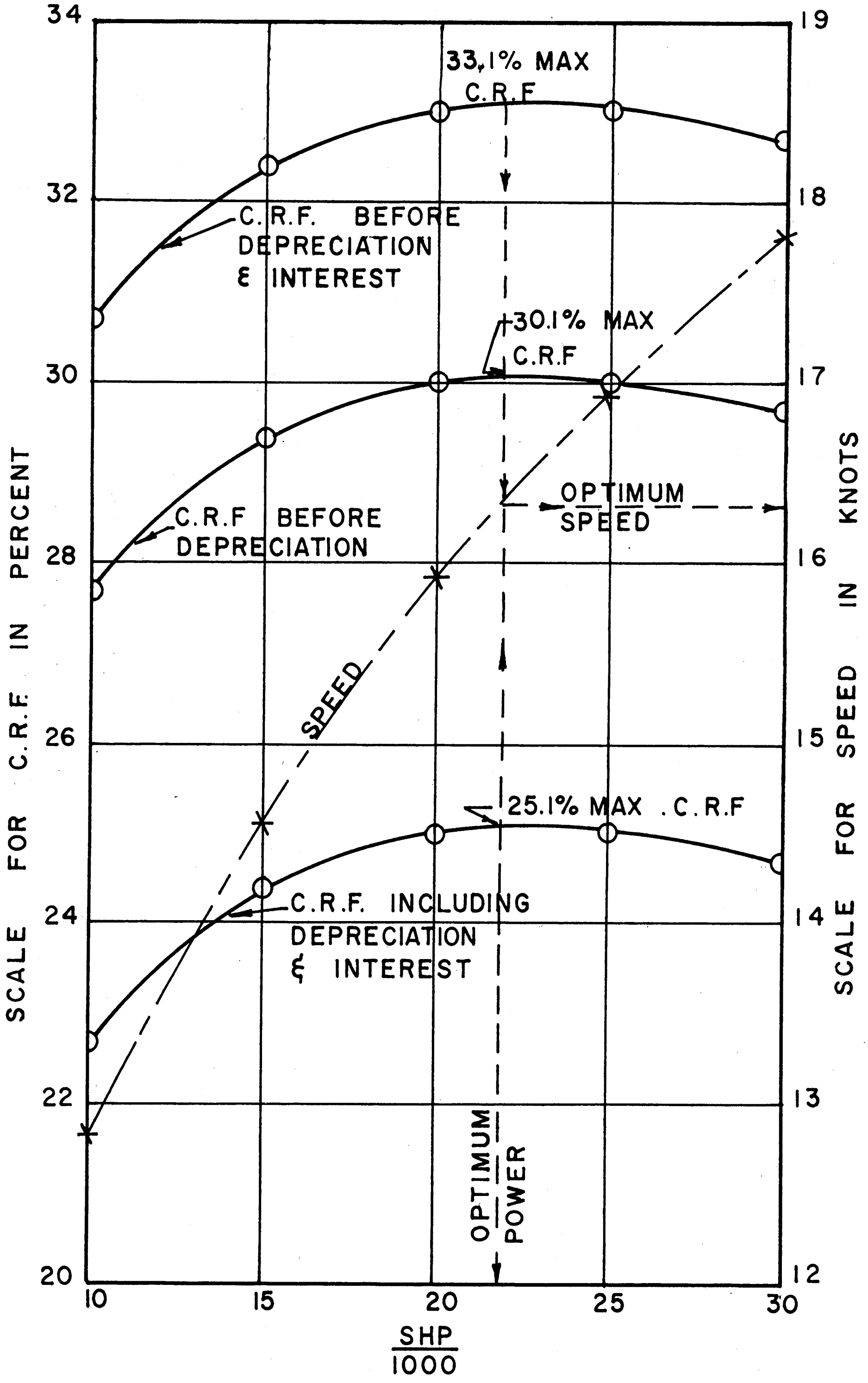


Figure 1. Graphic Solution for Optimum Speed

Shows that choice of speed and power is not affected by inclusion of capital charges in calculation of capital recovery factor

Approaching the question of the inclusion or exclusion of capital charges from another angle, it can again be shown that the issue is of little real importance. In Section G, for example, allowable fuel costs are derived for various assumed machinery costs on a basis of matching the potential capital recovery factors of conventional ships. The following table shows that the allowable fuel cost, so obtained, is unaffected by the inclusion or exclusion of capital charges:

TABLE II

DETERMINATION OF ALLOWABLE NUCLEAR FUEL COSTS
(Costs are in $÷1000)

Basis	C.R.F. before Depreciation & Interest	C.R.F. before Depreciation (inc. interest)	C.R.F. inc. Depreciation & Interest
Potential C.R.F., conventional (see Figure 1)	33.1%	30.1%	25.1%
Invested cost, nuclear ship	18,000	18,000	18,000
Annual profit required to match conventional C.R.F.	5,960	5,420	4,520
Annual income	7,000	7,000	7,000
Operating costs exclusive of nuclear fuel	1,000	1,000	1,000
Annual charge for interest (3%)	0	540	540
Annual charge for depreciation (5%)	0	0	900
Margin remaining for annual nuclear fuel cost	40	40	40

Where specific values of C.R.F. are mentioned in this paper, they do not include either interest or depreciation.

In recent years there has been a marked tendency to base economic studies on the criterion of operating cost per ton of cargo in the case of ships or cost per kilowatt-hour in the case of power plants. (See References 1, 5, 6, 7, and 8.) This approach, while eliminating cargo rate as a variable, is nevertheless quite misleading as may be seen in the example which follows. Assume you are asked to decide which of two ships to build. One is nuclear-powered and requires 50 percent greater investment but has such low fuel costs that cargo costs-per-ton are the same as those of a conventionally-powered ship. On this basis, the two proposals might appear to be equally attractive.

TABLE III

Ship Power	A Conventional	B Nuclear
Invested cost	$10,000,000	$15,000,000
Cargo tons per year	1,000,000	1,000,000
Crew and other operating costs per year	$ 600,000	$ 600,000
Insurance at 3%	$ 300,000	$ 450,000
Fuel costs per year	$ 600,000	$ 50,000
Amortization at 8%	$ 800,000	$1,200,000
Total operating costs per year	$2,300,000	$2,300,000
Cost per ton cargo	$2.30	$2.30

If we investigate the rate of return on investment, however, the picture changes drastically, as seen in the table on the following page.

TABLE IV

Ship	A	B
Power	Conventional	Nuclear
Invested cost	$10,000,000	$15,000,000
Cargo tons per year	1,000,000	1,000,000
Cargo rate per ton, say	$3.00	$3.00
Income per year	$3,000,000	$3,000,000
Crew and other operating costs per year	$600,000	$600,000
Insurance at 3%	300,000	450,000
Fuel cost per year	$600,000	$50,000
Profit per year (before interest or depreciation)	$1,500,000	$1,900,000
C.R.F. (Capital Recovery Factor)	15%	12.7%
Corresponding pay-off period	6.65 years	7.85 years

If you prefer to include amortization (depreciation plus interest), the last few lines above become:

Amortization (8%)	$800,000	$1,200,000
Profit per year	$700,000	$ 700,000
C.R.F.	7%	4.7%
Corresponding pay-off period	14.3 years	21.3 years

Since stockholders are rightfully concerned with the rate of return on their investments, it is clear from the foregoing that you would be doing them a dis-service to recommend the nuclear ship despite its seeming equality based on cost-per-ton.

Cost per cargo ton is a deceptive yardstick when only small differences in first cost exist. It is totally wrong when there is a large difference in first cost. Its use is therefore deplored in studies comparing nuclear versus conventional power.

Reference 4 contains an extensive discussion of the relative merits of a number of other economic criteria.

Throughout this study it is taken for granted that nuclear plants will, in general, have a useful life of twenty years, this being the figure most commonly used in cost studies pertaining to normal ships. As with the Deacon's Masterpiece, it is economically desirable that hull and machinery wear out at about the same time. It is quite possible that nuclear engineers may feel that a life span other than twenty years should be considered. Any decisions on such a question should be based on thorough cost studies not overlooking changes in cost resulting from modified hull corrosion margins. The relationship between the capital recovery factor and rate of return on investment would, of course, be altered by any change in projected plant life.

C. DESIGN ANALYSIS

1. Introduction

Intelligent economic analysis has, as a prerequisite, intelligent design work. For example, you should not compare conventional and nuclear power simply by assuming the substitution of a nuclear reactor for the boilers in a conventional ship. The best speed for any given service is strongly influenced by machinery and fuel costs. Changes in these factors obviously modify the optimum power and speed, and this in turn dictates changes in hull form characteristics, displacement and pay load capacity. If a meaningful comparison is to be made you must start with the economic potential of the optimum conventional ship as a criterion. Then, for each combination of assumed nuclear machinery costs and fuel costs, an investigation must be made to determine the best design characteristics of the nuclear ship. Finally, the best nuclear ship should be set off against the best conventional ship. After all, it is only fair that each opposing camp should be championed by its own best contender.

2. Method

In general, the design analysis presented in Reference 4 was used as a basis for the present study.

Operators and naval architects are accustomed to thinking and talking in terms of deadweight when referring to tanker size. This is somewhat misleading in cases where we wish to compare nuclear with conventional tankers. The nuclear vessel, by virtue of its greater machinery weight, is bound to have a smaller deadweight than a conventional tanker of equivalent power. The displacements are held the same in each case and the nuclear tanker's deadweight is actually somewhat less than the nominal figure given.

The design parameters used in the foregoing reference are necessarily somewhat broad and oversimplified. Further investigations into optimum length and full form could doubtlessly lead to small increases in the potential rates of return for either nuclear or conventional ships. It is doubtful that any modification of the qualitative results would occur, however. Reference 9 and the second appendix of Reference 4 deal with further studies in hull form economics.

3. Weights

Reference 10 estimates the complete weight of a heterogeneous pressurized water reactor of 70 megawatts at 1,000 tons. This system is proposed as a replacement for boilers weighing 250 tons in a "Mariner" class freighter. But the proposed reactor would be capable of satisfying only the "normal" requirements of 17,500 SHP whereas the boilers are of sufficient capacity to provide 20,000 SHP for "national defense" conditions. Knowing these facts, we may say that a reactor of equivalent power should weigh perhaps 1,150 tons. Reference 11 gives the total machinery weight for the "Mariner" as 1,009 tons. The ratio of nuclear to conventional machinery weights can then be approximated as follows:

TABLE V

	Tons
Total machinery weight, conventional	1,009
Minus boilers	- 250
Minus uptakes, stack, fuel oil system, draft system, etc. say	- 100
Subtotal	659
Plus reactor	+ 1,150
Total Machinery weight, nuclear	1,809

Machinery weight ratio: $\frac{1809}{1009} = 1.794$

say 1.8

Reference 12 gives the following figures for a 20,000 shaft horsepower marine plant:

TABLE VI

	Tons	Ratio
Conventional	983.7	1.0
Nuclear: closed cycle gas turbine	1268.7	1.29
Nuclear: pressurized water steam turbine	1793.4	1.82
Above plus liquid shielding	3513.4	3.57

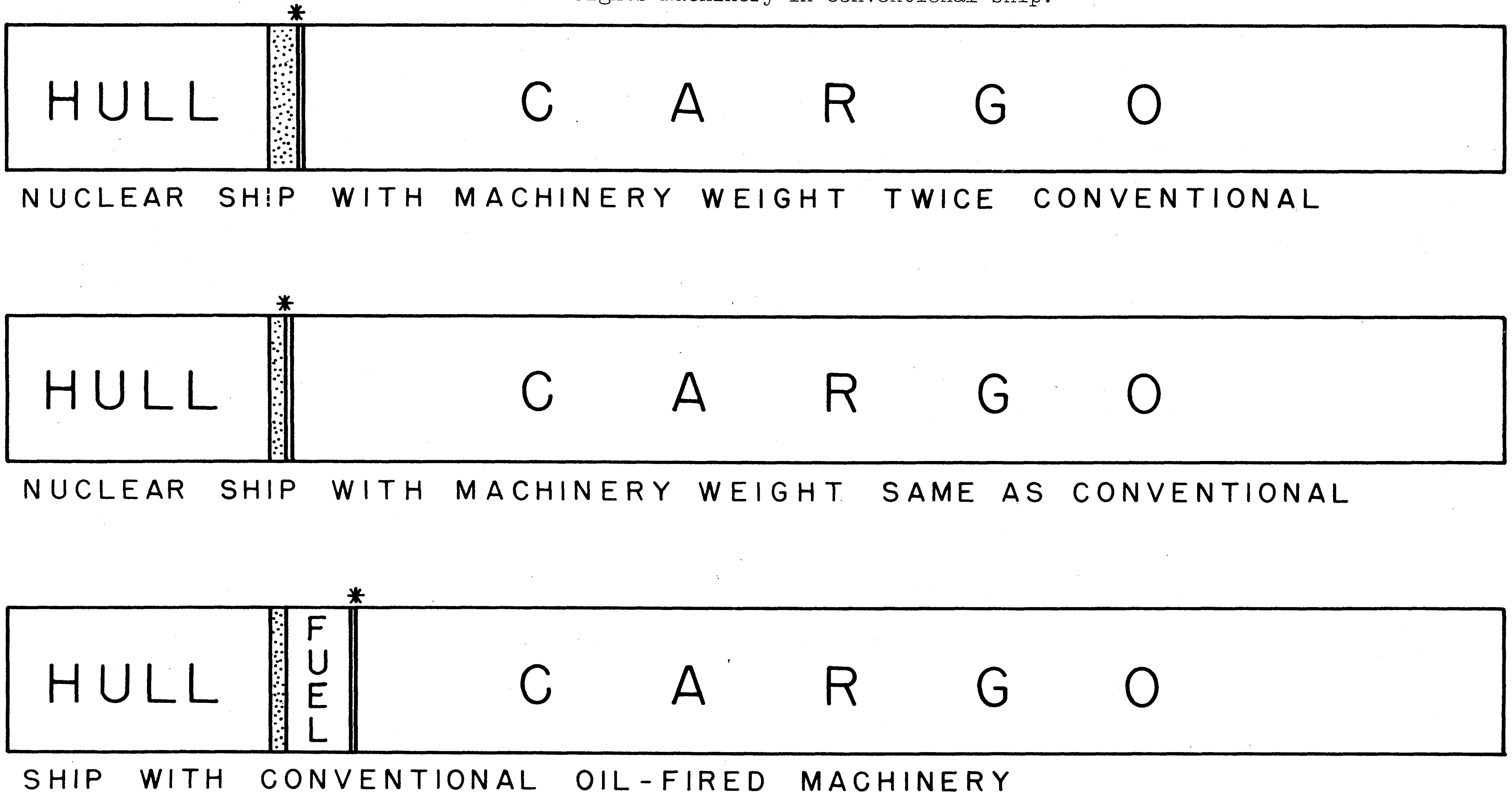
If we assume that cargo oil could be used for liquid shielding, it seems safe to assume that a range of machinery weights from one to two times that of conventional should suffice for these investigations. Figure 2 shows the minor part machinery weights play in the overall picture when large tankers are under consideration.

