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NOTES ON THE DESIGN AND OPERATION OF AUTOMATED SHIPS

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by

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Seminar on the Labour Problems Resulting from
Automation and Technological Changes on Shipboard
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ABSTRACT

In this paper I have tried to show how a ship designer may approach the problem of finding the most economical number of men to operate a proposed commercial ship. Although we are still ignorant of many cost factors, we can determine in a rough way about what the net annual saving in costs might be under various degrees of automation. A sample study illustrates the concepts discussed in the paper.

The potential gains from work rationalization are stressed. The concept of the two-watch system with equal paid time ashore is analyzed and shown to be economically sound.

PREFACE

My intent in writing this paper is to advance a general method for finding the most economical number of crew for any proposed commercial ship and to estimate the potential savings in average annual cost. Specific cost estimates are given where possible. There are, however, certain unknown cost factors that cannot be accurately analysed until more experience has been gained in the operation of automated ships.

I am using the term "automation" loosely so as to include not only sensing and control devices but also numerous less dramatic approaches to increasing the productivity of seagoing personnel, such as modified work practices (work rationalisation) and designing for reduced shipboard maintenance. I believe these less obvious methods offer at least as much potential benefit as automation per se.

I shall discuss the individual factors that will add or subtract from the cost of operating an automated ship, and then show how they may be brought together in order to find the numerically optimum crew complement in any given situation.

Where dollar costs are cited they are appropriate to U.S. conditions without reference to subsidy.

DESIGN OBJECTIVES

Before we can optimise a ship design, we must determine exactly why the ship is to be built. I think most objective observers would agree that a merchant ship is an investment that earns its returns as a socially useful instrument of transport. The best ship is the one that can provide the cheapest service to the public while returning a reasonable profit to the owner.

The foregoing concepts are admittedly slightly over-simplified. But, unless we keep our ultimate objectives clearly in mind, we are easily diverted by short-term problems. Such misdirection is all too likely when emotional issues are involved. And the very real - but essentially short-term - human problems incidental to shipboard automation are understandably sure to make people emotional. In the long run, then, any tendency to look upon a ship as a floating facility for keeping men employed will go against the welfare of both the public and the men themselves. I hope I may be forgiven for holding such nineteenth century economic views, but why keep rowing after the invention of the sail?

COST SAVINGS

Crew Wages

The average annual gross cost of wages plus fringe benefits per illet in a U.S. ship is in the neighbourhood of $12,000. This cost might be projected to perhaps $14,000 within a few years after the completion of a ship about to enter the design stage. But average costs are misleading because automation will primarily tend to displace men at the lower end of the wage scale. Thus, I would estimate the annual wage cost as follows:

$$\text{Annual wage cost} = \$30,200\ (N_c)^{0.8} \qquad (1)$$

where N_c = Number of men in the crew

See Figure 1.[1]

I believe that the wage costs for any given berth need be little affected by automation. The added technical knowledge required of officers will be offset by a reduction in supervisory duties.

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[1] Cost estimates in this paper are generally derived from Ref. 6, except as otherwise noted.

