OPTIMUM RELIABILITY AND MAINTENANCE SCHEDULE OF A CENTRIFUGAL PUMP

by

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A Thesis Submitted to the Faculty of the

AEROSPACE AND MECHANICAL ENGINEERING DEPARTMENT

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

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STATEMENT BY AUTHOR

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ACKNOWLEDGMENT

The author wishes to express his deepest gratitude to Dr. Dimitri B. Kececioglu, Professor of Aerospace and Mechanical Engineering and consultant to Northrop Space Laboratories, who suggested this investigation and devoted generously his time in directing this work to successful completion.

Suggestions by Mr. Roy C. Hughes, Reliability Engineer, Allis-Chalmers Mfg. Co., presently Research Associate at The University of Arizona, were also very valuable.

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LIST OF SYMBOLS

C_C = Customer's total cost

C_F = Corrective Replacement Cost

C_{iF} = Corrective Replacement Cost i^{th} component In Group 2

C_{jF} = Corrective Replacement Cost j^{th} component In Group 3

C_M = Manufacturer's Total Cost, or Total Maintenance Costs for the Machines

C_P = Preventive Replacement Cost

C_{iP} = Preventive Replacement Cost i^{th} component In Group 2

C_{jP} = Preventive Replacement Cost j^{th} component In Group 3

$C_{impeller}$ = Total Maintenance Cost for the impeller

k = Value Read from Normal Tables Depending Upon the Maximum Percentage Failure Requirement Between Two Scheduled Replacements

L = Lower Confidence Limit of Mean Wearout Life

M = Mean Wearout Life, or Mean Time to Failure

$\hat{M}$ = Estimate of Mean Wearout Life

M_h = Mean Time to Failure of the h^{th} Part In Group 1

LIST OF SYMBOLS
(Contd)

M_i = Mean Time to Failure of the i^{th} Part In Group 2

M_j = Mean Time to Failure of the j^{th} Part In Group 3

n = Number in Sample; or Total Number of Parts In System

n-1 = Degrees of Freedom

Q(t) = Unreliability of the System

R(t) = Total Chance and Wearout Reliability

$R_c(t)$ = Reliability of Chance Failures

R_h = Reliability of the h^{th} Part in Group 1

$R_w(t)$ = Reliability of Wearout Failures

s = Estimate of Standard Deviation

S_u = Upper One-Sided Confidence Limit for Component Standard Deviation

t = Probability Value for t Distribution, or Operating Time

T = Standardized Distance for Normal Distribution, $\frac{t - M}{\sigma}$, or Preventive Maintenance Time

T_1 = Preventive Replacement Time for Group 2 Components

T_2 = Preventive Replacement Time for Group 3 Components

χ^2 = Probability Value for Chi Square Distribution

σ = Standard Deviation

LIST OF SYMBOLS
(Contd)

λ = Mean Generic Failure Rate In Failures Per Million Hours

λ_M = Stabilized Average Failure Rate of the Machine

$100(1-\alpha)$ = Percent Confidence Level

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ABSTRACT

This study is concerned with the determination of the optimum level of the reliability for 5x4 SK and KSK pumps, made by the Allis-Chalmers Mfg. Co., Box 512, Milwaukee 1, Wisconsin, and used commercially and aboard aircraft carriers of the U. S. Navy.

The different parameters which might effect the optimum reliability level of these pumps are identified and evaluated to minimize the total cost of such pumps to the user. The following three parameters which can effect the optimum level of reliability are concentrated upon:

I. Cost of money procurement to the manufacturer and to the customer

II. Life of pump

III. Maintenance schedule time

Different preventive maintenance policies are discussed and optimum preventive maintenance times for main components of the pump are then numerically determined.

A math model is also developed for manufacturer's and customer's total cost versus reliability picture.

CHAPTER 1

INTRODUCTION

In recent years considerable time and money have been spent in the development and improvement of optimization techniques. These techniques have been used recently to determine the optimum level of reliability that should be designed into a product so that its total cost to the user is minimum. The urgent need for missiles has forced reliability engineers to concentrate on optimizing "one-shot devices," whereas, relatively little has been done for the systems which fail and undergo repair repeatedly during their operating life. There is a great need, therefore, to study and optimize the reliability of such repairable systems, which substantially outnumber the population of missiles.

Whether a product should be manufactured at the lowest selling price or manufactured at the highest possible reliability level is in essence a problem of balance in interest from the viewpoint of the manufacturer and the customer. This aspect of the problem has been studied by several investigators who have proved that there exists an optimum reliability level at which the customer's

total cost of purchasing and operating the equipment, for its intended life is minimum. Such studies are now beginning to influence manufacturers and customers in seeking the optimum level of reliability at which their products should be manufactured and bought, because this results in both of them "saving dollars."

Ryerson (1)* and RCA (2) develop a complete cost picture as shown in Figs. 1 and 2. In Fig. 1, Curve A, which increases with reliability, represents the customer's initial cost. Curve B, which decreases with increasing reliability, represents the support cost. Curve C is the sum of these two curves and represents the customer's total cost. In developing the optimum reliability point for the customer's minimum total cost, both of the referred to studies do not consider the manufacturer's total cost picture and no actual cost data in support of these curves are provided.

Delco-Remy (3) point out the existence of an optimum quality for the manufacturer. This study considers quality versus cost rather than reliability versus cost. Also it does not consider the customer's total cost picture. The result is similar to Curve C, in Fig. 1, representing the manufacturer's total cost.

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* Numbers in parentheses refer to those in the BIBLIOGRAPHY.