It seems probable that, in general, relative weights will tend to decrease as horsepower is increased.

4. General Arrangements

Many naval architects favor isolation of the reactor in a special compartment in what would be the aftermost centerline cargo hold in a conventional tanker. The cargo volume so lost can be partially regained by utilizing the space formerly given over to bunkers and settlers. Minor adjustments in hull length or depth may be required to satisfy the usual requirement of hold volume sufficient to accommodate full cargo weight in light gravity oils. Other minor modifications may be required to insure even keel trim in the full-and-down condition.

Shows relative unimportance of machinery weight in very large tankers.
Note how fuel outweights machinery in conventional ship.



WEIGHT DISTRIBUTION, 80,000 DWT TANKERS

PROPULSION MACHINERY : ▨
STORES, WATER & CREW : *
(BASED ON 20,000 SHP & 12,000 MILE ONE-WAY VOYAGE)

Figure 2.

It is doubtful if any significant increase in hull weights would result from these changes, however.

Twin reactors are not thought to be economically feasible within the assumed range of powers, and are therefore not dealt with here, only single reactors being considered. Advocates of twin reactors base their arguments on the safety margin provided by duplicate facilities. They are undoubtedly influenced by years of association with normal steam plants where twin boilers are the general rule. Experience with single boiler installations has been entirely satisfactory on a number of Great Lakes ore carriers, however. Further, nuclear engineers seem quite unanimous in their confidence that reactors will (because of stricter requirements) prove more reliable than either boilers or diesel engines. Twin reactors in a large high speed passenger ships should not be overlooked, however.

5. Take-Home Power

The first few commercial nuclear ships will probably provide a small emergency take-home plant of some sort. This paper is not concerned with the pioneer ships since no one expects them to be strictly commercially successful. If nuclear power is to be come competitive it must prove its dependability to the extent that take-home power will be considered unnecessary. It is therefore the assumption of this study that no such auxiliary power will be installed in nuclear ships--beyond the first few experimental installations. It may, of course, prove practical to arrange for emergency power, without any great increase in cost, utilizing start-up diesels - if such are called for in the reactor design.

D. CONSTRUCTION COSTS

1. General

The cost figures of Reference 4 are based on late 1955-early 1956 dollar values. The Suez crisis has pushed shipbuilding costs up ten to fifteen percent since that time. This paper is aimed at conditions ten years hence. We have no way of predicting shipyard dollar values in 1967-1968. If the relative costs of material and shipyard labor remain the same, the values given in the reference will yield valid comparisons. For want of anything better, this study makes use of the figures given in Reference 4 as a basis for computing shipbuilding costs. Direct comparison can therefore be made with conventional ship economics worked out in the earlier paper.

2. Hull Costs

There is little reason to expect that nuclear power will have any significant effect on steel hull, outfitting and hull engineering costs. The elimination of the boiler flat and possibly certain cofferdams will off-set the cost of foundation structure required to support the heavy shielding. The shielding itself is considered here as machinery weight.

3. Machinery Costs

As pointed out in the Introduction, the probable cost of nuclear machinery is a hotly debated question. This paper does not intend to take issue in the argument but will simply present nuclear machinery cost as one of the primary variables and try to show its bearing on allowable fuel costs. Its value will be given in terms of its ratio to the cost of conventional plants. Ratios from one to five are considered. A cost ratio of five would, in all likelihood, place nuclear ship propulsion well beyond the limits of competition so there is little cause for investigating higher values.

Machinery costs, as understood here, include the complete propulsion plant. This encompasses the boilers or reactor, shielding, propulsion machinery, gears, shafting, propellers, necessary auxiliaries, piping, liquids, spare parts, machinery space wiring, ladders and gratings, controls and instruments, all installed and tested.

As was the case with machinery weights, it seems likely that low cost ratios will be easier to attain as power capacities are increased.

Figure 3 may be used to estimate conventional machinery costs.

Figure 4 compares conventional machinery costs with known land-based power reactor costs. These indicate a present day differential of at least two to one. Costs are from References 5 and 14.

The principal causes for higher costs of nuclear machinery may be summarized as follows:

a. Ignorance--This factor will be much diminished within ten years, particularly with the cooperation of federal authorities in releasing technical information.

b. Navy influence--Military designers lack the commerical incentives which are of such prime importance in merchant ship design. The merchant marine will probably have to go its own nuclear way if it wishes to make significant economic progress.

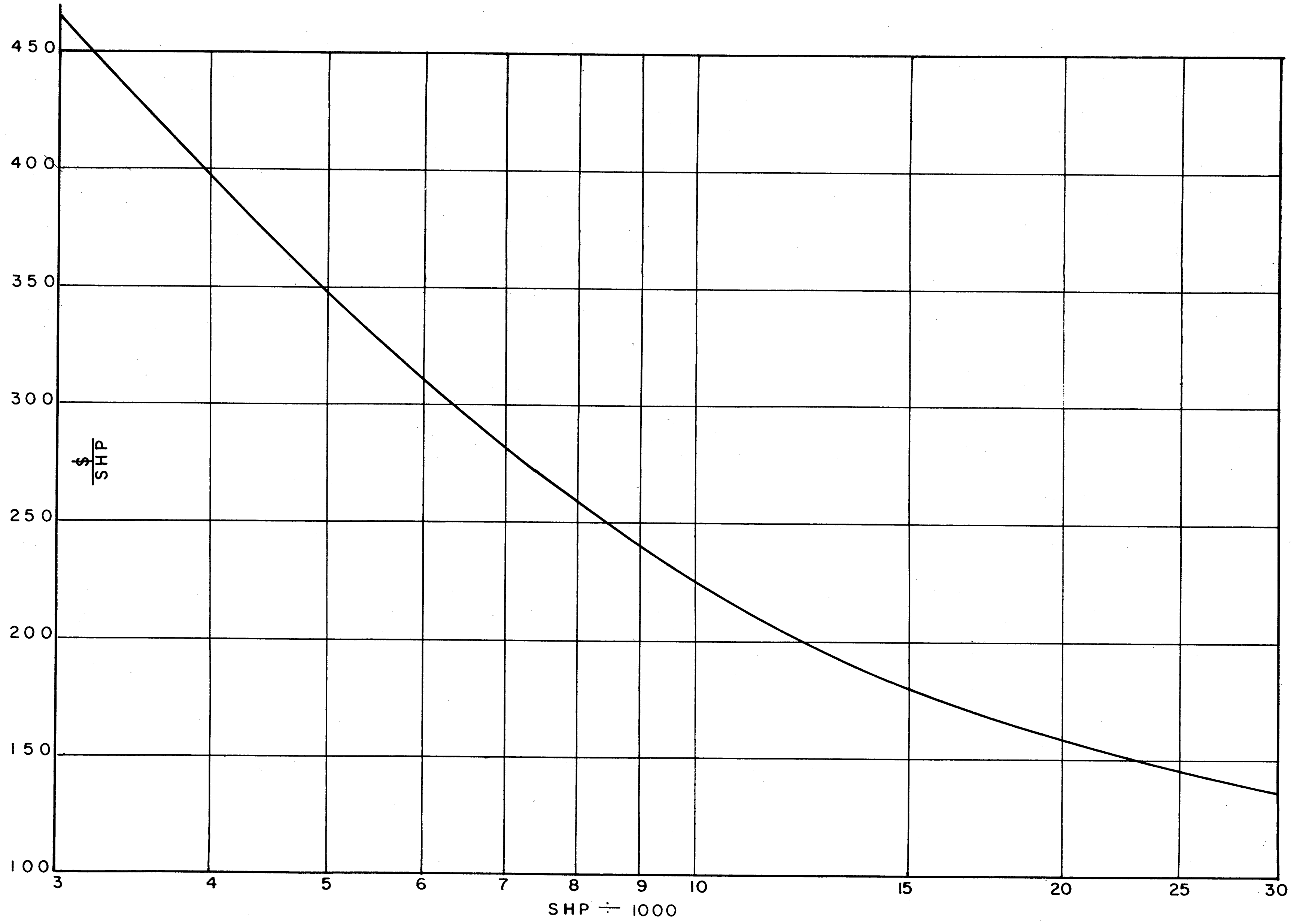


Figure 3. Capital Costs of Conventional Machinery

This figure applies to single-screw geared steam turbine, water tube boiler, installations. Complete engine room costs are covered. 1955-56 dollar values are assumed. Labor is taken at $2.30 per hour, overhead at 75% and profit at 7½%

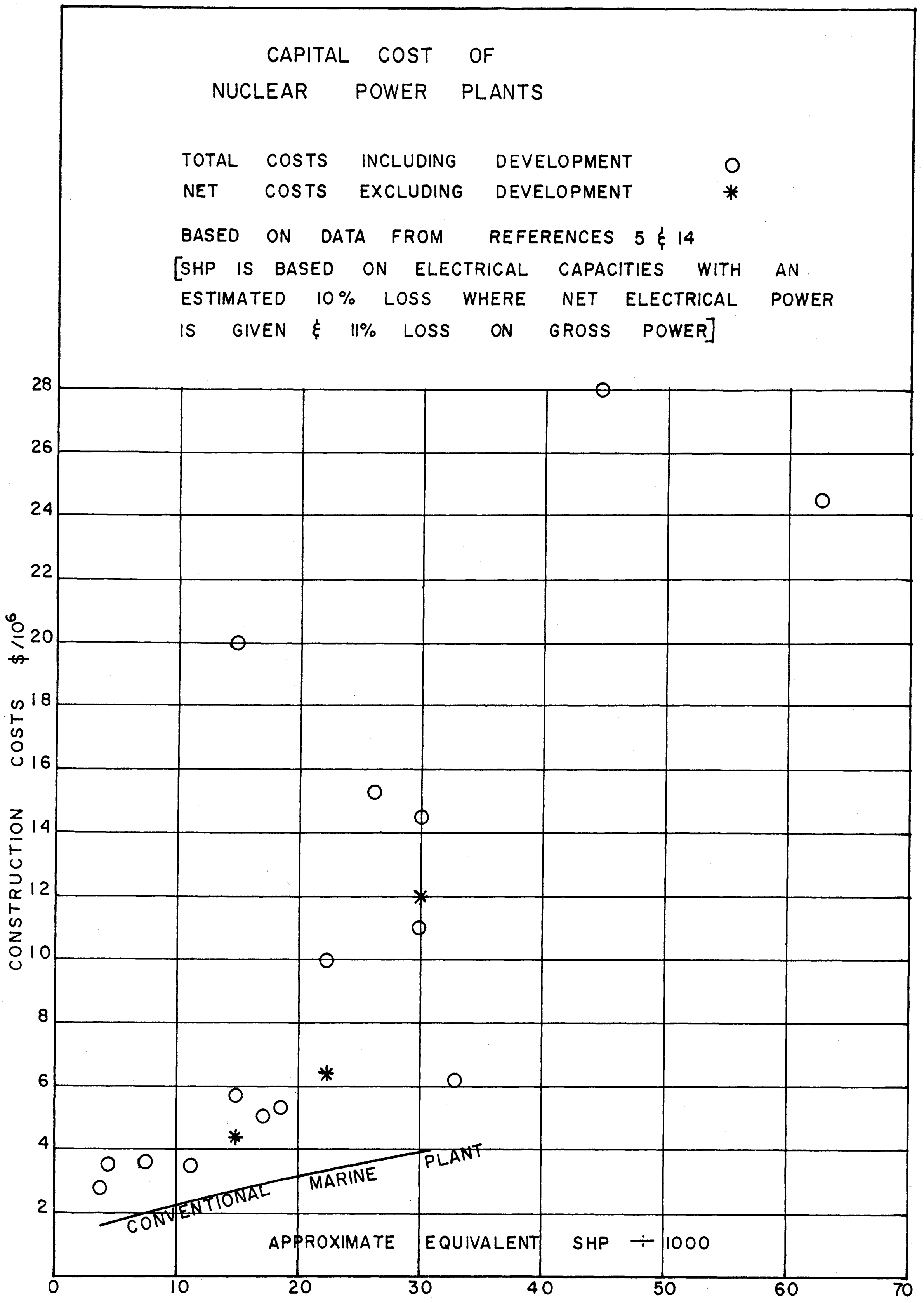


Figure 4. Capital Costs of Nuclear Power Plants

SHP is based on electrical capacities with an estimated 10% loss where net electrical power was given and 11% loss on gross power.

c. Weight--More material means more cost although a large share of nuclear machinery weight may be in relatively cheap shielding.

d. Space--Minimization of shielding dictates small component clearances with consequent large number of man-hours for installation.

e. Cleanliness--Extreme care is required to prevent contamination of many of the nuclear components.

f. Unusual materials and parts--This factor should diminish considerably within the next ten years.

g. Severe safety requirements--These include precautions for the strict confinement of radio-active material, elaborate control systems, remote operations, etc. Many such expenses will continue to plague nuclear plants although significant economies will no doubt be found.

h. Engineering, research and development--These items are closely related to the first one: "Ignorance," and should fall off rapidly in future years.