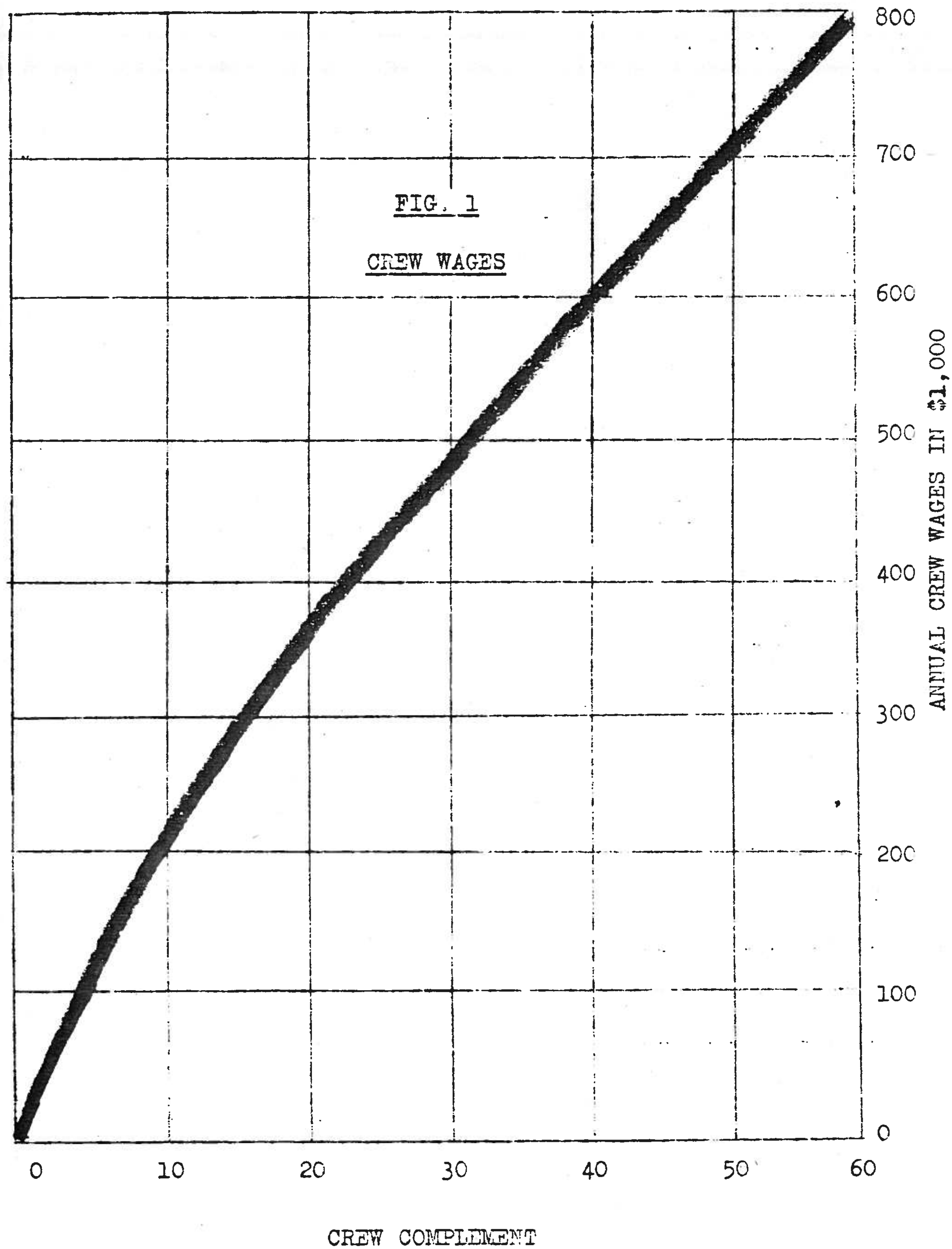


FIG. 1
CREW WAGES
800
700
600
500
400
300
200
100
0
ANNUAL CREW WAGES IN $1,000
0
10
20
30
40
50
60
CREW COMPLEMENT

Accommodation Costs

Several independent estimates of crew accommodation costs agree that the average initial cost per billet is at least \$30,000. This includes joiner bulkheads, steel deckhouses, furniture, galley and equipment, hotel service systems, and life-saving devices. But again averages are misleading. The cost of providing the accommodation for an imaginary one-man ship would be many times the added cost of accommodating the 51st member. The cost relationship is impossible to establish accurately. For an approximation, however, I recommend:

$$\text{Invested cost of accommodation} = \$180{,}000\ N_c^{0.56} \qquad (2)$$

where again

N_c = Number of men in the crew

Figure 2 shows initial cost values corresponding to equation 2. The right-hand scale converts initial costs to average annual costs using a capital recovery factor of 20 per cent. A factor of 20 per cent produces an after-tax interest rate of return of 11.5 per cent, assuming 48 per cent tax, 25-year life, straight line depreciation and all-equity capital.

Hidden Savings

Every man in the crew brings with him the need for many hidden expenses. Some of these are discussed below.

Food. The average annual cost for food supplies is about \$770 per man. The cost of food preparation is dealt with later.