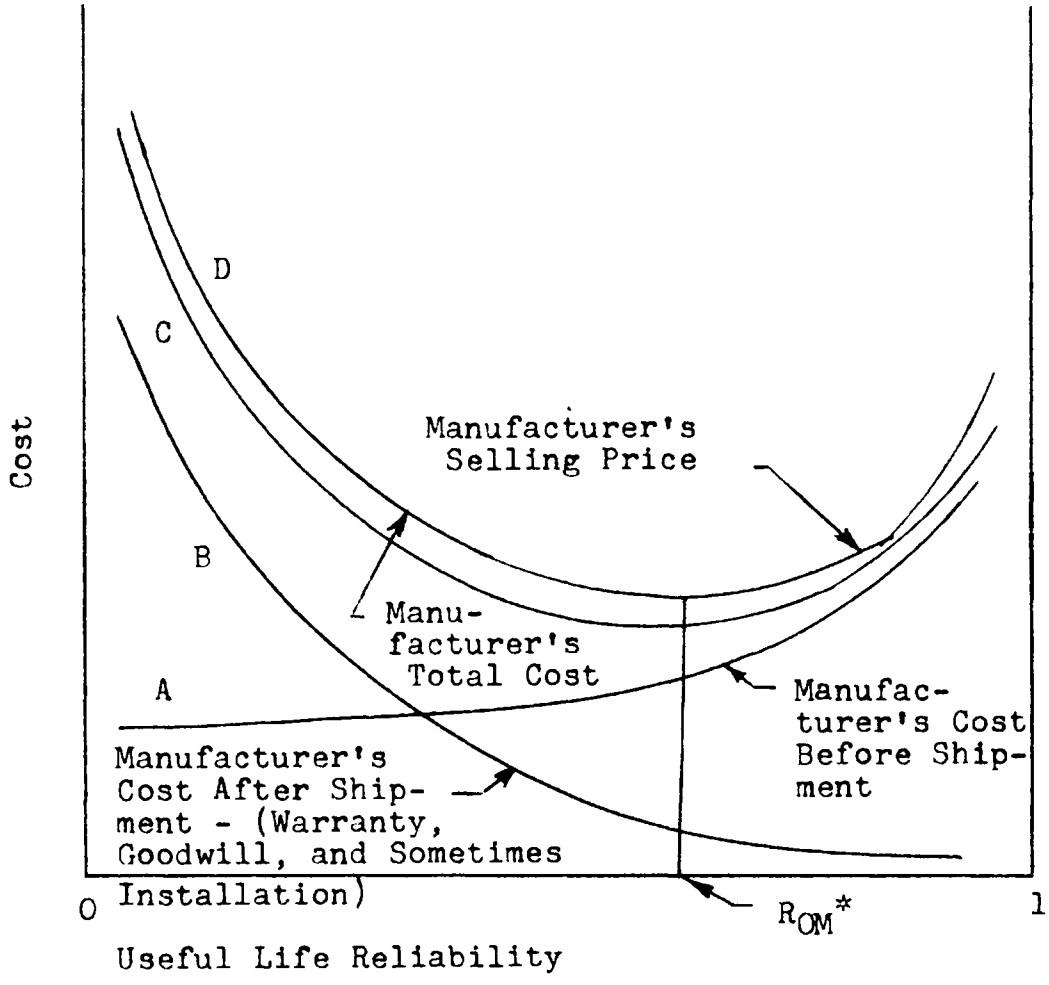


Fig. 1 (15, Fig. 1) - Effect of Level of Reliability on the Manufacturer's Total Product Cost

*R_{OM} = Optimum reliability for minimum manufacturer's selling price.

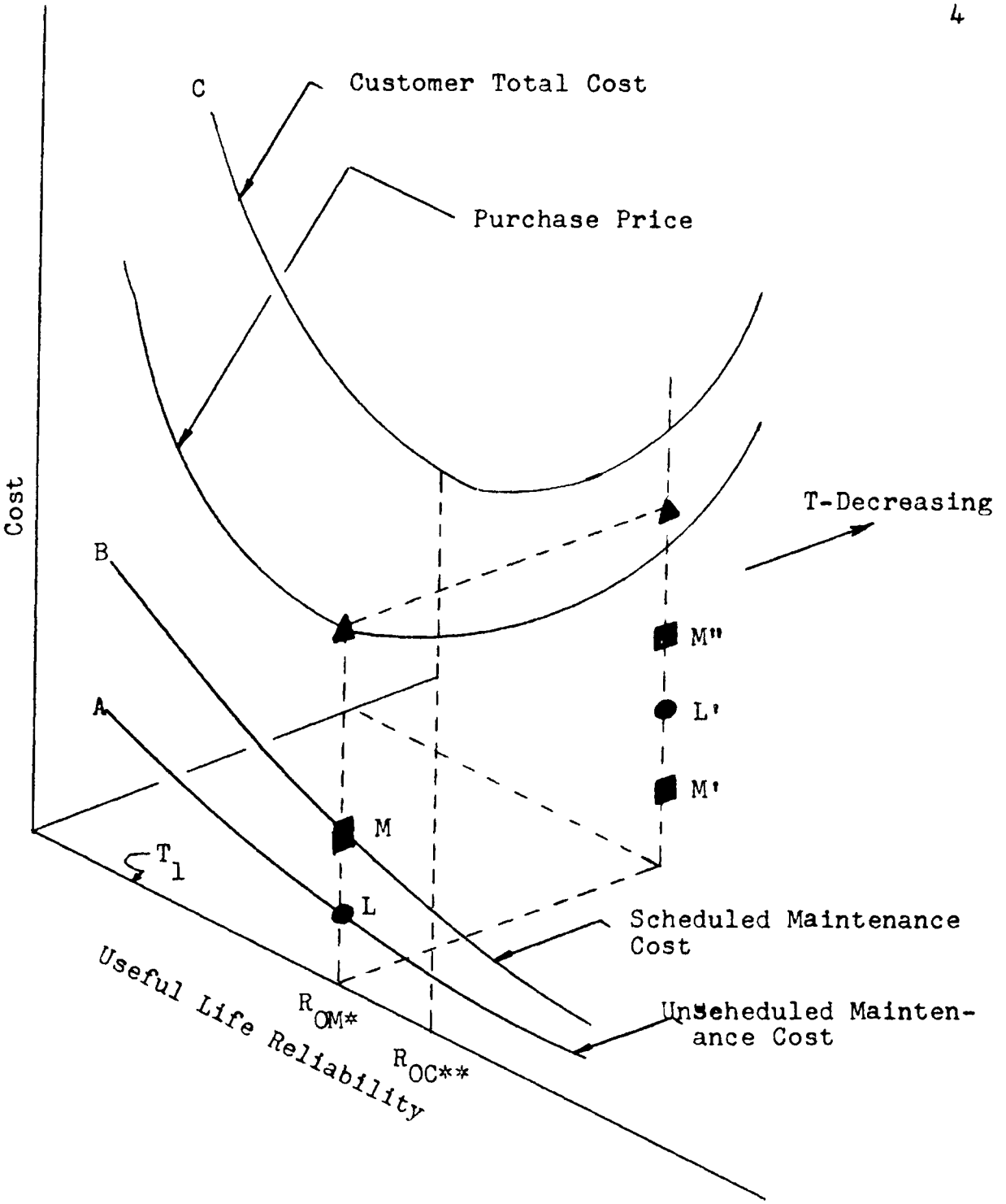


Fig. 2 (15, Fig. 2) Reliability and the Customer's Total Cost Picture Showing the Relative Effect of a Different Scheduled Maintenance Time.

*R_{OM} = Optimum Reliability for Minimum Manufacturer's Product Cost

**R_{OC} = Optimum Reliability for Customer's Minimum Product Cost.

Carhart and Herd (4) develop a simple cost model for optimizing reliability. This model is utilized to describe a means of allocating expenditures between development and operating requirements by selecting that reliability which will minimize the total cost. The major difficulty in using this cost model is the lack of required data.

Miller (5) proposes a method to optimize total mission cost versus reliability in a complex weapon system. He suggests different variables which can effect the total cost per mission. Though the model developed takes into account the complexity, operating time, variable costs which must be increased in order to increase reliability in the system, and state-of-art of equipment reliability, the amount of data available is found to be very limited to use these cost models.

Kalbach (6) presents a simplified mathematical model which provides a working hypothesis of relationships between the amount of preventive maintenance and the reliability of electronic data processing machines. Due to insufficient data, the relationships have not been thoroughly tested; however, several years of actual experience appear to support the theory.

Price (7) derives a "Reliability-Economic Decision Equation" on the basis that if a net monetary saving can

be realized, the reliability improvement should be made. The major difficulty is found in the prediction of the cost-saving data.