E. TRADE

The Introduction points out that nuclear marine power would probably show up to best advantage in large tankers engaged in long ocean hauls. The crude oil movement from the Persian Gulf to Northern Europe or the East Coast of the United States seems to fit these specifications to a maximum degree. Reference 4 showed that 80,000 ton tankers should be economical in this trade despite the fact that their loaded draft forced them to go around the Cape of Good Hope rather than by way of Suez.

The principal portion of this paper is devoted to the economics of operating 80,000 ton tankers in the aforementioned trade, although somewhat larger deadweights have been shown to be practicable (Reference 13). The assumption is made that the return trip in ballast could be made through the Suez Canal. It is by no means certain that the Suez Canal authorities--whoever they may turn out to be--will admit nuclear vessels. These studies are based on the pious hope that they will. To assume otherwise would place the nuclear ship at a serious--albeit hypothetical--disadvantage. This would destroy the generality of any conclusions reached relative to comparative economics.

Two basic ships, built and operated under different conditions, are considered:

a. Built in the United States and operated under U.S. flag.

b. Built abroad and operated under foreign flag (European wages).

In each case, the nuclear economics are compared with conventionally-powered ships under similar conditions of construction and operation.

For further interest, a shorter voyage of 3,500 miles is investigated. This would represent the movement of crude oil from New Orleans to New York or from Aruba to Philadelphia. American construction and operation are assumed.

F. OPERATING COSTS

1. General

Until experience has been gained in commercial operation of nuclear ships, we cannot say for sure what effect the new energy source will have on the various factors which go to make up operating costs. Remembering that the aim is to predict costs ten years hence, an attempt is made to bracket these costs between reasonably optimistic and reasonably pessimistic limits. What is "reasonably" optimistic or pessimistic is, of course, a matter of opinion. The reader, if he cannot agree with those set forth in the following paragraphs, is certainly welcome to establish his own limits and to rework the calculations to suit.

As may be noted in the following discussion, considerable wordage is devoted to the larger, more contentious divisions of operating costs. The smaller items are not felt to be worth any great debate and are therefore generally dismissed in a more or less arbitrary yet, it is hoped, not too unreasonable manner.

For convenience, the items in this section are presented in the same sequence as the corresponding material in Reference 4.

2. Power and Speed

For each combination of sea route, deadweight, machinery weight ratio, machinery cost ratio and operating cost assumptions, there is an optimum speed. This must be found in order to establish the best design (speed, power, hull form) for the combination of circumstances in question. As shown in Reference 4, this is most conveniently done by taking arbitrary values of the normal shaft horsepower. A table is made and the desired factor found for each horsepower. Optimum values are then arrived at by means of curve plotting.

Horsepowers range from 10,000 to 30,000, the former figure being used only as an aid in fairing curves. For purposes of these computations, nuclear plants are assumed to have a lower commercial limit of 15,000 shaft horsepower. 30,000 shaft horsepower is considered to be about the upper limit for single screw merchant ship propulsion. It is assumed that the normal installed power is utilized as much as possible while at sea.

Nominal sea speeds are assumed to be the same as those worked out in Reference 4, Figures 2 or 11.

3. Port Time

It is assumed that nuclear ships will require the same port time per round-trip as equivalent conventional ships. See Figure 26, Reference 4.

4. Canal Time

One day is allocated per one-way passage through the Suez Canal. This is the same as for a conventional ship.

5. Operating Days per Year

Optimistic: same as conventional tanker (342)

Pessimistic: one week less than conventional tanker (335)

The latter figure allows extra time for possible complications involved in refueling a nuclear vessel.

6. Variable Weights

Nuclear fuel weights are small enough to be considered as part of the machinery weight. For the optimistic view, weights of water, stores, provisions, lube oil, crew and effects are taken same as conventional. See Figure 30, Reference 4. For the pessimistic view, an increase of 20 percent is allowed.

7. Fuel Costs

Present-day nuclear fuel costs are difficult to estimate because of current "security" restrictions on the publication of reprocessing and other costs. How the picture will look ten years hence is even more of a mystery. This very important factor is therefore left as one of the basic variables in this study.

The Atomic Energy Commission has recently released the price schedule for enriched uranium (Reference 27). Figure 5 presents this information in graphic form. For comparison, if we assume 18,500 BTU per pound fuel oil costs at $2.50 per barrel and take the available heat value of U-235 at 60 million BTU per gram, the equivalent cost (in terms of U-235) would be $24 per gram, or roughly fifty percent over the figures quoted by the A.E.C. There are two ways of looking at this, however: 1) The uranium costs presented here are by no means complete. Large increments must be included for such expenses as fabrication, reprocessing, waste disposal, etc. 2) On the other hand, future developments in breeder plants will allow large reductions in current fissionable material costs.

Some idea of element fabrication costs may be gleaned from References 25 and 26.

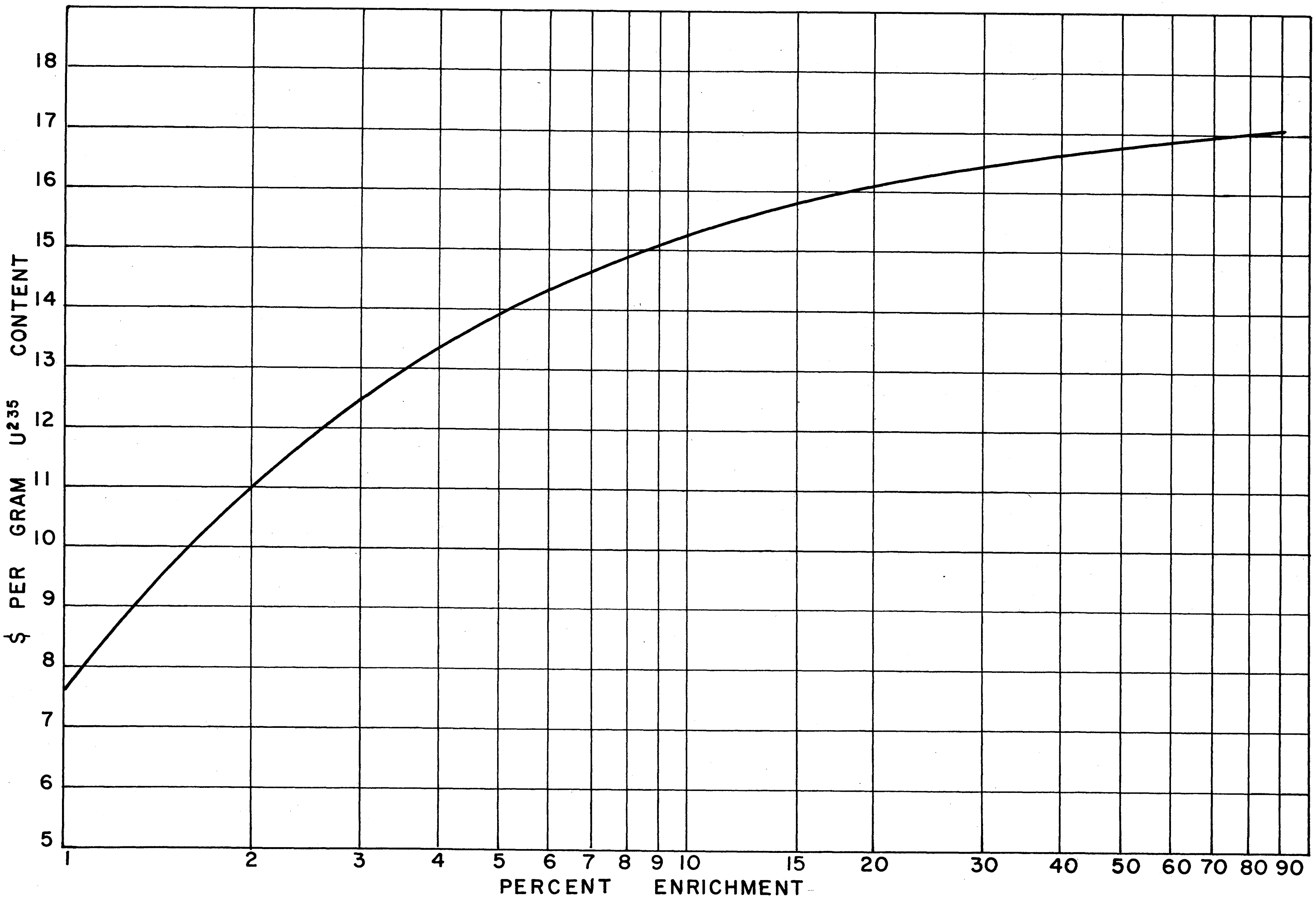


Figure 5. A.E.C. Enriched Uranium Price

(Base price, f.o.b. Oak Ridge)

With the exception of inventory charges, all remaining elements of nuclear fuel costs are difficult--if not impossible--to estimate unless you have access to classified information. It is to be hoped that the A.E.C. will see fit to release all such data in the near future. Other expenses will depend on whether developments proceed along the lines of homogeneous or heterogeneous fuel. Homogeneous fuel costs may be considerably lower than the other type, but any savings in this direction may be more than offset by higher maintenance costs, longer periods out of service, and use of heavy water.

Closely tied in with the subject of fuel costs is that of thermal efficiency. For a given shaft horsepower requirement, a highly efficient plant will require a relatively low heat output and hence a smaller consumption of fuel. Reference 12 indicates the following overall efficiencies based on shaft horsepower and heat input:

TABLE VII

Gas turbine closed cycle nuclear	32.0%
Steam turbine pressurized water nuclear	20.4%
Steam turbine oil-fired boilers	26.8%

It can be concluded from the above table that existing nuclear plants have lower thermal efficiencies than do conventional plants of equal power. Future nuclear developments, however, can be expected to overcome and possibly reverse this handicap. Whether the added first cost of an advanced plant--such as the nuclear gas turbine--can be justified on the basis of reduced fuel costs is difficult to say. (It is hoped that this paper can be applied to exactly that sort of problem). In any event, thermal efficiencies must not be overlooked in any comparative fuel-cost studies.

8. Port and Canal Fees

Optimistic· same as conventional, these being approximated:

$$\text{Port charges per round-trip} = \$1000 + \frac{\text{Deadweight}}{10}$$

Suez Canal fees (round-trip) = \$ 500 + \$0.75 Deadweight

Suez Canal fees (one-way in ballast) = \$ 250 + \$0.236 Deadweight

Pessimistic: 20% greater than normal

Note: "Deadweight" as used throughout this paper is the nominal value for a conventional tanker of equal power and displacement. The true deadweight of the nuclear tanker will be somewhat less because of greater machinery weight.

There is the distinct possibility that the normal use of certain harbors and canals will be denied to nuclear ships because of the inherent danger to surrounding ships and shore facilities in the event of collision or other accident. The 20 percent increase assumed for the pessimistic cost is based on supplemental charges which harbor authorities may see fit to apply because of the need or desire for extra safeguards.

9. Crew Wages

Optimistic: Same as conventional. See Figures 31 and 32, Reference 4.

Pessimistic: 5% greater than conventional

Some nuclear engineers feel that the automatic controls associated with reactors may allow a reduction in crew size. Any such reduction is unlikely, at least on American flag ships, because of the manning policies of our labor unions. Even granting a numerical reduction of no more than one man per watch, it seems probable that the engineering officers would command a higher wage than their counterparts on a conventional ship. This would at least partially cancel the gains achieved through reduction in numbers. The five cent increase is based on the possibility of the addition to the crew of a special nuclear engineer.