Supplies. The majority of shipboard supplies (non-food) are used for shipboard maintenance. Their annual cost varies with the crew complement and can be estimated as follows:

For Crews of 50 or More

$$\text{Annual cost of stores and supplies} = \$50{,}000 + \$4{,}000(N_c - 50) \qquad (3)$$

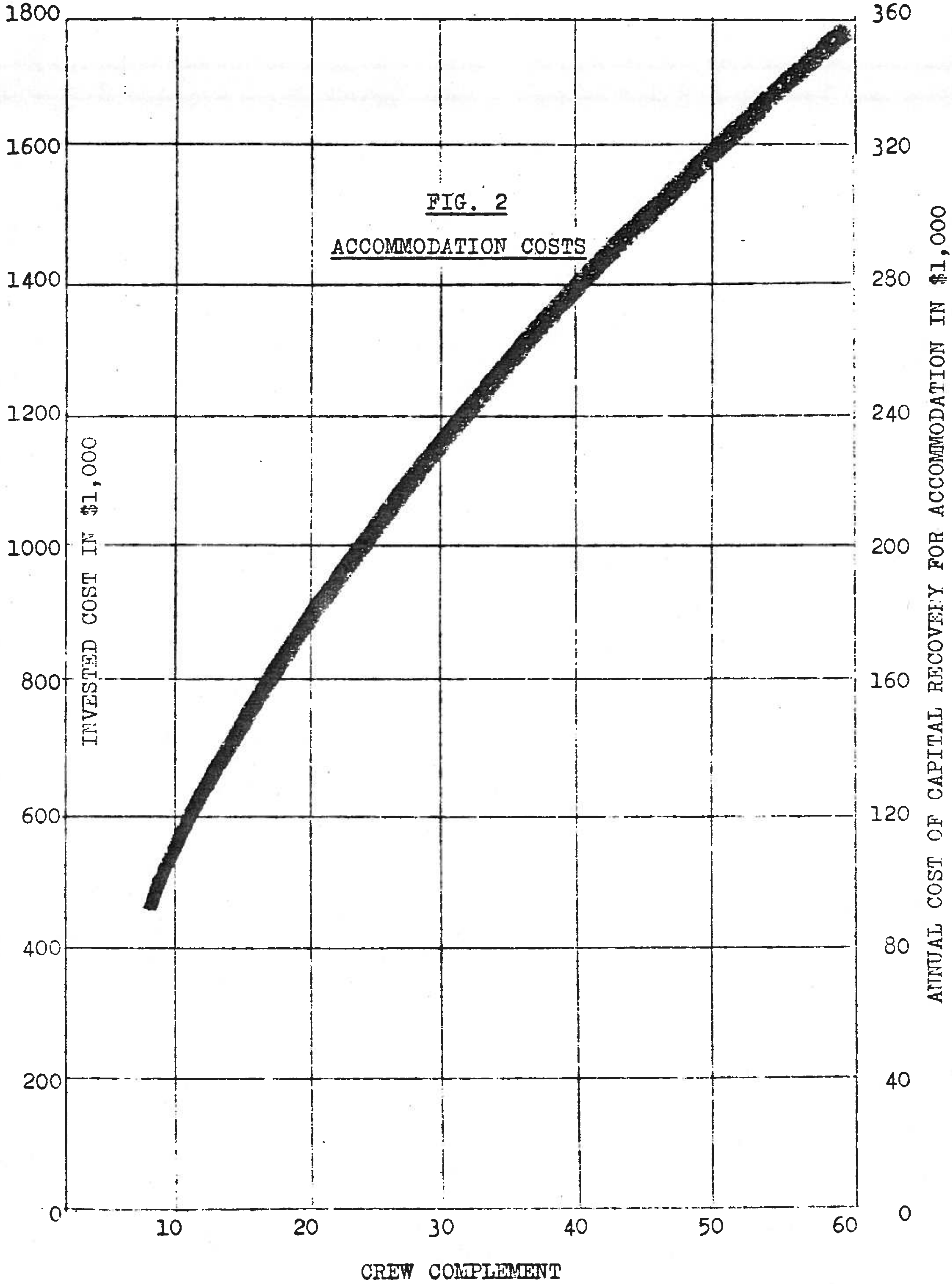
For Crews of Fewer than 50

$$\text{Annual cost of stores and supplies} = \$80(N_c/10)^4 \qquad (4)$$

(Figure 3 shows the annual cost of supplies as a function of the complement.)