Cox and Harter (8) derive a reliability optimization model for a one-shot mission. They develop curves between the reliability improvement effort and the reliability resulting from this effort for one-shot devices.

Stevens (9) shows that in the long run the cost of reliability improvement of electronic subsystems for military aircraft is more than offset by the dollars saved on maintenance.

McLaughlin and Voegtlen (10) determine the support cost of special purpose and waveguide tubes in prime search radar and navigation aid and UHF communication at four Air Control and Warning sites located within the Central Air Force Defense Command. Seventy-five percent of the true equipment failures, as well as an equal proportion of replacements, are found to be due to tube deterioration and failure. Forty percent of the total maintenance hours are found to be required to maintain these tubes. It is concluded that development of improved parts and state-of-art advances in this area are most urgently required to reduce the present heavy burden of support. They find out that the present practice of considering only unit purchase price in the procurement of

equipment is inadequate, and state that means must be found for basing development and production decisions on the total cost of the equipment for their service life.

Welker (11) constructs a mathematical model to describe the expected average hourly operating cost when the simple equipment is subjected to periodic parts replacement. When failure rate increases with time, he determines an optimum replacement interval, that is, interval yielding minimum expected average hourly cost. This study does not consider the dollar value of specific reliability improvements.

Barlow and Hunter (12) and (13) present excellent math models for system reliability. They suggest two types of preventive maintenance policies to be considered to investigate the repair feature of the model. The optimum times to perform preventive maintenance are, in each case, unique solutions of certain integral equations depending on the failure distribution. The same models give minimum cost solutions when average times to repair are replaced by costs to repair. The major difficulty in the use of these models is the knowledge of different parameters required to evaluate the expected reliability of the system under both types of preventive maintenance policies.

Bazovsky, MacFarlane, and Wunderman (14) develop generalized mathematical, linear and non-linear cost models for single component and also for complex equipment. They calculate the failure rates, the number of unscheduled and preventive maintenance actions, part wearout life, time between failures, maintenance time, part replacements, and costs of repair maintenance and preventive maintenance, and the resulting total maintenance cost. In doing this they establish optimum reliability levels to minimize the total maintenance cost of a steam turbo-pump aboard BuShips surface ships. Because of lack of sufficient high-confidence level operating, reliability, maintenance and cost data, they feel handicapped in applying their theory in its totality.

Kececioglu and Hughes (15) undertook the first major effort in developing actual manufacturer's and customer's cost data for a class of pumps used commercially and aboard aircraft carriers of the U. S. Navy. The manufacturer's total cost was based on his cost before and after shipment and his profit; whereas, the customer's total cost was based on his cost of buying and maintaining these pumps, including downtime cost, for their life. From a combined plot of these data, the optimum level of reliability to which the pumps should be designed and manufactured is determined for both the manufacturer and

the customer. This study does not consider the cost of money procurement, assumes a pump life of 30,000 hours, and does not optimize the preventive maintenance schedule based on the assumption that the manufacturer's recommended maintenance schedule was already at the optimum. Among the purposes of this thesis are included the consideration of the first and last factor and the determination of the effect of different pump lives on the optimum pump reliability.

Bazovsky (16) presents excellent numerical evaluation of the reliability and maintainability parameters which will permit realistic estimation of maintenance manhours, spare parts supplies, total maintenance cost for long-term operations, and optimization of preventive maintenance periods for minimum cost, predetermined operational reliability and operational availability. These mathematical models are applied to shipboard machinery and it is found that basic information on failure rates and longevity of mechanical parts is not easily available.

Sasaki (17) presents a mathematical method of designing the system having the highest reliability. This method can determine the optimum types and quantities of redundant components that should be used in order to make the electronic system as reliable as possible, subject to a given cost, weight, volume and other

constraints. The same method can also determine the minimum values of cost, volume, weight, and other matters necessary for achieving a designated system reliability.

Diederich (18) discusses in general terms the nature of trade-offs among reliability, performance, cost, and maintenance schedule. He also describes the use of these trade-offs in program-management.

Webster (19) discusses the problem of finding a system configuration which will have the highest reliability with the lowest over-all system production cost, weight, and maintenance and stock costs. He expands the procedures to include consideration of the different types of redundancy and various probability combinations of open and short component failures.

This study considers the effect of cost of money procurement and life of equipment on reliability-cost optimization. As the availability of data is the major requirement for such a study, the equipment selected must have the necessary data available. The equipment selected is 5x4 SK and KSK pumps manufactured by Allis-Chalmers Mfg. Co., Box 512, Milwaukee 1, Wisconsin. This study also considers the effect of maintenance schedule time on the optimum reliability of these pumps.

CHAPTER 2

COST OF MONEY PROCUREMENT

2.1 Time Value of Money

Generally, money cannot be borrowed without an agreement to pay interest; therefore, interest is a part of the cost. The investment in a machine or structure should, hence, be considered to be the original investment plus interest over the life of the machine or the structure.

Even when ownership funds are available without borrowing money, interest should still be considered as a cost just as much as if it had to be paid out, because there is an economic sacrifice of a possible income that might have been obtained by investment elsewhere.

Most economists include interest as a cost because of the business fact: "If you borrow money, it is necessary to pay interest; if you have money, you can get interest for it." Thus it is necessary to recognize the time value of money in cost studies, regardless of whether or not money is to be borrowed.

2.2 Historical Behavior of Capital

As the costs of various types of securities are constantly changing, the question arises whether it is appropriate to use as the capital cost what the firm originally paid for its capital or what the capital would cost at the present time. By the economic principle of opportunity costs, the historical costs of a particular issue are not important as the likely costs of the next issue; but costs in the near future may be inferred, as a first approximation from the present level and historic behavior of the market. In other words, the firm should charge as the cost of its capital what the capital would cost if it were currently to be acquired rather than what it happened to have cost when the capital was acquired. According to Weston (20), therefore, the cost of debt would not be the coupon rate but the current yields on its bonds at the time of the calculation.

Thus it is concluded that for current decisions, current facts must be used and not the historical information.

2.3 Cost of Capital

Cost of capital is defined as the burdens of a particular security to the amounts that can be raised by issuing that security. There are two ways to determine the cost of capital contained in a financing arrangement:

1. Find the difference between the net proceeds actually made available to the company and the total burden incurred during the arrangement.

2. Find the rate that must be earned on the net proceeds to provide the cost elements of the money borrowed at the times they are due.

In this study, cost of capital will be expressed in terms of rate of interest, i.e.,

$$\text{Cost of capital over some period} = \frac{\text{interest paid on the money borrowed over that period}}{\text{net proceeds available}}$$

2.3.1 Cost of Preferred Stock and Long-Term Debt

According to Howard and Miller (21), preferred stock and long-term debt are fixed income securities, where compensation to the investor in the form of dividends is fixed by the amount specified at the time of issue.

The cost of capital is the annual percentage outlay on the dollars provided. The dollars provided are the net proceeds available for investment in corporate activity, i.e., the sum provided by the investor, less the costs of issue, including the amount retained by the investment banker handling the issue, and the expenditures incurred directly by the issuer.