Reference 15 makes the flat statement that it is "conservatively estimated" that nuclear power will double the total wages for engineering personnel. Such an increase would add about 45% to the total crew costs. Most experts (for example, Reference 12) are in sharp disagreement with this particular claim and it is therefore discounted in this study. It is obvious that any plant so complicated as to require a doubling of the already ample operating crew has no place in the merchant marine.

10. Overhead and Miscellaneous

Optimistic: same as conventional, or:

$$\$44,500 + \$15 \frac{\text{Deadweight}}{1000}$$

Pessimistic: $10,000 per year greater than normal, or:

$$\$54,500 + \$15 \frac{\text{Deadweight}}{1000}$$

The added $10,000 is to support a shoreside nuclear engineer. The expenses (wages, office equipment, secretarial, etc.) are assumed split between two nuclear ships.

11. Maintenance and Repair

Figure 6 shows assumed correction factors to be applied to the conventional maintenance and repair costs given in Figure 33, Reference 4.

The probable cost of maintenance and repairs on nuclear ships is understandably one of the points of widest divergence of opinion. Reference 15 again "conservatively estimates" that repair costs will double on a nuclear ship although they are not clear as to whether this factor applies to the entire ship or only to the power plant. Other authorities (References 3, 10, 12, 16, and 17) imply no major differences between nuclear and conventional machinery for maintenance and repair. Some nuclear engineers feel that a reactor plant will actually cost less to maintain than boilers of equal capacity, this because of the greater precautions used in nuclear construction.

The optimistic position taken in this paper grants that nuclear plants might cost less to maintain than a conventional plant of equal size if we assume equal construction costs. Increased cost ratios would reflect in somewhat higher repair bills although how much this would be is difficult to determine. Money spent to increase the reliability of a reactor, for example, might easily reduce maintenance costs. On the other hand, money spent for fancy gadgetry would in all likelihood increase these costs. In any event, increased first costs can be expected to result in increased expenditures for replacement parts.

The optimistic correction factors shown in Figure 6 were arrived at by the following series of suppositions:

FIG. 6

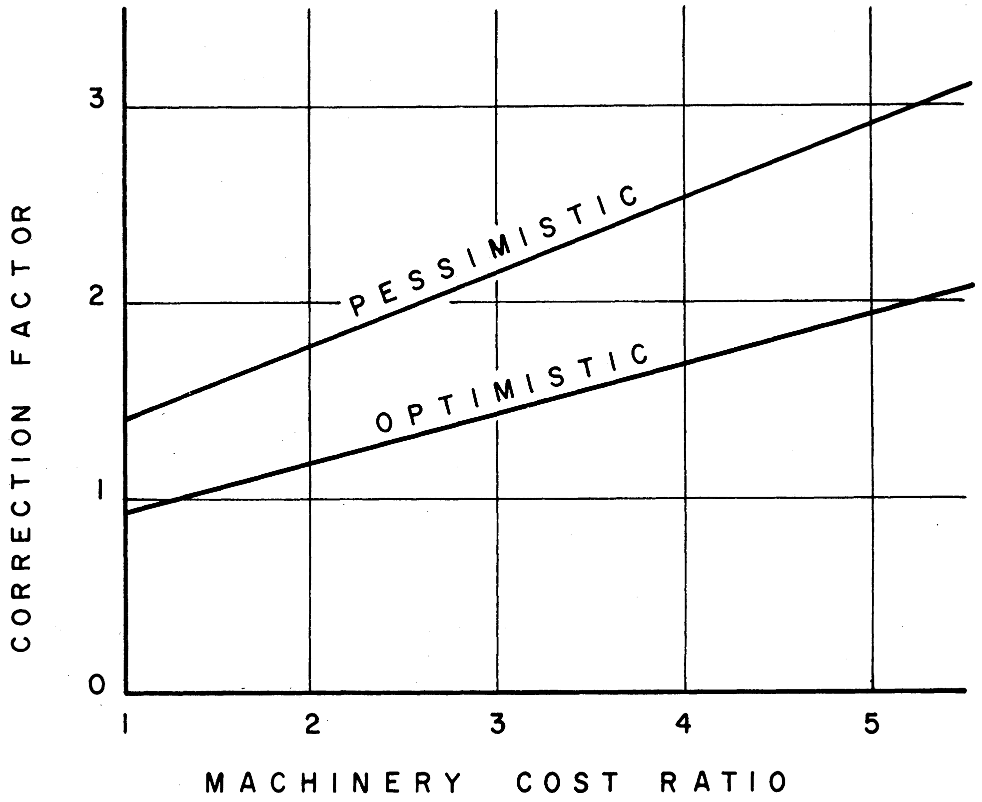


Figure 6. Correction Factors for Maintenance and Repair Costs on Nuclear Tankers

These factors are to be applied to values shown in Figure 33 of Reference 4.

a. In a conventional ship, the first cost for the boilers equals one third the total machinery cost.

b. Under the most reasonably optimistic circumstances, the maintenance and repair costs for a reactor might be as low as sixty percent of the corresponding figure on a boiler of equal cost and power.

c. In large deadweight, conventionally powered tankers, half the total cost of maintenance and repair is chargeable to dry dock, hull, outfitting, hull engineering and other items independent of the costs associated with propulsion machinery.

d. For more expensive nuclear plants, a 100 percent increase in first cost would result in a fifty percent increase in annual machinery maintenance and repair bills.

The pessimistic correction factors are arbitrarily set fifty percent higher than the ones arrived at by the optimistic approach. The fifty percent applies to the entire annual cost.

Some nuclear engineers are of the opinion that, until certain metallurgical problems are overcome, a liquified metal fuel reactor will have a useful life of five years or even less. The heat exchangers, they feel, will last between five and ten years. These rather discouraging figures are based on the realization that the highly concentrated heat source will create severe corrosion and mechanical problems. The extremely high standards required to insure against the hazards associated with fuel contamination may require the relatively brief periods of plant life mentioned above. If these gentlemen are correct in their estimates, it is safe to say that liquified metal fuel reactors can be temporarily ruled out as candidates for commercial ship propulsion.

12. Stores and Supplies

Optimistic: same as conventional tanker. See Figure 34, Reference 4.

Pessimistic: 15% greater than conventional tanker

The increase allows for somewhat greater expenses brought on by higher maintenance standards.

13. Insurance

Optimistic: same as for a conventional tanker of equal cost. See Page 64, Reference 4.

Pessimistic: 50% greater than for a conventional tanker of equal cost.

Appendix II discusses in detail the problem of estimating the cost of nuclear marine insurance. References 18 through 23 may also be consulted.

The large and important item of insurance costs is one of the most difficult to estimate for atomic ships, or for any other ship featuring radically new devices. There are, as yet, many unsettled legal points in this connection. Nuclear insurance costs will probably tend to be markedly high, at least until many existing elements of doubt have been cleared up. Whether the wheels of justice will have ground out significant decisions within the next ten years is not altogether certain. Much of what is said in Appendix II must be eyed with suspicion until a number of complicated issues are settled. It seems safe to assume, however, that the above-mentioned range of costs offers sufficient latitude for a study of this sort.

14. Subsistence Costs

Optimistic: same as conventional ship. See Page 64, Reference 4.

Pessimistic: 2% over normal.

The latter figure covers extra food required by the addition to the crew of a nuclear engineer.

15. Annual Income

For purposes of this study, the U. S. Maritime Commission flat rates are adopted as standard. Higher rates would put the nuclear plant in a slightly less favorable light whereas lower rates would have the opposite effect. See Section G-5.

The flat rates applicable to this study are as follows:

Ras Tanura to Philadelphia via Cape of Good Hope	$14.95 per ton
Aruba to Philadelphia	$ 2.70 per ton

As pointed out in Reference 4, nuclear vessels will suffer a slight penalty in draft when operating from the Persian Gulf around the Cape of Good Hope to European (other than Mediterranean) or East Coast American ports (North of Cape Hatteras). This is because these voyages require passage through the "winter zones" of either Northern or Southern Hemispheres for eleven months out of the year. Conventional ships, although loaded to summer draft, generally burn enough fuel oil after leaving the Persian Gulf to bring the hull up to the winter draft by the time they reach the "winter zone" of the Cape. Nuclear ships will lose weight only in the negligible amount of fresh water and supplies consumed; fuel weight will, of course, remain unchanged. Such vessels would, therefore, find it necessary to curtail pay load capacities most of the time. Winter freeboard is obtained by increasing summer freeboard by one quarter inch per foot of summer draft. This means that draft and cargo capacity would each be decreased about two percent. See Figure 13, Reference 4. This small difference is neglected in these studies in the interest of increasing the generalities of the conclusions.

16. Invested Cost

The invested cost is assumed to include certain owner's expenses in addition to the shipyard bill. This is taken at the same value used in Reference 4, Page 66. Two-ship contracts are assumed.

(It is interesting to study the effect that the cost reductions, effected by multiple ship contracts, have on choice of power and speed. Obviously, reductions in first cost will increase rates of return. The choice of optimum power and speed is, however, independent of any savings arising through multiple contracts. In other words, the number of ships in the contract will affect the profits but not the design.)

G. ECONOMIC ANALYSES OF COMPARATIVE FUEL AND MACHINERY COSTS

1. Introduction

The design and cost data formulated in the preceding sections can be used to make economic analyses of nuclear tankers in any desired crude oil trade. The movement of black oil from the Persian Gulf to the East Coast of the United States is investigated here because nuclear ship advocates are currently interested in that trade. Foreign competition discourages the use of American flag ships in the Persian Gulf trade, however. In order to bring a more domestic trade into the picture, a shorter voyage of 3,500 miles round trip is also investigated. This would be appropriate for vessels operating between our Gulf Ports and the East Coast, or between Aruba and Philadelphia.

2. Basic Assumptions

It is assumed that a nuclear tanker, to be economically feasible, must at least equal the capital recovery factor attainable by a conventional tanker of equal size in the same trade.

Using the methods outlined in Reference 4, the following potential rates of return can be shown to be attainable by conventional tankers in the crude oil trade:

TABLE VIII

Trade	Dead-Weight	Built	Operated	C.R.F.
Persian Gulf to East Coast via Cape of Good Hope	80,000	U.S.	U.S.	33.1%
	80,000	foreign	foreign	54.7%
3,500 mile coastwise	28,000	U.S.	U.S.	13%

The above figures are based on fuel oil costs of \$2.50 per barrel. Corporate income taxes are specifically omitted from these calculations for reasons stated in Reference 4.

3. Determination of Allowable Nuclear Fuel Costs from Assumed Machinery Costs

If various nuclear machinery costs are assumed, corresponding allowable nuclear fuel costs can be derived. The method is explained below. For convenience, nuclear machinery costs are used in terms of their ratios to costs of equivalent conventional plants:

Machinery Cost Ratio (M.C.R.) = Nuclear Machinery Cost ÷ Conventional Machinery Cost

(See Appendix I for details)

Since hull costs should remain largely the same regardless of motive power, the total cost of a nuclear ship can be expressed as follows:

Invested Cost = Conventional Hull Cost + M.C.R. x [Conventional Machinery Cost]

Remembering the basic intention that the nuclear ship should show a rate of return equal to that of a conventional ship, and assuming equal useful lives, we can say:

$$[\text{C.R.F.}]_{\text{Nuclear}} = [\text{C.R.F.}]_{\text{Conventional}}$$

By definition:

C.R.F. = Annual Profit ÷ Invested Cost

or:

Annual Profit = C.R.F. x Invested Cost

but

Annual Profit also = Income - Operating Expenses - Fuel Costs

Thus:

Fuel Costs = Income - Operating Expenses - Profit

[Income, fuel costs, etc. are all on an annual basis]

For convenience, the fuel costs so arrived at are related to the annual fuel costs on the corresponding conventional ship:

Fuel Cost Ratio = F.C.R. = Allowable Annual Nuclear Fuel Cost ÷ Conventional Ship Fuel Oil Costs at $2.50 per barrel

Nuclear fuel costs must be taken to include all expenses associated with the use of such fuels. These include, for example: fissionable material, fabrication, processing, loading and unloading, shipping, disposal of waste products and inventory charges on unused fissionable material.

Fuel cost ratios arrived at in the manner outlined above are based on relative costs for the production of a given amount of energy applied to the propeller. If the ratio is to be applied to the more basic concept of relative cost per BTU, then any differences which may exist between the conventional and nuclear thermal efficiencies must be taken into account.

Since the allowable nuclear fuel cost ratios are based on an assumed cost of Bunker-C fuel oil of $2.50 per barrel, future changes in bunker oil costs will require modification of the Fuel Cost Ratio by an amount equal to the actual cost of Bunker-C divided by $2.50.

Changes in fuel oil costs really should add a secondary correction to the fuel cost ratio. This is because of the influence of bunker oil costs on the attainable C.R.F. The studies of Reference 4 show that in a typical tanker an increase of fifty percent in the fuel costs would change the rate of return only two percentage points. It seems reasonable to neglect this factor although the reader is fully equipped to solve for the new rate of return appropriate to a change in fuel oil cost if he so desires.

With reference to the above remarks on changing fuel oil costs, please note that increases due to continuing inflation are not significant. It is only when fuel costs rise faster than the general cost index that they will have any real influence on the rate of return. Figure 25 in Reference 4 shows that fuel oil costs, when corrected for inflating dollars, have remained reasonably constant since 1940.