FIG. 2

ACCOMMODATION COSTS



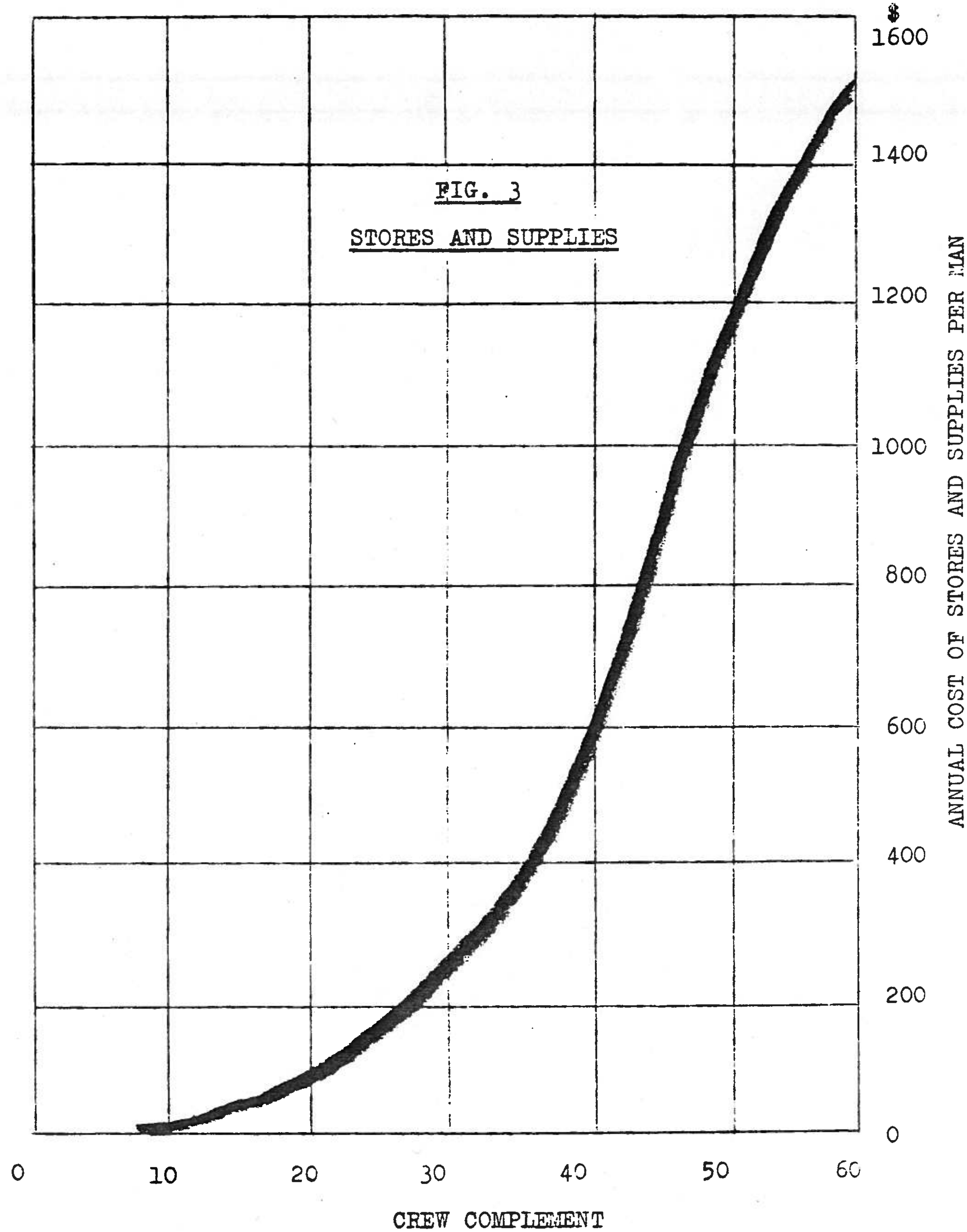


FIG. 3
STORES AND SUPPLIES
$
1600
1400
1200
1000
800
600
400
200
0
ANNUAL COST OF STORES AND SUPPLIES PER MAN
0
10
20
30
40
50
60
CREW COMPLEMENT

Protective and indemnity insurance. P and I insurance claims arise principally from the crew of the ship. Thus a goodly share of P and I insurance costs would vary with crew numbers. In an automated ship, each billet eliminated might save the owner $770 per year.