As the costs of issue and other costs mentioned above are insignificant compared with the total dollars

provided, for the purpose of this study one hundred percent of the normal value of the preferred stock and long-term debt will be considered as the market value.

2.3.2 Cost of Common Stock

There are two major ways of calculating the cost of common stock:

1. The dividend-yield basis
2. The price-earnings ratio basis.

In view of wide variations in dividend pay-out policies, the use of dividend-yield basis is clearly not appropriate. Competent studies also indicate that the dividend pay-out rate, whether high or low, does not have a generally marked influence on stock prices. The main influence on stock prices is the firm's underlying earning power rather than the percentage of its earnings paid out in dividends. The price-earnings ratio is the most dependable basis for calculating the cost of common stock, and this is the ratio that will be employed.

2.3.3 Cost of Retained Earnings

Frequently the point of view is encountered that the cost of retained earnings is zero because the company did not pay anything in order to obtain the retained earnings. This view, however, is clearly wrong. Retained earnings represent funds left in the business by the owners of the business and should be treated the same

way as the initial investment in the common stock of the company. Some authorities have suggested that only fifty percent or seventy-five percent, or some fraction of retained earnings be counted as the net worth. However, as a practical matter, the problem does not arise if the market values are employed.

2.4 Cost of Capital Calculations

As discussed earlier, the most meaningful and recommended method for the calculation of the cost of capital is to use the market values of the securities and the current yields as the rate to be applied to these securities. Calculations can be made either before taxes or after taxes. As business decisions must consider after-tax effects, the calculations of the cost of capital will be made after taxes.

Since the calculation is intended to be after taxes and a fifty percent corporate tax rate is used, the rate of long-term debt will be reduced by fifty percent. The current earning-price ratio of the common stock will be applied to the market value of the common stock.

Moody's Industrial Manual (22) gives the consolidated balance sheet (Table I), as of December 31, 1963, of Allis-Chalmers Mfg. Co. To calculate the cost of capital, we have to consider long-term debt, preferred stock

TABLE I
(Ref. 22, pages 1359-1362)

CONSOLIDATED BALANCE SHEET, AS OF DEC. 31, 1963

ALLIS-CHALMERS MFG. CO.

Assets	$	Liabilities	$
Cash	22,293,617	Notes Payable	40,000,000
Notes & Accounts Receivable (net)	144,756,752	Current Payment (long-term debt)	3,670,000
Other Current Assets	903,659	Accounts Payable & Payrolls	46,014,855
Inventories	205,187,724	Reserved for Completion of Contracts billed	6,463,675
Progressive Billing & Advertising Collect on Contracts cr	17,782,371	General Taxes Accrued	6,725,229
		Federal & Canadian Income Taxes Accrued	1,734,249
		Sundry Items	4,424,757
Total Current Assets	$335,359,381	Total Current Liabilities	$109,032,765
Net Property (after deducting depreciation)	120,795,585	Long-Term Debt	82,465,000
Investment in Subsidiaries	34,787,976	Reserved for Discontinued Operations	16,904,244
Other Assets	10,941,826	4.08% Preferred Stock (par $100)	9,441,600
		Common Stock (par $10)	88,932,630
		Retained Earnings (earned surplus, unappropriated)	119,289,927
		Capital Surplus	95,818,602
Total	$521,884,768	Total	$521,884,768

and common stock as given in the consolidated balance sheet.

As explained earlier, to evaluate the market price of long-term debt and preferred stock, one hundred percent of the normal value will be considered. The market value of the common stock (par value $10) is approximated as $19 per share (high 23-7/8, low 15-3/4) according to the figures given in "The Wall Street Journal," Vol. LXXI, No. 107, Pacific Coast Edition, Nov. 30, 1964, page 22. Also the recent price for common stock (Allis-Chalmers Mfg. Co.) is given as $19 in "Standard & Poor's Industry Surveys," Vol. 2(M), Standard & Poor's Corporation, New York, N. Y., June 11, 1964, page M4.

"Standard and Poor's Industry Surveys" also give the Price Earning Ratio of the common stock (Allis-Chalmers Mfg. Co.) as 26.0. From this we get Earning Price Ratio as 3.85 percent. This is the rate of interest for common stock.

Allis-Chalmers Mfg. Co. has a long-term debt note with rate of interest varying from 3-5/8 percent to 4-7/8 percent (Ref. 22, page 1361). As this figure has to be reduced by fifty percent to account for the corporate taxes, 2.5 percent will be taken as the rate of interest for long-term debt notes.

Table II gives the market values and dollar costs of the securities to be accounted for calculating the cost of capital. Then the weighted average cost of capital will be the sum of dollar costs divided by the sum of market values of each form of financing.

$$\text{Average cost of capital} = \frac{\text{sum of dollar costs}}{\text{sum of market values}}$$

$$= \frac{8,472,264}{260,878,577}$$

$$= 3.25 \text{ percent}$$

This is the cost of money procurement.

2.5 Effect of Cost of Money Procurement on the Optimum Reliability of 5x4 SK and KSK Pumps

To incorporate the effect of cost of money procurement, reference is made to work done by Kececioglu and Hughes (15), who have given the actual manufacturer's costs for 5x4 SK and KSK pumps. They divided all the pumps into eight different groups depending upon shaft, bearings, fittings, etc. As these pumps experienced cost fluctuations because they were manufactured over a span of ten years (1954 to 1964), they established 1954 as the base year and reduced all the cost figures to a 1954 cost basis to present unbiased comparisons and thus eliminate the fluctuations caused by inflation, wages, and market changes.

TABLE II

MARKET VALUES AND DOLLAR COSTS OF THE SECURITIES

ALLIS-CHALMERS MFG. CO.

	Normal Value	Market Price	Market Value	Rate of Interest After Taxes	Dollar Cost
Long-Term Debt	$82,465,000	100%	$82,465,000	2.5%	$2,061,625
Preferred Stock	9,441,600	100%	9,441,600	4.08%	385,217
Common Stock ($10) (8,893,263 shares)	88,932,630	$19 per share	168,971,977	3.85%	6,025,422
Total			$260,878,577		$8,472,264

Table III (Ref. 15, Table XV) gives the actual manufacturer's cost for 5x4 SK and KSK pumps without the cost of money procurement adjustments. For the simplicity of calculations, a base value has been selected and all the cost figures are expressed as relative to that base. Figure 3 (Ref. 15, Fig. 21) gives a picture of the manufacturer's total cost versus pump reliability. To obtain this figure, all the failure rates of different pump groups had to be adjusted to a common application and operation environment to permit comparison. Thus, all the pump failure rates are adjusted to a shipboard environment pumping sea water. As the cost figures have been taken from Table III, this picture does not include the cost of money procurement. In the figure, Curve A represents the manufacturer's cost before shipment; Curve B represents the manufacturer's after shipment cost; Curve C represents the manufacturer's total cost; and Curve D represents the manufacturer's selling price which is 7% greater than the manufacturer's total cost. Seven percent is the amount of profit which is accepted by the Department of Defense according to the contract signed by the manufacturer, Allis-Chalmers Mfg. Co. From the figure it is seen that the optimum level of reliability for minimum total cost occurs in a range of 250 to 275 fr/10^6 hr. for the manufacturer.