For the reader's convenience, Figure 7 shows the annual fuel consumption for three typical tankers. This figure can also be used as a starting point for estimating nuclear fuel costs.

4. Range of Investigation

To make the study valid, it is necessary to determine the optimum power and speed under each set of assumed conditions. In order to do this, it is further necessary to establish a number of arbitrary powers and to determine which of these will yield the lowest fuel cost ratio. This is done for the following range of conditions:

Two trades

a. Persian Gulf to East Coast: 20,500 miles (In this trade, the practical size limitation is assumed to be 80,000 tons deadweight. This is felt to be the approximate practical upper limit for single-screw propulsion. At least three twin-screw tankers, each over 100,000 tons in deadweight are currently under contract. Future trends will almost certainly lead to even greater sizes. Every advance in size and power should add slightly to the net advantage of nuclear power.)

b. Coastwise: 3,500 miles (with a deadweight capacity of 28,000 tons - set by draft restrictions in the trade)

Two assumptions relative to construction and operation:

a. Foreign built and operated

b. American built and operated

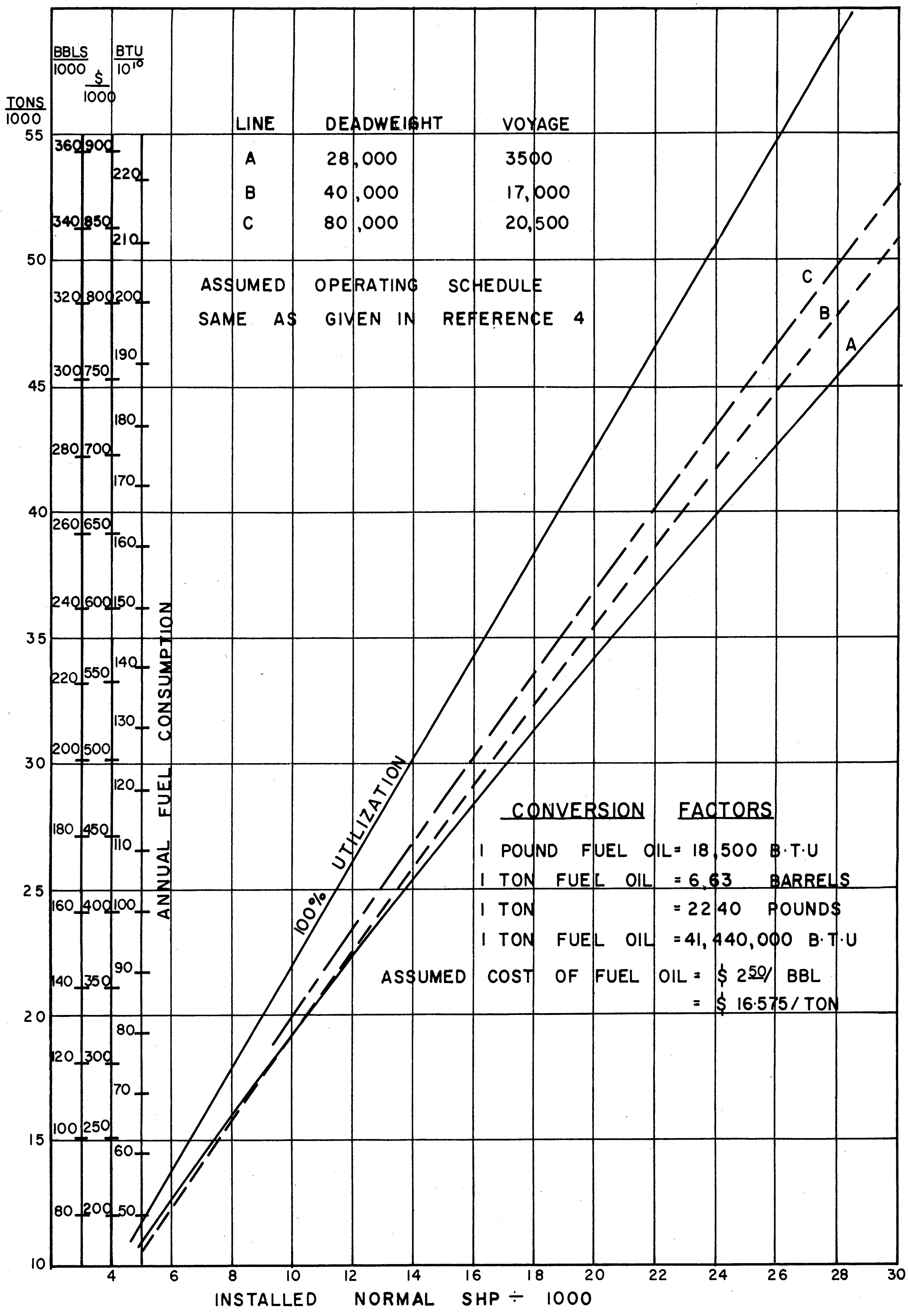


Figure 7. Annual Fuel Consumption--Conventional Tankers

Nine machinery cost ratios:

1, 1-1/2, 2, 2-1/2, 3, 3-1/2, 4, 4-1/2 and 5

Two weight ratios (relative to conventional):

a. One (same as conventional)

b. Two (double conventional)

(See Figure 8, Reference 4)

Two sets of operating cost assumptions:

a. Optimistic

b. Pessimistic

(See Section F)

Five normal shaft horsepowers:

10,000, 15,000, 20,000, 25,000, and 30,000

In addition, certain studies of intermediate conditions are required to establish trends. Further, to aid in setting minimum standards, most of the above work is repeated on the basis of a capital recovery factor of 13-1/3% corresponding to a 7-1/2 year pay-off period. In all, over 700 data points are worked out, each requiring a large number of individual steps as shown in the sample calculation (Appendix III).

5. Results and Conclusions

Figures 8 through 12 summarize the results of this study in graphic form. Individual curves of Allowable Fuel Cost Ratios, appropriate to various rates of return, are drawn for each of the assumed combinations of machinery weight and operating costs. In addition, a mean line is provided for each rate of return. The mean line represents a reasonable compromise between the estimated upper and lower limits of weight and operating costs.

Figure 8 shows the relationship between nuclear fuel costs and nuclear machinery construction costs for the following set of conditions:

Deadweight: 80,000 long tons

Route: Persian Gulf to East Coast via Cape of Good Hope,
return via Suez

Construction: U.S.

Operation: U.S.

Cargo rate: U.S.M.C. flat rate ($14.95 per ton)

The curves in the lower set are of the most interest. They are based on a rate of return equal to that attainable by conventionally powered tankers of comparable size in the same trade. These curves make it clear that nuclear machinery costs must be reduced to less than two times conventional machinery costs if atomic power is to become competitive. For example, if nuclear fuel becomes only half as expensive as bunker oil--at $2.50 per barrel--then the machinery costs are limited to about 45% over conventional.

These curves also make it clear that weight-saving is a relatively unimportant factor in the economic picture. As an example, a twenty percent reduction in machinery weight will allow an increase in machinery cost of only two percent. This indicates that concrete or ferrous radiation shielding should be preferable to more expensive lead.

Portions of the curve below the "Free Fuel Line" indicate the rather ridiculous circumstance of some generous party paying the shipowner to use nuclear fuel. Such a condition is unlikely to obtain unless the A.E.C. should, by some administrative error, be placed under the Department of Agriculture.

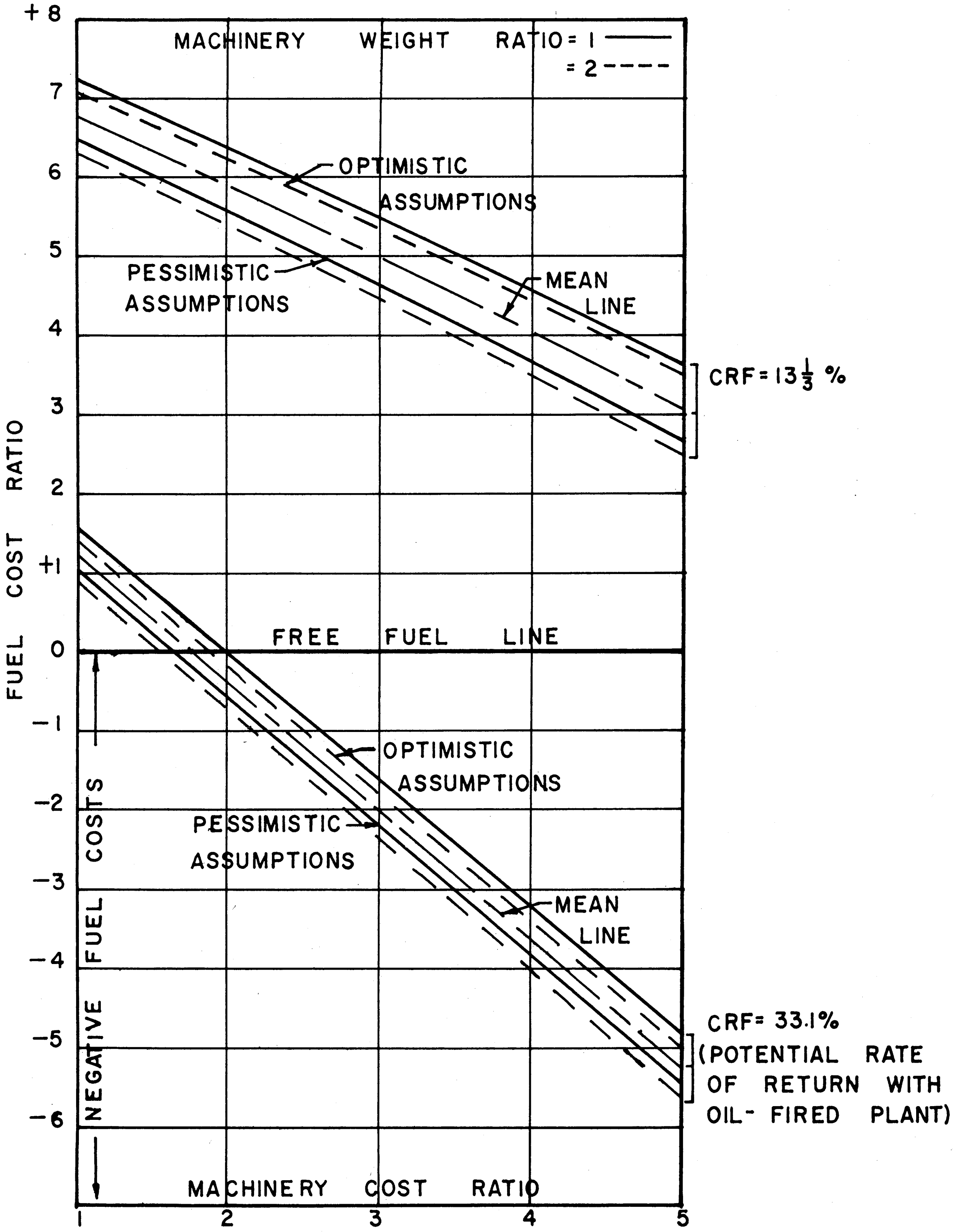


Figure 8. Fuel versus Machinery Costs--80,000 Ton American Tankers

See Appendix III for definitions of machinery and fuel cost ratios. Lower set of curves are based on equal competition with conventional ships. Upper set of curves are based on an arbitrary pay-off period of 7-$\frac{1}{2}$ years. Income is based on U.S.M.C. flat rate.

The upper set of curves may be of interest if you want to build a nuclear tanker but are not concerned with competing with conventionally powered vessels. They are based on an arbitrary capital recovery factor of 13-1/3% corresponding to a reasonable-enough pay-off period of 7-1/2 years. These curves show that nuclear power--when applied to the proper trade--can prove a worthwhile investment even though both first cost and fuel cost remain high. For example, if nuclear machinery costs are triple conventional machinery costs, fuel costs can be as high as five times Bunker-C costs. Investing in a nuclear ship under these circumstances would, of course, be foolish since a conventional tanker would return its investment over twice as fast. Such a move could only be justified if the vessel were primarily experimental or the world's oil supply were to become suddenly exhausted.

Figure 9 was prepared to show the economic relationships which may be brought about by future reductions in cargo rates. It is probable that increasing numbers of exceptionally large tankers will be built to take advantage of the potentially high rates of return in the Persian Gulf trade. In time, free competition should cause a reduction in cargo rates. The curves in Figure 9 are based on exactly the same assumptions as those of Figure 8 except the cargo rate is taken at 45 percent below the U.S.M.C. flat rate. In a conventional tanker, this would lower the potential capital recovery factor to 13.2 percent and that figure forms the basis for the curves in Figure 9.