Accommodation insurance. Hull and machinery insurance costs vary directly with initial cost. The average annual premium is about 1 per cent. of the investment. Every thousand dollars saved in accommodation cost thereby reduces annual H and M insurance costs by ten.

Miscellaneous savings. There are several additional hidden expenses associated with each crew member. I find it hard to generalise about their costs so will merely tabulate them as follows:

- Hotel service fuel
- Laundry
- Dishes
- Linen
- Medical expenses
- Medical claims
- Repatriation
- Overhead
- Morale items

Secondary Savings

We must of course remember that every four men in the deck or engine crew seem to require one man in the steward's department. And these, in turn, bring their own hidden costs as well as costs of wages and accommodations.

ADDED COSTS

The added costs of shipboard automation are more difficult to estimate than are the savings. We have less history to guide us. Furthermore, the optimum trade-off between first cost and maintenance cost requires a separate study in itself.

To simplify matters, I am specifically omitting the costs of overcoming the temporary human problems caused by automation. This important topic is a subject for the bargaining table, not engineering analysis. My hope, however, is that studies of the sort I propose can provide reliable estimates that will allow informed negotiation between labour and management.

The principal components of added cost of automated operation are discussed below.

Increased Reliability

No item of mechanical equipment can ever be made 100 per cent. foolproof. The best we can do is to find the proper balance between the high first cost of good reliability and the high operating cost of poor reliability. The operating costs are made up of two parts:

(1) maintenance and repair; and

(2) indirect costs resulting from breakdown.

The second category obviously involves some difficult statistical contemplations that quite possibly defy accurate quantitative analysis. Both categories vary inversely with the number in the crew. We should remember, too, that our analysis must look at each individual component of the ship as well as the entire ship system and numerous subsystems. All this involves additional questions of optimum degree of redundancy, maximum credible accident, and so on.

The theory of optimum reliability determination is now well understood by marine engineers. Its practical application, however, is difficult because of the imponderables implied in the second category of costs above. Perhaps the complications can be successfully analysed. But I strongly suspect our engineers, statisticians and computer facilities could be put to more fruitful tasks. In short, I hesitatingly advocate that decisions pertaining to reliability be left where they presently are: in the realm of much art and little science.

The concept of reliability can be extended to routine maintenance problems. For example, better protective coatings increase first cost but reduce the need for shipboard labour. Indirect costs, however, would be essentially zero because the results of failure are seldom serious in this area of concern.

Routine Maintenance

The trend toward fewer crew will probably be accompanied by a transfer ashore of much maintenance work now done on board. We shall, I believe, see several concurrent changes in design and operation. Standardised machinery components will be arranged for easy removal and replacement on a substitution basis, aesthetic standards may be lowered; corrosion-free design will be stressed; and machinery plants may be simplified, purposely accepting a slight increase in fuel rate. The inherently greater efficiency of automated control may more than offset this, however (1). Eventually we may see shipboard maintenance confined to occasional emergency jobs and light housekeeping - the latter being retained primarily for crew morale.

The net effect of transferring maintenance work ashore will I believe be economically beneficial. Shipyard workers are better equipped than their seafaring brethren. They also work under better conditions, as any seaman can tell you after painting rigging on a 20-knot ship heading into a 25-knot wind. But, since we have earlier taken credit for wages, etc. saved through crew size reduction, we must now add the cost of doing more of the maintenance work ashore. Unfortunately, accounting systems do not give us an accurate idea of present shipboard maintenance costs, which we could use as a basis for estimating the cost of doing the same work ashore (2). As one possible approach we can estimate the increase in annual ship-repair costs that would result from doing all of the maintenance work ashore. At most, I believe, this would double the annual shipyard repair bill. This would lead to the following approximations for general cargo ships:

$$\text{Added annual cost of hull M and R} = \$10{,}000(CN/1000)^{2/3} \quad (5)$$

and

$$\text{Added annual cost of machinery M and R} = \$4{,}500(SHP/1000)^{2/3} \quad (6)$$

where

$$CN = \text{Cubic number} = \frac{L \times B \times D}{100}$$

SHP = Maximum continuous shaft horsepower

L = Length between perpendiculars

B = Beam

D = Depth to uppermost continuous deck

For metric units, substitute \$108,000 for \$10,000 in equation 5.