TABLE III (Ref. 15, Table XV)

ACTUAL MANUFACTURER'S RELATIVE COSTS FOR 5x4 SK AND KSK PUMPS

WITHOUT COST OF MONEY PROCUREMENT ADJUSTMENT

No.	Manufacturer's Costs*	Units	Pump Groups							
			I	II	III	IV	V	VI	VII	VIII
1	Spec. Cost (Matrl., labor, burden)	Relative to Base	3.78	3.78	4.22	4.22	12.26	11.93	3.57	3.57
2	R&D Eng. (For Improvement)	Spec. %	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
3	Net Eng. Expense (Product Section)	Spec. %	5.9	5.9	5.9	5.9	6.2	6.2	5.9	5.9
4	Eng. Change During Mfg.	Spec. %	.4	.4	.4	.4	.4	.4	.4	.4
5	New Patterns (Repair + Storage)	Spec. %	2.0	2.0	2.0	2.0	1.0	1.0	2.0	2.0
6	Small Tools (Drills, Fixtures, etc.)	Spec. %	.5	.5	.5	.5	.4	.4	.5	.5
7	Adjusted Mfg. Burden (Correction)	Spec. %	3.9	3.9	4.6	4.6	9.8	8.8	3.6	3.6
8	Shipping Expense (Crate + Labor)	Spec. %	3.0	3.0	3.0	3.0	4.0	4.0	3.0	3.0

TABLE III (Ref. 15, Table XV) (Contd)

ACTUAL MANUFACTURER'S RELATIVE COSTS FOR 5x4 SK AND KSK PUMPS

WITHOUT COST OF MONEY PROCUREMENT ADJUSTMENT

No.	Manufacturer's Costs	Units	Pump Groups							
			I	II	III	IV	V	VI	VII	VIII
9	Miscellaneous (Variance Costs)	Spec. %	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
10	Total % of Spec. Cost	in %	19.0	19.0	19.7	19.7	25.1	24.1	18.7	18.7
11	Total Relative Costs Added to Spec. Cost	Relative to Base	0.72	0.72	0.83	0.83	3.07	2.88	0.67	0.67
12	Manufacturer's Total Relative Before Shipment Costs	Relative to Base	4.50	4.50	5.05	5.05	15.33	14.81	4.24	4.24
13	After Shipment Costs (No-Charge or Goodwill and Warranty Costs)	Spec. %	1.6	2.1	2.6	0.5	0	0	0.2	3.8
14	Manufacturer's Total Relative After Shipment Costs	Relative to Base	0.061	0.080	0.067	0.021	0	0	0.007	0.136

TABLE III (Ref. 15, Table XV) (Contd)

ACTUAL MANUFACTURER'S RELATIVE COSTS* FOR 5x4 SK AND KSK PUMPS

WITHOUT COST OF MONEY PROCUREMENT ADJUSTMENT

No.	Manufacturer's Costs	Units	Pump Groups I	II	III	IV	V	VI	VII	VIII
15	Manufacturer's Total Cost	Relative to Base	4 561	4 580	5 117	5 071	15.33	14.81	4.247	4.377
16	Manufacturer's Selling Price **	Relative to Base	4 87	4 89	5.47	5.42	16.40	15.85	4.53	4.68

* Do not include costs which do not affect, or are not affected by, reliability.

** With 7% Fee as accepted by the Department of Defense.

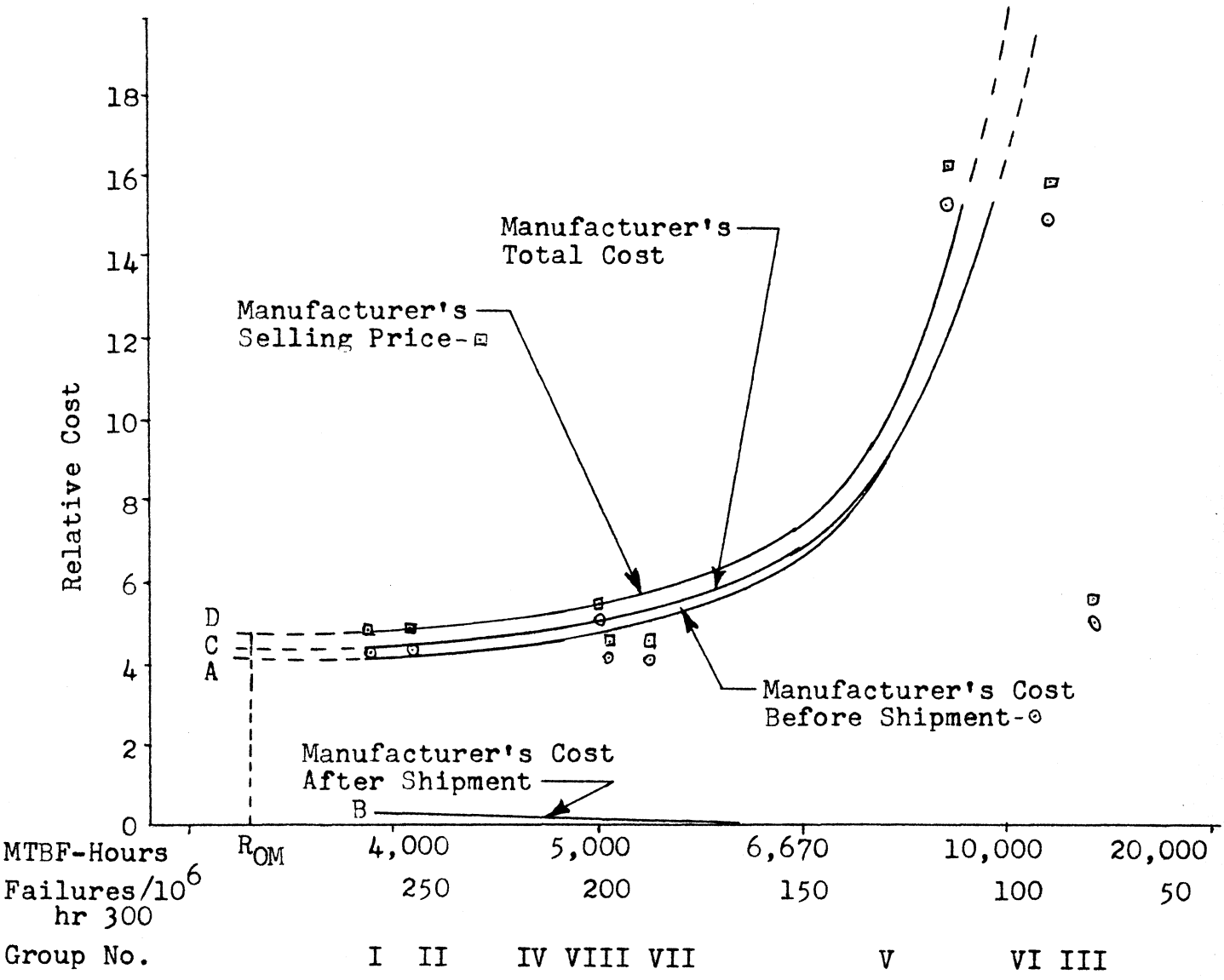


Fig. 3 (15, Fig. 21) Reliability and Manufacturer's Cost (without cost of money procurement adjustment) for a 5x4 SK and KSK Pump (Shipboard Saltwater Environment)

Table IV gives the manufacturer's relative total cost including cost of money procurement. This results in an increase in both the manufacturer's total cost and selling price.