Comparing Figures 8 and 9, we can see that lowered cargo rates will benefit nuclear propulsion somewhat, at machinery cost ratios above 1.25. The reason for this is that lowering the required

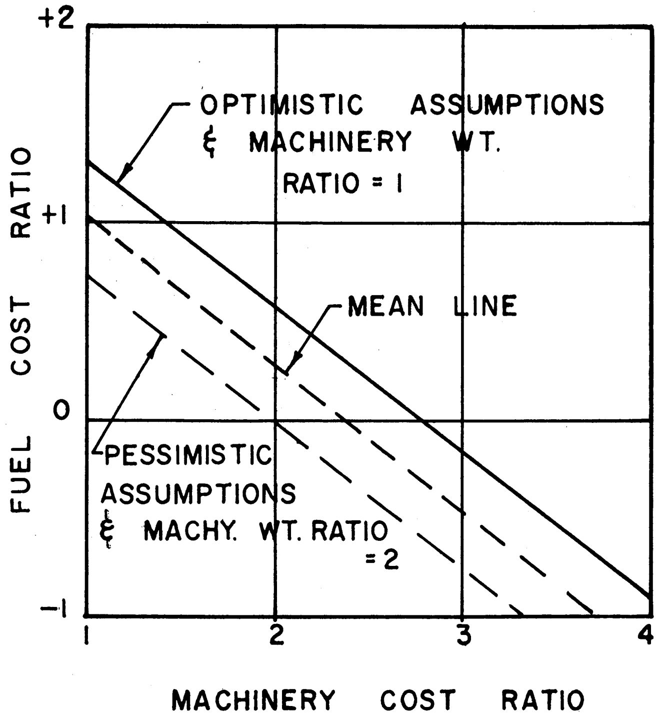


Figure 9. Fuel versus Machinery Costs--80,000 Ton American Tankers - Based on Reduced Cargo Rates

Same as Figure 7 except income is based on cargo rate of U.S.M.C. minus 45%.

rate of return, makes the allowable fuel costs less sensitive to increases in machinery cost.

Figure 10 is basically the same as Figure 8 except that building and operating costs are taken at foreign--rather than U.S.--levels. The curves in the lower set are based on a capital recovery factor of 54.7%, attainable with foreign costs. This compares with 33.1% attainable with U.S. costs. A comparison of the lower set of curves in Figures 8 and 10 indicates very little real difference between the fuel and construction cost relationships. What little difference there is favors the American vessels at the higher machinery cost ratios. This does not mean that nuclear tankers should be American-built and operated. It simply means that if we want a nuclear tanker to be American-built and operated we are going to have to be satisfied with a lower rate of return on our investment and can therefore accept higher machinery costs with any given saving in fuel cost. Since nuclear machinery costs are largely a function of the man-hours involved, it seems reasonable to suppose that current differentials in U.S. and foreign costs (as exemplified by shipbuilding) will still be largely in evidence ten years from now.

The upper curves in Figure 10 are based on a capital recovery factor of 13-1/3%--as was the corresponding set in Figure 8. Comparing the two figures, we can see that--for a given rate of return and machinery cost ratio--foreign ships can afford to pay more for nuclear fuel. For example, assuming nuclear machinery to cost three times as much conventional, the allowable fuel costs are as follows:

U.S. built and operated: 5.0
Foreign built and operated: 7.7
7.7 ÷ 5.0 = 1.54

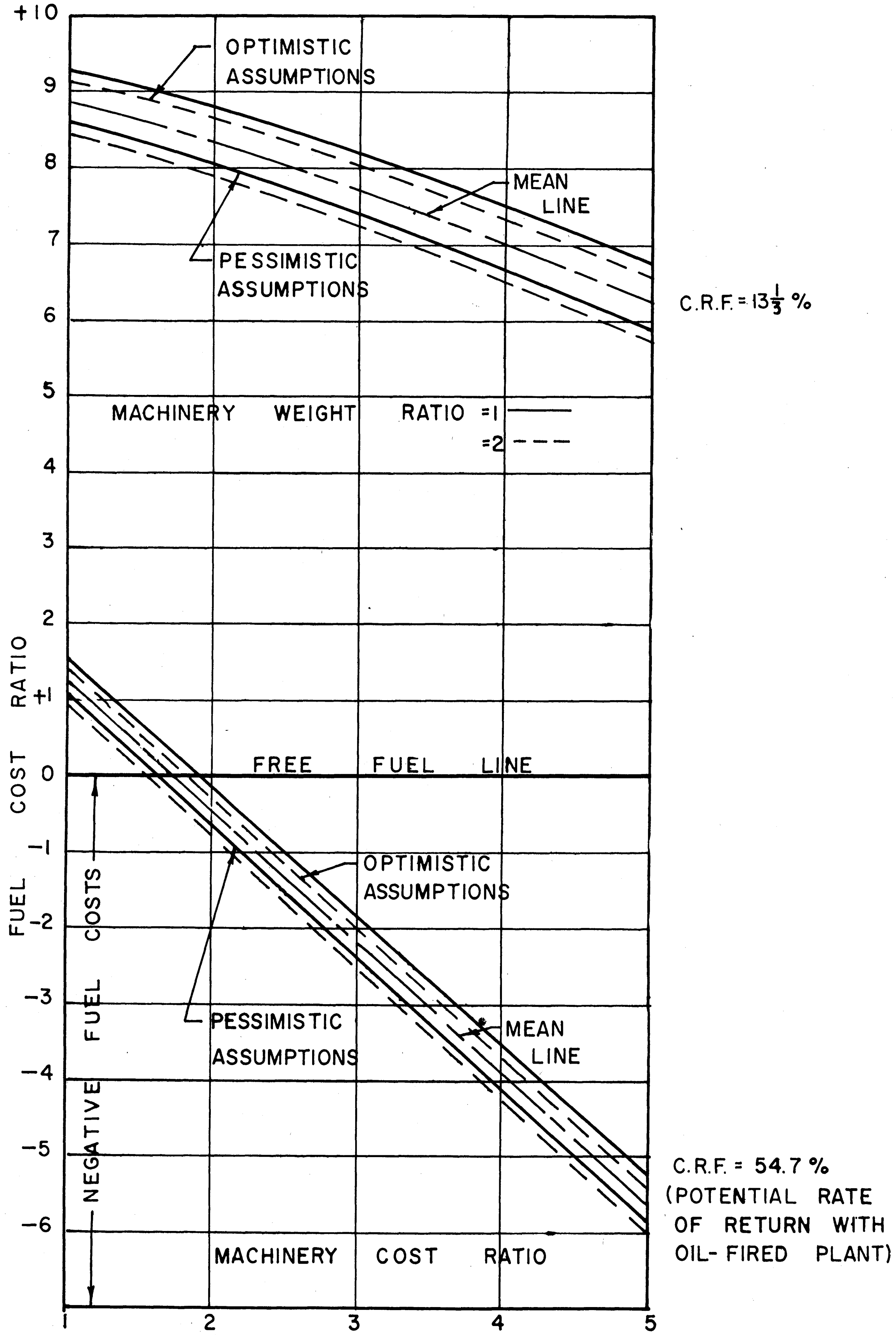


Figure 10. Fuel versus Machinery Costs--80,000 Ton Foreign Tankers

Same as Figure 7 except foreign costs are assumed for construction and operation

In other words, our foreign competitors could match us commercially even though their nuclear fuel costs were more than fifty percent above ours. Such a differential is, of course, not to be expected.

Figure 11 was derived from the mean lines of Figures 8 and 10. It may be used to estimate the potential earning capacity for any combination of fuel and machinery costs. It applies only to 80,000 ton tankers in the Persian Gulf to East Coast trade. The advantage of foreign operation is quite apparent from the relative position of the lines representing American and foreign construction and operation.

Figure 12 is generally similar to Figure 8, except that a 3,500 mile round-trip voyage is assumed. American construction and operation are also assumed. Practical considerations dictate a smaller tanker than that previously used. A lower capital recovery factor is also appropriate, a value of 13% being the estimated potential figure for a conventional vessel.

A study of Figures 8, 9 and 12 indicates that, as expected, nuclear power looks less favorable in the combination of smaller ship and shorter voyage.

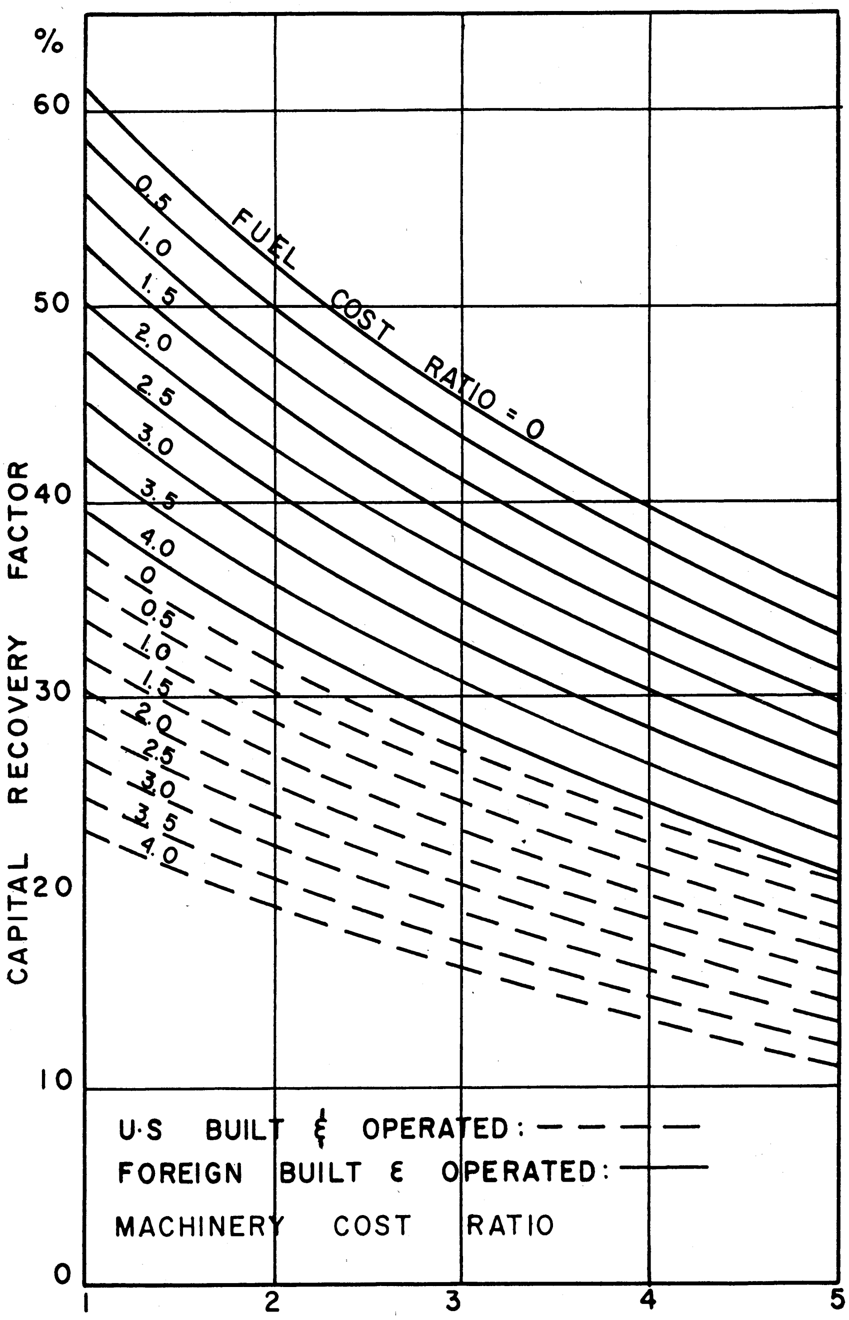


Figure 11. Potential Earning Capacities--80,000 Ton Tankers in the Persian Gulf Trade

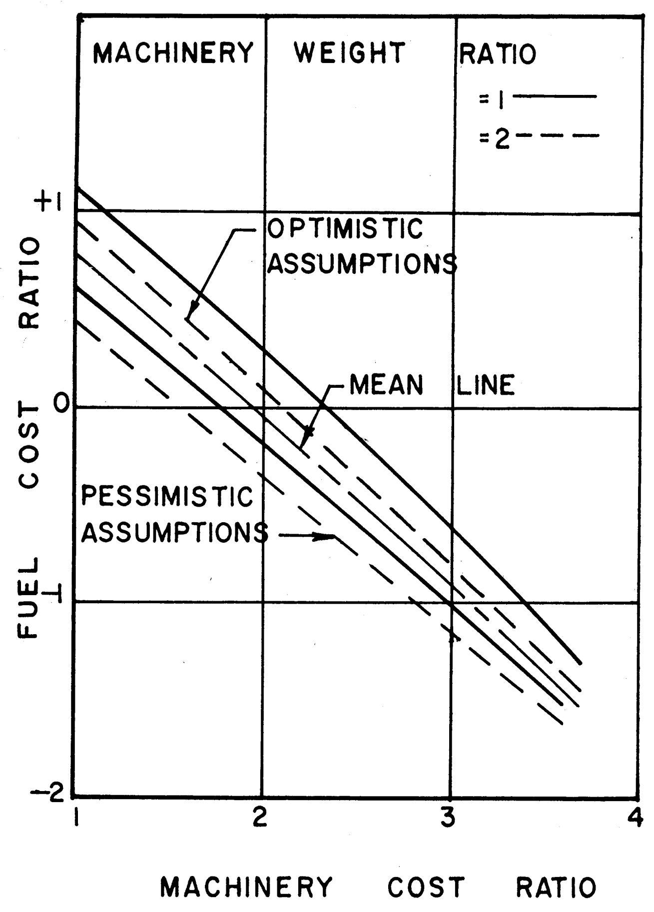


Figure 12. Fuel versus Machinery Costs--28,000 Ton American Tankers

Same as Figure 7 except smaller size and short voyage are assumed. Appropriate for coastwise tankers.