These costs are concerned only with the transfer of maintenance work now done by the ship's crew. Changes in cost resulting from increased reliability and better protective coatings might reduce these added costs by perhaps one-third.

Equipment

The special equipment going into an automated ship can be subdivided into two groups according to function. One group, mechanisation equipment, replaces human muscles. The other, automation equipment, replaces human sensing, control and recording.

Some of the items of mechanisation equipment might well be adopted for purposes other than the reduction of crew complement. Deck cranes in place of kingposts and booms are an example. In addition to furnishing approximately equal functional capabilities, deck cranes require much less routine maintenance and little or no rigging and securing. They also allow immeasurably better visibility from the bridge. Both factors lend themselves to operating with fewer crew.

Wire mooring lines on automatic tensioning winches should also become standard equipment. And within a few years we may well see radically different approaches to the mooring function. Food handling and meal preparation can also be greatly eased through modern technology.

Automation equipment need not add greatly to the cost of the ship, assuming we retain at least a skeleton crew. This is particularly true of diesel ships, which comprise the great majority of the world's merchant fleet. The ideal extent of automation equipment is not easy to establish but, in my opinion, its priority ranks below that of many of the other changes discussed here.

Harlander (3) cites several useful cost estimates for progressively automating steam turbine machinery plants. I use his figures later in this paper.

One final point on automation equipment is well put by Elden (2):

> "Needless to say, there will be some who will object that, in eliminating the engine crew, there will be no one left for the highly skilled task of cleaning the bilge pump strainer. The answer to this is that with no crew in the engine room, there will be nobody to throw cigarettes, pocket combs and old magazines into the bilges and block up the strainer."

WORK PRACTICES

Improved work practices (work rationalisation) can do much to increase the productivity of shipboard labour. For example, seagoing ships might well follow the lead of the towboat operations on the great rivers of North America. Here we find vessels operating around the clock but manned with two, rather than three watches. The men work six-on and six-off, seven days a week without overtime or holiday pay. For every day worked, however, they are given one day ashore at full pay. They rotate on a monthly basis and have the psychological advantage of working with different shipmates each time. They enjoy an almost normal family life, which makes it easier to attract and retain good workers.

The river towboat operation is highly productive. A boat with a complement of only nine men can routinely handle a flotilla of barges 1,200 feet long by 120 feet wide with a displacement of 35,000 tons. The men are by no means overworked and I have heard them remark that putting in fewer than 12 hours a day would bore them.

As an example of towboat efficiency I can mention that the captain and his alternate (called the pilot) control the operation single-handedly. Each is his own helmsman and sits at a console with all necessary controls within easy reach. The elimination of the helmsman makes the control function safer and more precise. Since the towboat may be a thousand or more feet abaft the bow of the flotilla, the captain maintains radio communication with lookouts stationed, when necessary, at the bow.

There are several working restrictions on ocean ships that are open to review. For example, the arbitrary barriers between the deck, engine, and steward's departments might well be lowered, if not eliminated. No one would have to work any harder, but could be used wherever most needed. Peak loads could thereby be met with fewer total crew. The U.S. Merchant Marine Academy has recently announced that it will experimentally train 25 selected cadets for both deck and engineer licenses. The superintendent of the Academy is quoted as saying (4):

"I believe that the advent of automation will not only necessitate but will facilitate the production of an omnicompetent officer, I do not foresee any problems which would not be susceptible of resolution by commonsense and a willingness to resolve them."