Figure 4 shows the picture of reliability versus manufacturer's total cost including cost of money procurement adjustment. The effect on the optimum level of reliability for the minimum total cost still remains in the same range of 250 to 275 fr/10^6 hr. for the manufacturer.

As the customer's cost must be compared on pump operation in the same environment, all the customer's costs are determined as if all the groups were operating on shipboard pumping sea water.

The adjusted customer's relative costs for all groups are tabulated in Table V (Ref. 15, Table XIX) for the pumps operating in a shipboard sea water environment, per 1000 hours of operation, and are plotted versus failure rate and MTBF in Fig. 5 (Ref. 15, Fig. 22).

The total cost picture shows that the optimum reliability is in the range of 125 - 145 fr/10^6 hr. Table VI gives the adjusted customer's relative costs per 1000 hours of pump operation including cost of money procurement adjustment for 5x4 SK and KSK pumps. Figure 6 shows the picture of customer's total cost including cost of money procurement adjustment versus

TABLE IV

MANUFACTURER'S RELATIVE TOTAL COST INCLUDING

COST OF MONEY PROCUREMENT

Manufacturer's Cost	Units	Pump Groups							
		I	II	III	IV	V	VI	VII	VIII
1. Manufacturer's Total Cost	Relative to Base	4.561	4.580	5.117	5.071	15.33	14.81	4.247	4.377
2. Cost of Money Procurement (3.25 percent of Manufacturer's Total Cost)	Relative to Base	.149	.149	.166	.165	.498	.481	.138	.142
3. Manufacturer's Total Cost Including Cost of Money Procurement	Relative to Base	4.710	4.729	5.283	5.236	15.828	15.291	4.385	4.519
4. Manufacturer's Selling Price*	Relative to Base	5.040	5.060	5.653	5.603	16.936	16.361	4.692	4.835

* With 7% Fee as accepted by the Department of Defense.

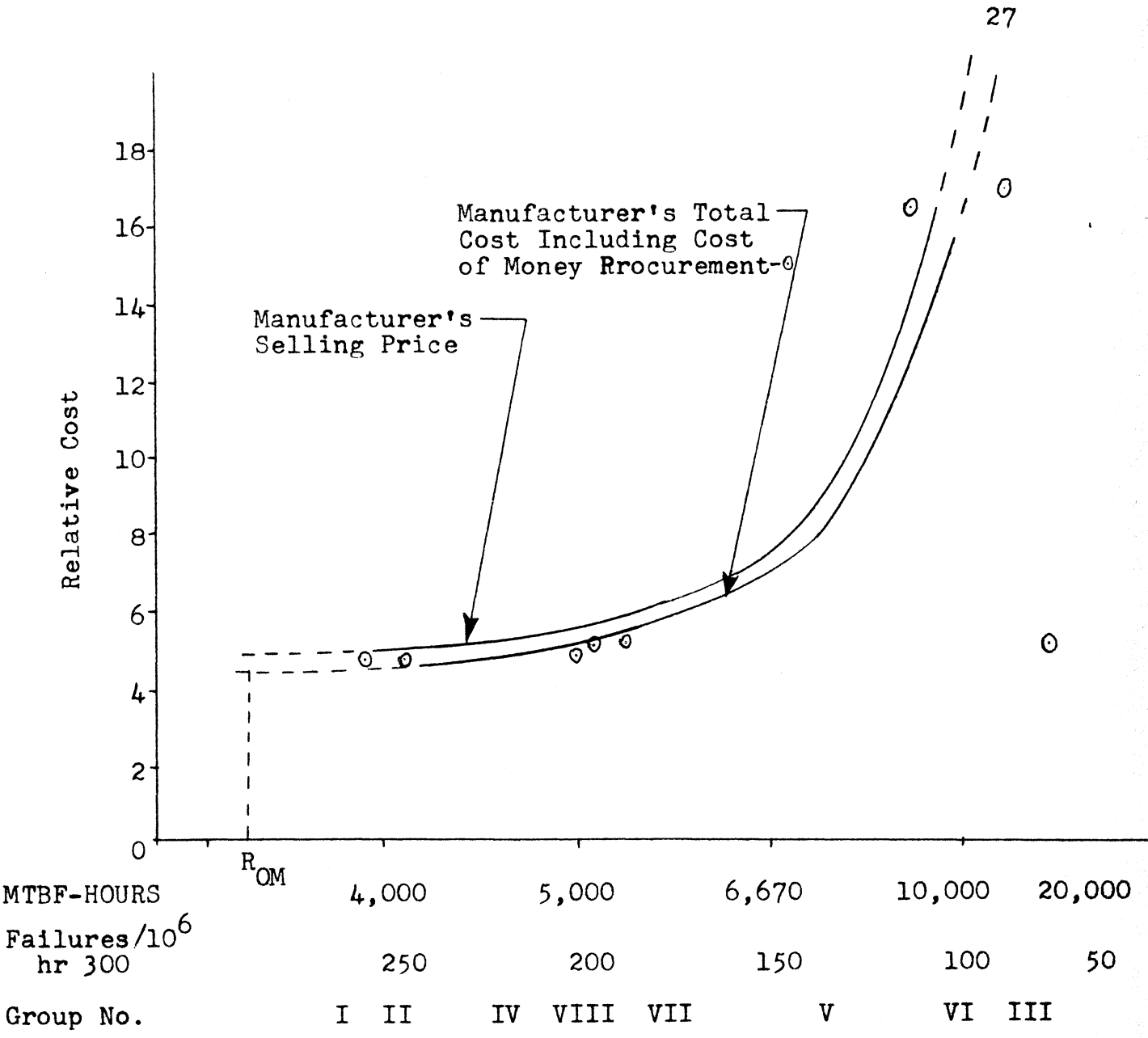


Fig. 4. Reliability and Manufacturer's Cost (Including Cost of Money Procurement Adjustment) for a 5x4 SK and KSK Pump (Shipboard Saltwater Environment)

TABLE V (Ref. 15, Table XIX)