H. METHOD FOR DETERMINATION OF OPTIMUM POWER AND SPEED

An engineer can establish the best speed and power for his nuclear ship if he has what is to him, at least, a dependable set of cost figures suitable for a nuclear ship. The table which follows is based on a purely hypothetical set of conditions and will illustrate the method. The final figures from the table are shown in Figure 13 which is used for graphic solution of the optimum conditions. These turn out to be:

Optimum SHP: 22,700
Corresponding speed: 16.5 knots
Potential C.R.F.: 32.1%

Determination of Optimum Speed

Hypothetical Conditions:

a. Nominal deadweight: 80,000 long tons

b. Voyage: Persian Gulf to East Coast via Cape of Good Hope loaded, return via Suez Canal (20,500 miles round-trip).

c. Cargo rate: U.S.M.C. flat rate ($14.95 per ton)

d. Nuclear machinery costs: 1.5 times conventional

e. Nuclear fuel costs:

Fissionable material
Cladding
Fabrication
Reprocessing
Transportation
Waste disposal
Inventory charges
Miscellaneous

$25 per gram
(arbitrary price)

Reloading: $5,000 per year

f. Nuclear machinery weight: double conventional

g. Weight of stores, water, and crew: same as conventional

h. Operating costs and conditions: "optimistic" as defined in earlier section (about same as for conventional tanker of equal size and power)

i. Construction and operation: American

j. Thermal efficiency: same as conventional

Notes:

Weights are in long tons

Costs are in \$ ÷ 1000

Heat value of U-235 taken as 75×10^6 BTU per gram

LINE	ITEM & NOTES					
GENERAL:						
1.	SHP (NORMAL) ARBITRARY VALUE	10,000	15,000	20,000	25,000	30,000
2.*	DEADWT. COEFF., REF. 4, FIG. 10	0.8173	0.8156	0.8140	0.8123	0.8105
3.	DISPLACEMENT - 80,000 ÷ LINE 2	97,880	98,081	98,283	98,486	98,690
WEIGHTS:						
4.*	MACHY. LBS PER SHP, REF. 4, FIG. 8	168	136	118	107	100
5.	MACHY. WT., LINE 4 x SHP ÷ 2240	750	911	1,054	1,194	1,339
6.	MACHY. WT., 2 x LINE 5	1,500	1,822	2,108	2,388	2,678
7.	ACTUAL DEADWT., 80,000 + LINE 5 - LINE 6	79,250	79,089	78,946	78,806	78,661
8.	STORES, WATER & CREW, REF. 4, FIG. 30	225	235	245	255	265
9.	CARGO PER ROUND TRIP, LINE 7 - LINE 8	79,025	78,854	78,701	78,551	78,396
SCHEDULE:						
10.	SEA SPEED, REF. 4, FIG. 11	12.83	14.59	15.90	16.93	17.81
11.	SEA DAYS PER R.T. - 20,500 ÷ (24 x LINE 10)	66.58	58.54	53.72	50.45	47.96
12.	PORT DAYS PER R.T., REF. 4, FIG. 26	5.66	5.66	5.66	5.66	5.66
13.	CANAL DAYS PER R.T.	1.00	1.00	1.00	1.00	1.00
14.	TOTAL DAYS PER R.T.	73.24	65.20	60.38	57.11	54.62
15.	R.T. PER YR., 342 ÷ LINE 14	4.670	5.245	5.664	5.988	6.261
INVESTMENT - CONVENTIONAL SHIP ($ ÷ 1000):						
16.	$ PER TON DWT., REF. 4, FIG. 19	173	180	187	193	198.5
17.	SHIPYD BILL, ONE SHIP - 80,000 x LINE 16	13,840	14,400	14,960	15,440	15,880
18.	UNIT MACHY COST, FIG. 3	226	180	158	145	136
19.	TOTAL MACHY COST, SHP x LINE 18	2,260	2,700	3,160	3,625	4,080
INVESTMENT - NUCLEAR SHIP:						
20.	MACHY COST - 1.5 x LINE 19	3,390	4,050	4,740	5437.5	6,120
21.	SHIPYD BILL, ONE SHIP - LINE 17 + LINE 20 - LINE 19	14,970	15,750	16,540	17252.5	17,920
22.	INVEST. COST EACH OF 2 SHIPS	14520.9	15277.5	16043.8	16734.9	17382.4
ANNUAL INCOME						
23.	TONS CARGO - LINE 9 x LINE 15	369,046	413,589	445,762	470,363	490,837
24.	INCOME AT USMC FLAT RATE - 14.95 x LINE 23 ($ ÷ 1000)	5517.2	6183.2	6664.1	7031.9	7338.0
ANNUAL FUEL CONSUMPTION - IN B.T.U. x 10^{-10}:						
25.	B.T.U. AT SEA PER R.T.					
26.	B.T.U. IN PORT PER R.T.					
27.	B.T.U. FOR CANAL PER R.T.	IN THIS CASE THE TOTAL BUT'S CAN BE TAKEN FROM FIG. 7.				
28.	SUB-TOTAL	IN GENERAL, FIGURES 27 & 29 OF REF. 4 CAN BE USED.				
29.	PRODUCTIVE BTU PER YR.	1 TON FUEL OIL = 41,440,000 BTU. CORRECT FOR DIFFERENCE				
30.	BTU FOR IDLE STATUS	IN THERMAL EFFICIENCY.				
31.	TOTAL BTU PER YR.	82.8	118.1	152.5	18186.3	219.7
ANNUAL NUCLEAR FUEL COSTS ($ ÷ 1000):						
32.	GRAMS U-235, LINE 31 ÷ (75 x 10^6)	11,040	15,750	20,330	24,840	29,290
33.	VARIABLE COSTS, 25 x LINE 32 @ $25 PER GRAM	276.0	393.7	508.2	621.0	732.2
34.	TOTAL FUEL COST, $5000 + LINE 33	281.0	398.7	513.2	626.0	737.2
PORT & CANAL PER ROUND TRIP ($ ÷ 1000):						
35.	CHARGE PER R.T., REF. 4, PAGE 58	27.9	27.9	27.9	27.9	27.9
OPERATING COSTS ($ ÷ 1000):						
36.	CREW WAGES, REF. 4, FIG. 31	382.6	388.9	393.0	396.7	399.9
37.	O.H. & MISC., REF. 4, PAGE 60	45.7	45.7	45.7	45.7	45.7
38.	MAINT. & REPAIR, FIG. 5	152.6	158.8	164.8	169.8	175.0
39.	STORES & SUPPLIES, REF. 4, FIG. 34	23.6	25.2	26.4	27.5	28.6
40.	INSURANCE, REF. 4, PAGE 64	179.3	188.3	197.5	205.8	213.6
41.	SUBSISTENCE, 0.094 x LINE 36	36.0	36.6	36.9	37.3	37.6
42.	PORT & CANAL, LINE 35 x LINE 15	130.3	146.3	158.0	167.1	174.7
43.	TOTAL OP. COSTS EXCL. FUEL	950.1	989.8	1022.3	1049.9	1075.1
44.	TOTAL OP. COSTS INCL. FUEL	1231.1	1388.5	1535.5	1675.9	1812.3
ANNUAL PROFIT ($ ÷ 1000):						
45.	ANNUAL PROFIT, LINE 24 - LINE 44	4286.1	4794.7	5128.6	5356.0	5525.7
RETURN ON INVESTMENT - %:						
46.	C.R.F., LINE 45 ÷ LINE 22	29.52	31.38	31.97	32.00	31.79

* BASED ON CONVENTIONAL TANKER

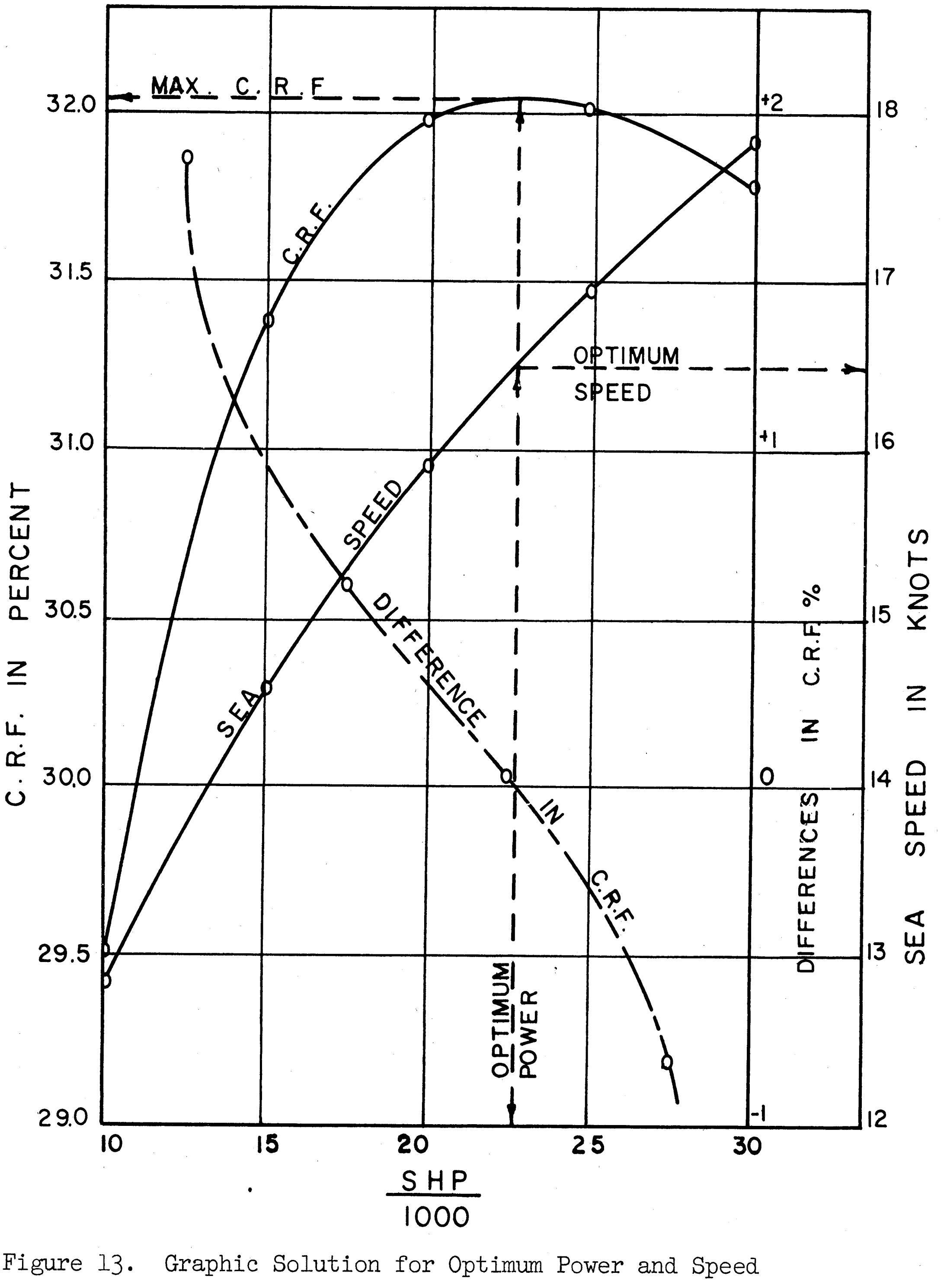


Figure 13. Graphic Solution for Optimum Power and Speed

Shows how to find the speed which will give the maximum economic benefit. Used in conjunction with accompanying tabular calculation

APPENDIX I

Definitions

Fuel Cost Ratio	Total annual cost of nuclear fuel (including handling, processing, fabrication, etc.) divided by annual fuel cost for a comparable conventional vessel with Bunker-C priced at \$2.50 per barrel. Ratio considers any differences in thermal efficiency as well as in costs per unit of heat.
Machinery Cost Ratio	Installed cost of complete nuclear propulsion plant (including everything from reactor to propeller and all auxiliaries) divided by installed cost of conventional plant of equal shaft horsepower.
Conventional Power Conventional Plant	Single screw, geared steam turbine, two oil-fired watertube boilers. Steam conditions average modern practice for installed SHP.
Conventional Tanker	Twin bulkheads, largely welded construction, conventional plant. See Reference 4.

APPENDIX II

Insurance Cost Considerations

Most ship owners purchase insurance policies in order to protect themselves against financial loss resulting from circumstances beyond their normal expectations or control.

The cost of insurance in a free market economy is primarily a function of the risk involved. The term "risk" must be taken to include not only the size of the financial liability but the estimated likelihood of the occurrence of some misadventure. The latter factor will doubtlessly result in rather high premiums for nuclear propulsion for a number of years until history can prove its safety and reliability. If we assume that the dependability of this source of power will prove to be the equal of conventional steam plants, then the underwriters should eventually be willing to sell insurance at rates comparable to those available to conventional plants. Of course one cannot say with certainty that equivalent reliability will be achieved and higher insurance rates may be required. Looking in the other direction, there is reason to believe that nuclear plants might prove to be even more reliable than steam plants. There is not much room for improvement in this respect, however, and the commercial feasibility of substantially reducing insurance rates seems doubtful.