A subsequent news release reports that the Brotherhood of Marine Operators not only has applauded the Academy's move, but has made plans to start a dual training programme of its own. The union, which is made up of both deck and engine officers, agrees that officers should be "omnicompetent".

Advocates of reduced crew complements are continually belaboured by pessimistic souls who mournfully point out that labour unions and regulatory agencies, such as the U.S. Coast Guard, prohibit certain manning changes. Their defeatism reminds me that Venetian law once dictated a complement of one man for every 10,000 pounds of deadweight. This law was eventually repealed, no doubt under pressure from some determined shipowners who felt the heat of foreign competition. Had the law become universally accepted and left unchanged, the 160,000-ton tankers now abuilding would require crews of 36,000 men. Now there would be a problem in sewage disposal alone.

SAMPLE STUDY

Let me illustrate how you might go about finding the most economical crew complement and estimating the relative net annual saving. Let us say that we are designing a 20-knot general cargo liner of the mariner type. It would have a propulsion plant of 19,000 SHP with single-screw steam turbine drive. Under past practice, such a ship would have a crew of perhaps 54 men, assuming no passengers, no cadets, and no refrigerated cargo (5).

Following Harlander's example, more or less, let us imagine the design and operation of such a ship with progressively greater degrees of automation. Superimposed on each phase is an alternative (A) with a two rather than three-watch system. Table 1 summarises crew requirements. The phases are arbitrary in the assumed extent of automation and there could be intermediate phases or, in some cases, different sequences of progression. The situation with a diesel plant would of course be considerably different.

Phase I represents standard practice before the advent of automation.

Phase II is based on work rationalisation. Also, shipboard maintenance is somewhat reduced. An investment allocation of $160,000 is made for better protective coatings and more reliable machinery components. An extra $20,000 per year is allowed for shoreside repairs. Deck cranes replace masts and booms.

Phase III assumes the boilers are automated at a cost of $150,000, mooring is mechanised for another $150,000, and essentially no routine maintenance is done by the crew. Costs cited are from Ref. 3. An additional $200,000 is allowed for more extensive protective coatings, more reliable machinery components, and contingencies. Shoreside repairs are estimated to increase by $30,000 per year. These costs are all in addition to those used in Phase II.

Phase IV moves to bridge control with a central engine-room monitoring station. The automation equipment is estimated to cost $500,000 and an additional $400,000 is allocated for increased reliability of components (3). A contingency allocation of $50,000 is added. At this stage, the only further additions to shoreside repair costs would be those required for the additional automation equipment.

TABLE 1 - ASSUMED CREW COMPLEMENTS

	PHASE									
	I	IA	II	IIA	III	IIIA	IV	IVA	V	VA
Deck Officers	7	6	5	4	5	4	5	4	4	3
Deck Ratings	14	9	10	7	3	2	3	2	3	2
Total Deck	21	15	15	11	8	6	8	6	7	5
Engine Officers	10	7	6	5	6	5	5	4	3	2
Engine Ratings	12	8	7	4	4	2	0	0	0	0
Total Engine	22	15	13	9	10	7	5	4	3	2
Stewards	11	6	8	4	5	3	3	2	3	1
Total	54	36	36	24	23	16	16	12	13	8

Phase V adds computer controls in the engine room at a first cost of $300,000 (3). An extra $90,000 is allowed for increased reliability and contingencies. The crew now numbers 13 men on three watches or eight men on two.

If these numbers seem unbelievable, let me remind you that barges of comparable displacement are routinely pushed or pulled over long distances by towboats or tugs with crews in that numerical range. And I do not know what it proves, but that crew of eight finally brings us back to where we were on our coastwise schooners a century ago.

Table 2 summarises the annual costs and savings based on the foregoing figures.

CONCLUSIONS

My primary intent has been to demonstrate a method for finding the most economical number of crew for any proposed commercial ship. The cost estimates cited have necessarily been rather inexact, but I believe they have erred on the side of conservatism. In the sample study, the optimum number of crew seems to be about 23 with the three-watch system or 16 with the two-watch system. My guess is that experience will show that the true optimum number will be even smaller. This would surely be true with diesel propulsion.