ADJUSTED CUSTOMER'S RELATIVE COSTS* FOR 5x4 SK AND KSK PUMPS

WITHOUT COST OF MONEY PROCUREMENT ADJUSTMENTS

Cost Item	Group No. I	II	III	IV	V	VI	VII	VIII
1. Purchase Price	0.162	0.163	0.182	0.181	0.547	0.528	0.151	0.156
2. Unscheduled Replaced Parts	0.505	0.300	0.140	0.191	0.274	0.065	0.350	0.289
3. Unscheduled Labor	0.155	0.112	0.046	0.095	0.053	0.032	0.117	0.083
4. Unscheduled Downtime Cost	2.92	2.11	0.865	1.78	0.995	0.602	2.20	1.56
Total Unscheduled Repair Costs	3.580	2.522	1.051	2.066	1.322	0.699	2.667	1.932
5. Scheduled Replaced Parts	0.302	0.304	0.340	0.339	1.02	0.96	0.282	0.291
6. Scheduled Labor	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094
Total Scheduled Repair Cost	0.396	0.398	0.434	0.433	1.114	1.054	0.376	0.385
Total Customer Cost	4.138	3.083	1.667	2.680	2.983	2.281	3.194	2.473

* Relative cost per 1000 hours of pump operation

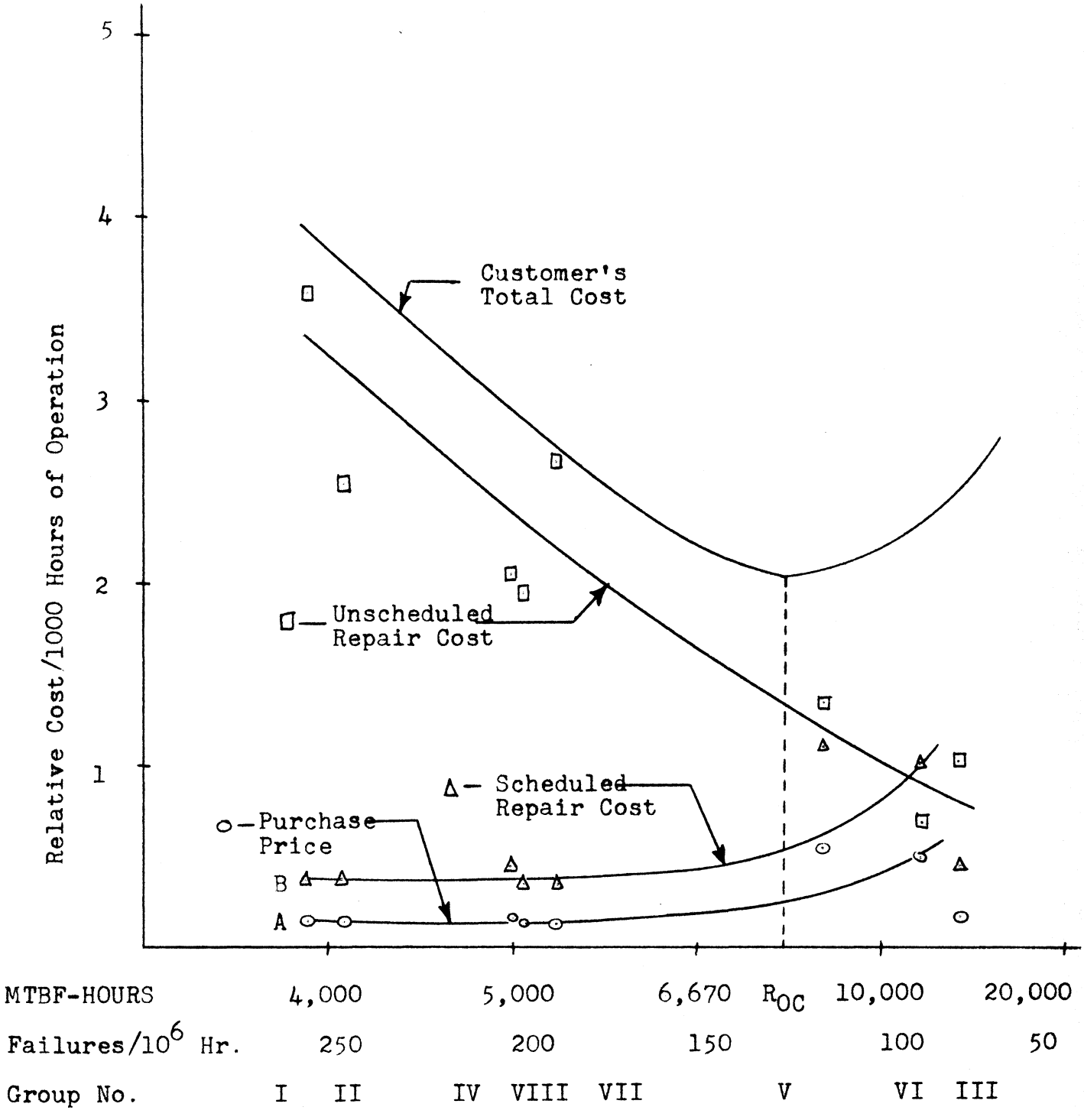


Fig. 5 (15, Fig. 22) Reliability and Customer's Cost for a 5x4 SK and KSK Pump (Shipboard Saltwater Environment)

TABLE VI

ADJUSTED CUSTOMER'S RELATIVE COSTS* FOR 5x4 SK AND KSK PUMPS

INCLUDING COST OF MONEY PROCUREMENT

Cost Item	Group No. I	II	III	IV	V	VI	VII	VIII
1. Manufacturer's Total Cost Including Cost of Money Procurement	4.710	4.729	5.283	5.236	15.828	15.291	4.385	4.519
2. Customer's Purchace Price**	5.040	5.06	5.653	5.603	16.936	16.361	4.692	4.835
3. Customer's Purchase Price*	0.168	0.169	0 188	0.187	0.565	0.545	0.156	0.161
4. Total Unscheduled Repair Costs*	3.580	2.522	1.051	2.066	1.322	0.699	2.667	1.932
5. Total Scheduled Repair Costs*	0.396	0.398	0.434	0.433	1.114	1.054	0.376	0.385
6. Total Customer's Cost Including Cost of Money Procurement	4.144	3.089	1.673	2.686	3.001	2.298	3.199	2.478

* Relative Cost Per 1000 Hours of Pump Operation
** With 7% Fee as accepted by Department of Defense.