Hull insurance can be adapted to nuclear machinery by an appropriate addition to the "Inchmaree" clause covering machinery damage.

Rates for war peril insurance would presumably be little affected by the type of machinery in the vessel.

Protective and indemnity insurance rates furnish the most provocative source of debate relative to nuclear ship insurance because of the well-publicized possibilities of extensive radioactive damage resulting from possible accidents involving such a ship. Questions of owner's liability for such damage involve many fine points of the admiralty law with variations between different nations. It is beyond the scope of this paper to deal with these in detail. Briefly, it can be said that all major maritime nations protect ship owners with what is known as "limits of liability." If a nuclear ship should suffer a catastrophe in a busy harbor damaging other ships or shore facilities or causing personal injury or loss of life, the owner may invoke limitation of liability _if_ he can establish that he provided a competent crew on a seaworthy ship and that the accident occurred without his "privity or knowledge."

The actual limits set by law amount to the value of the owner's interest in the ship plus any sums due him for the carriage of cargo on the particular voyage. Variations exist between nations as to whether these values are taken before or after the accident with consequent differences in the risk the underwriter assumes in issuing protective and indemnity insurance.

In the event of loss of life or personal injury, many nations extend the limits to an amount proportional to the gross tonnage. Under U.S. laws the figure is $60 per ton. The working of the law exempts a number of miscellaneous types including "tank vessels." This has been interpreted as applying only to harbor tankers or lighters, however, and would not benefit a sea-going tanker such as we are dealing with here.

We must assume that any owner of a nuclear ship will take cognizance of the extreme damage for which he could be held liable and will bend every effort to meet the requirements for limitation of liability. On top of this, some owners may feel it judicious to restrict operations, as much as possible, to little-frequented harbors. In any event, the cost of insurance would probably be based on the assumption that limitation of liability could be invoked and the coverage would not extend to cases where, because of negligence on the part of the owner, limitation of liability would not be allowed. In addition, Reference 18 recommends a special clause limiting the underwriters' liability.

References 19, 20, 21, 22, and 23 may also be consulted for authoritative opinions on questions of law and insurance.

In summary, there seems some reason to hope that future insurance costs on a nuclear ship may be based on the same rate as for a conventional ship. If the individual shipowner feels the need of additional coverage, he can purchase extended coverage. If, in spite of this, he feels that nuclear propulsion involves appreciable risks to himself which cannot be covered by insurance, he is faced with an intangible factor tending to increase the desired rate of return on the investment.

APPENDIX III

SAMPLE CALCULATION

DETERMINATION OF ALLOWABLE FUEL COST RATIO

VESSEL BUILT: U. S.   DWT: 80,000   COST RATIO: 4

VESSEL OPERATED: U. S.   WT. RATIO: 2

ROUTE: Persian Gulf to East Coast   R.T. DIST.: 20,500

OPERATING COSTS & SCHEDULE: Optimistic Assumptions

(WTS. ARE IN LONG TONS. COSTS ARE IN $/1000. UNLESS OTHERWISE NOTED, FIGURES REFER TO NUCLEAR POWERED VESSELS. FIGURES ARE BASED ON A 7-1/2 YEAR PAYOFF PERIOD, C.R.F. = 13.33%)

LINE	ITEM & NOTES					
x	SHP (NORMAL) - ARBITRARY VALUES	10,000	15,000	20,000	25,000	30,000
y	Δ: SAME AS CONVENTIONAL. SEE REF. 4	97,880	98,081	98,283	98,486	98,690
CONVENTIONAL SHIP COSTS:						
1	$ PER TON DWT. FIG. 19, REF. 4	173	180	187	193	198.5
2	SHIPYD BILL FOR ONE SHIP	13,840	14,400	14,960	15,440	15,880
3	CONVENTIONAL MACHY COST, FIG. 3	2,260	2,700	3,160	3,625	4,080
NUCLEAR SHIP COSTS:						
4	NUCLEAR MACHY COST - 4 x LINE 3	9,040	10,800	12,640	14,500	16,320
5	SHIPYARD BILL, ONE SHIP - LINE 2 + LINE 4 - LINE 3	20,620	22,500	24,440	26,315	28,120
6	INVESTED COST, EACH OF 2 SHIPS	20,001	21,825	23,707	25,526	27,276
7	REQUIRED ANNUAL PROFIT, 0.1333 x LINE 6	2,667	2,910	3,161	3,403	3,637
WEIGHTS:						
8	CONVENT. #/SHP MACHY, REF. 4, FIG. 8	168	136	118	107	100
9	CONVENT. MACHY WT. - LINE 8 x SHP + 2240	750	911	1,054	1,194	1,339
10	NUCLEAR MACHY WT. - 2 x LINE 9	1,500	1,822	2,108	2,388	2,678
11	NUCLEAR SHIP DWT - 80,000 + LINE 9 - LINE 10	79,250	79,089	78,946	78,806	78,661
12	STORES, WATER & CREW, REF. 4, FIG. 30	225	235	245	255	265
13	CARGO PER R.T. - LINE 11 - LINE 12	79,025	78,854	78,701	78,551	78,396
SCHEDULE:						
14	SEA SPEED, REF. 4, FIG. 11	12.83	14.59	15.9	16.93	17.81
15	SEA DAYS PER R.T. - DIST. + (24 x LINE 14)	66.58	58.54	53.72	50.45	47.96
16	PORT DAYS PER R. T., REF. 4, FIG. 26	5.66	5.66	5.66	5.66	5.66
17	CANAL DAYS PER R.T.	1.00	1.00	1.00	1.00	1.00
18	TOTAL DAYS PER R.T.	73.24	65.20	60.38	57.11	54.62
19	R.T. PER YR. - 342 + LINE 18	4.670	5.245	5.664	5.988	6.261
20	CARGO PER YR. L.T., LINE 19 x LINE 13	369,046	413,589	445,762	470,363	490,837
21	INCOME PER YR. @ USMC FLAT RATE - $14.95 x LINE 20	5517.2	6183.2	6664.1	7031.9	7338.0
OPERATING COSTS:						
22	PORT & CANAL PER R.T., REF. 4, PAGE 58	27.9	27.9	27.9	27.9	27.9
23	CREW WAGES, REF. 4, FIG. 31	382.6	388.9	393.0	396.7	399.9
24	O.H. & MISC., REF. 4, PAGE 60	45.7	45.7	45.7	45.7	45.7
25	MAINT. & REPAIR, FIG. 5	249.3	260.6	268.8	277.2	285.7
26	STORES & SUPPLIES°, REF. 4, FIG. 34	23.6	25.2	26.4	27.5	28.6
27	INSURANCE, REF. 4, PAGE 64	245.0	267.4	289.8	311.3	332.3
28	SUBSISTENCE, 0.094 x LINE 23	36.0	36.6	36.9	37.3	37.6
29	PORT & CANAL, LINE 22 x LINE 19	130.3	146.3	158.0	167.1	174.7
30	TOTAL OP. COSTS EXCL. FUEL	1112.5	1170.7	1218.6	1262.8	1304.5
SUMMARY:						
31	ALLOWABLE ANNUAL FUEL COSTS, LINE 21 - LINE 30 - LINE 7	1737.7	2102.5	2284.5	2366.1	2396.5
32	BUNKER C F.O. COSTS @ 2.50/BBL, SEE REF. 4, PAGE 54	331.1	472.4	610.0	744.9	878.2
33	RATIO: NUCL FUEL TO BUNKER C, LINE 31 + LINE 32	5.25	4.45	3.74	3.18	2.73

THE HIGHEST PERMISSIBLE NUCLEAR FUEL COST OCCURS AT 10,000 S.H.P. SINCE POWERS BELOW 15,000 S.H.P. ARE ASSUMED IMPRACTICAL FOR NUCLEAR PLANTS, THE VALUE OF 4.45 (AT 15,000 SHP) IS TAKEN AS THE BEST OBTAINABLE FOR THE SET OF CIRCUMSTANCES SPECIFIED ABOVE. THIS FIGURE IS USED AS ONE POINT ON ONE CURVE IN FIGURE 8.

REFERENCES

1. Anon. "Outlook for a Nuclear Merchant Fleet," Nucleonics, Vol. 14, No. 5, May 1956.

2. Folsom, R. G., Ohlgren, H. A., Lewis, J. G., and Weech, M. E. Nuclear Propulsion of Merchant Ships--an Engineering Summary, Engineering Research Institute, Ann Arbor, June 1955.

3. Maddocks, K., "Nuclear Power for Commercial Vessels," Transaction IMA, Vol. LXVIII, No. 5, May 1956.

4. Benford, Harry, Engineering Economy in Tanker Design, University of Michigan, Industry Program Release No. 189, Ann Arbor, Michigan, November, 1956.

5. Lane, James A., "Where Reactor Development Stands Today," Nucleonics, Vol. 14, No. 8, August 1956.

6. Lewis, W. B., "Canadian Experiments Aim at Economic Nuclear Power," Nucleonics, Vol. 14, No. 18, October 1956.

7. Anon. "Economics and Future Design," (re Calder Hall), Nucleonics, Vol. 14, No. 12, December 1956.

8. Tobias, Melvin and Clarborne, H. C., "Fuel Costs in Homogeneous Reactors are Insensitive to Nuclear Parameters," Nucleonics, Vol. 14, No. 12, December 1956.

9. Lewis, Edward V., Optimum Fullness for Deadweight Cargo Ships in Moderate Weather Services, Philadelphia Section SNAME, October 1956.

10. Crouch, Holmes F. and Fayram, R. A., An Evaluation of Nuclear-Reactor Powerplant for Mariner-Class Vessels, University of California, Berkeley, February 1955.

11. Arnott, David, Design and Construction of Steel Merchant Ships, SNAME, 1955.

12. Gibbon, R. P. and Kurz, G. H., Closed Cycle Gas Turbine Nuclear Propulsion Plants for Merchant Ships, N.Y. Metropolitan Section SNAME, January 1957.

13. Anon. "Universe Leader--the World's Largest," Marine Engineering, February 1957.

14. Anon. Nuclear Reactor Data, 2nd Edition, 1956, Raytheon Manufacturing Company, Waltham, Massachusetts.

15. Anon. "How Will Nuclear Power Affect You?" Marine Engineering-Log, June 1956.

16. Schoupp, W. F. and Witzke, R. L., "Nuclear Power for A Tanker," *The Log*, May 1955.

17. Witzke, R. L. and Haverstick, S. A., *Nuclear Power Plants for Ship Propulsion-Application*, AIEE, January 1954.

18. Stewart, A. B., *Nuclear Fission*, International Union of Marine Insurance Conference, September 1956. Reprinted in *Fairplay*, Vol. 187, October 25, 1956.

19. Bross, Steward R., *Ocean Shipping*, Cornell Maritime Press, Cambridge, Maryland, 1956.

20. Winter, William D., *Marine Insurance*, McGraw Hill Book Company Inc., New York, 1952.

21. Hinslea, Lee C., *Highlights of the Admiralty Law*, Great Lakes Section SNAME, circa 1947.

22. Robinson, Gustavus H., *Handbook of Admiralty Law in the United States*, West Publishing Company, St. Paul, Minnesota, 1939.

23. Lord, George de Forest and Sprague, George C., *Cases on the Law of Admiralty*, West Publishing Company, St. Paul, Minnesota, 1939.

24. Johnson, C. H. and Johnson, P. V., "Nuclear Power for Merchant Ships," *Marine Engineering*, January and February 1956.

25. Anon. "Reactor News; B. and W. gets ETR Fuel Contract," *Nucleonics*, November 1956.

26. Kallman, Donald, *Parametric Studies for the Estimation of Fuel Fabrication Expense*, Paper presented before 1957 Nuclear Congress, Philadelphia, Pennsylvania, March 13, 1957. Published by the Babcock and Wilcox Company, New York City.

27. Anon. "AEC Declassified Its Enriched Uranium Price Schedules," *Nucleonics*, December 1956.

SUPPLEMENTARY REFERENCES

1. Anon. "Cities Service V-P Discusses Nuclear Propulsion," Marine Engineering, March 1956.

2. Van Sicklen, F. Douglas, "Atoms for Ship Operators," The Log, August 1955.

3. Iliffe, C. E., "Nuclear Reactors for the Generation of Power," Trans. N.E.C., 1956-57.

4. Weech, Marx and Bulmer, J. J., A Peacetime Survey of Nuclear Energy from an Industrial Viewpoint, University of Michigan, Engineering College Industry Program Release No. 100, November 1954.

5. Wilson, Robert E., "Will Atomic Energy Replace Oil?" Petroleum Refiner, November 1956.

6. Crever, F. E. and Trocki, T., Nuclear Power Plants for Ship Propulsion, AIEE, January 1954.

7. Kasten, P. R. and Claiborne, H. C., "Fuel Costs in Homogeneous U-235 Burners," Nucleonics, November 1956.

8. Landis, John W., "Tables Simplify Comparison of Nuclear Power Feasibility Studies," Electrical World, November 9, 1953.

9. Godwin, Richard P., "Nuclear Powered Merchant Ship," Proceedings of the Merchant Marine Council, U. S. Coast Guard, Vol. 14, No. 3, March 1957.