Since the net cost saving of Phase III and Phase IIIA are virtually the same, authorities concerned with the unemployment problem might favour Phase IIIA. The crew complement would thereby be reduced to 16 rather than 23, but the total number of seamen employed would be two times 16, or 32. On the other hand, the shortage of engineering officers lends weight to Phase V or VA. Of the two, Phase VA might be preferred; it is economically better and the month-on, month-off feature would help attract the right talent.

The maximum net annual saving indicated in Table 2 is $445,000. This compares with the total average annual cost of a conventional ship (exclusive of cargo handling) of about $3,300,000. This saving is of course only approximate. But it indicates the sort of funds that should become available for reducing the need for subsidy, improving the seaman's lot, increasing profitability and eventually decreasing the cost of ocean transport.

TABLE 2 - AUTOMATED SHIP COST ANALYSIS (All Costs Shown are in $1,000)

	PHASE									
	I	IA	II	IIA	III	IIIA	IV	IVA	V	VA
Watches	3	2	3	2	3	2	3	2	3	2
Incremental Advance	Current Practice		Work Rationalisation. Less Shipboard Maintenance.		Automated Boilers. Mechanised Mooring. No Shipboard Maintenance.		Bridge Control		Computer Control	
Total Complement	54	36	36	24	23	16	16	12	13	8
Reduction in Complem.	0	18	18 (1)	30 (1)	31 (2)	38 (2)	38 (3)	42 (3)	41 (4)	46 (4)
Investment Additions	-	0	160	160	660	660	1,610	1,610	2,000	2,000
Investment Savings (5)	0	346	346	616	639	833	833	959	925	1,107
Net Investment Change	0	-346	-186	-456	21	-173	777	651	1,075	893
<u>Annual Cost Savings</u>										
Capital Recovery (6)	0	69	37	91	-4	35	-155	-130	-215	-179
Wages (7)	0	-96	202	134	362	300	456	391	498	484
Food (8)	0	14	14	23	24	29	29	32	32	35
Supplies (9)	0	22	52	56	64	65	66	66	66	66
P and I Insurance (10)	0	14	14	23	24	29	29	32	32	35
H and M Insurance (11)	0	3	2	5	0	2	-8	-7	-11	-9
Shoreside M and R (12)	0	0	-20	-20	-50	-50	-50	-50	-50	-50
M and R Adjustment (13)	0	7	7	12	6	10	-1	1	-6	2
Miscellaneous (14)	0	11	11	18	19	23	23	25	25	28
Total Annual Cost Saving ($1,000)	0	44	319	342	445	443	389	360	371	412

Notes for Table 2

1. Added investment for Phase II:

Protective coatings	$60,000
Greater reliability	$100,000
Total	$160,000

2. Added investment for Phase III:

Automation for boilers	$150,000
Mechanised mooring	$150,000
Protective coatings	$60,000
Greater reliability	$100,000
Contingencies	$40,000
Phase II costs	$160,000
Total	$660,000

3. Added investment for Phase IV:

Automation for bridge	$500,000
Greater reliability	$400,000
Contingencies	$50,000
Phase III costs	$660,000
Total	$1,610,000

4. Added investment for Phase V:

Computer control	$300,000
Greater reliability	$60,000
Contingencies	$30,000
Phase IV costs	$1,610,000
Total	$2,000,000

5. Accommodation costs are based on equation 2.
6. Average annual cost of capital recover is taken at 20 per cent of invested cost.

7. Crew wages are based on equation 1.

8. Food costs are based on $770 per man.

9. Costs of stores and supplies are based on equations 3 and 4.

10. Protection and indemnity insurance cost savings are based on $770 per crew member reduction.

11. Hull and machinery insurance is taken at 1 per cent of the invested cost.

12. Added costs of shoreside maintenance and repair might double if no shipboard maintenance were done. The present level for ship repair work is about $80,000 per year. However, the use of better protective coatings and more reliable machinery components might reduce this amount to $50,000. This estimate is necessarily rough.

13. Maintenance and repair costs must be adjusted in recognition of net changes in the ship itself. The adjustment is taken as 2 per cent of the change in investment exclusive of the costs of increased realibility and better protective coatings.

14. Miscellaneous savings are arbitrarily set at $600 per man per year.

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