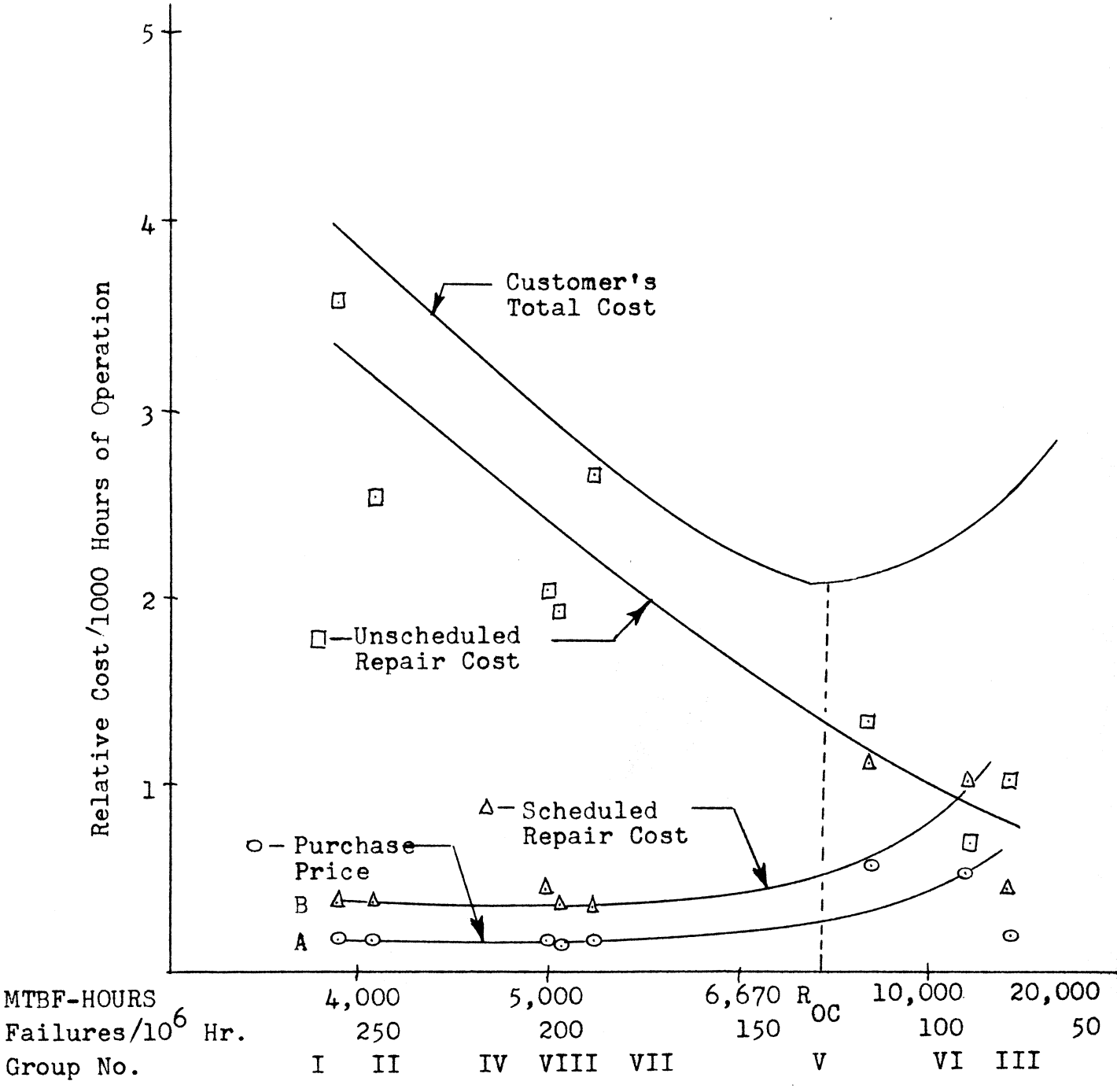


Fig. 6 Reliability and Customer's Cost, including Cost of Money Procurement Adjustment, for a 5x4 SK and KSK Pump (Shipboard Saltwater Environment)

failure rate and MTBF. Say, theoretically, customer's cost of money procurement should be included in Table VI; however, this as in the case of the manufacturer would insignificantly affect the optimum customer's reliability; consequently, this has not been added to item 2 of Table VI. From the figure, optimum level of reliability is found to be in the same range of 125 - 145 fr/10^6 hr. This may be because of the fact that out of three major cost components shown in Fig. 5, the initial purchase price is the lowest and if the cost of money procurement is added to this initial cost, it will not considerably affect the customer's total cost picture. Consequently, the optimum reliability for the customer's minimum total cost remains in the same range of 125 - 145 fr/10^6 hr.

CHAPTER 3

MATH MODELS BETWEEN TOTAL COSTS FOR THE MANUFACTURER AND THE CUSTOMER AND RELIABILITY

3.1 Difficulties in Obtaining Exact Mathematical Formula

Development of a math model for any considerable number of points is liable to require an excessive amount of numerical nature and the model developed will be long and unwieldly for practical applications. This shows that it is not advisable to go for absolute accuracy, since simplicity in the formula is an important practical consideration.

The object of a method of approximation is to obtain the simplest mathematical formula which will represent given data with sufficient accuracy to serve the purpose for which the formula is intended. There are various methods of approximation, the most important and most frequently used one being "Approximation by Method of Least Squares."

In this study, the method of least squares is used to develop a math model between total costs for the manufacturer and the customer and reliability.

3.2 Math Model for Manufacturer's Total Cost with Cost of Money Procurement Adjustment and Reliability

Here we have to develop a math model to represent a curve of the manufacturer's total cost with the cost of money procurement adjustment versus reliability (Fig. 4). This is done by selecting the following four points on the above curve:

Failure Rate (λ)	Manufacturer's Total Cost (C_M)
fr/10^6 hr.	Relative dollars
100	15.6
125	9.5
175	5.6
225	4.7

Now let us assume the math model to be in the form

$$a + b\lambda + c\lambda^2 = C_M \tag{3.1}$$

and substitute the given values for λ and C_M, obtaining

$$\begin{aligned} a + 100\,b + 10{,}000\,c &= 15.6 \\ a + 125\,b + 15{,}625\,c &= 9.5 \\ a + 175\,b + 30{,}625\,c &= 5.6 \\ a + 225\,b + 50{,}625\,c &= 4.7 \end{aligned}$$

$$4a + 625\,b + 106{,}875\,c = 35.4 \tag{3.2}$$

We now multiply each equation by the coefficient of a in that equation and add, as shown above; next we multiply each equation by the coefficient of b in that equation and add; then we multiply each equation by the coefficient of c in that equation and add, as shown below:

$$\begin{aligned}
100\,a + 10{,}000\,b + 1{,}000{,}000\,c &= 1{,}560.0\\
125\,a + 15{,}625\,b + 1{,}953{,}125\,c &= 1{,}187.5\\
175\,a + 30{,}625\,b + 5{,}359{,}375\,c &= 980.0\\
225\,a + 50{,}625\,b + 11{,}390{,}625\,c &= 1{,}057.5\\
\hline
625\,a + 106{,}875\,b + 19{,}703{,}125\,c &= 4{,}785.0
\end{aligned} \tag{3.3}$$

and

$$\begin{aligned}
10{,}000\,a + 1{,}000{,}000\,b + 100{,}000{,}000\,c &= 156{,}000.0\\
15{,}625\,a + 1{,}953{,}125\,b + 244{,}140{,}625\,c &= 148{,}437.5\\
30{,}625\,a + 5{,}359{,}375\,b + 937{,}890{,}625\,c &= 171{,}500.0\\
50{,}625\,a + 11{,}390{,}625\,b + 2{,}562{,}890{,}625\,c &= 237{,}937.5\\
\hline
106{,}875\,a + 19{,}703{,}125\,b + 3{,}844{,}921{,}875\,c &= 713{,}875.0
\end{aligned} \tag{3.4}$$

Solving simultaneously the three equations just obtained, we find a = 47.63, b = -0.433, c = 0.00108, so that the desired equation is

$$C_M = 47.63 - 0.433\,\lambda + 0.00108\,\lambda^2 \tag{3.5}$$

3.3 Math Model for Customer's Total Cost with Cost of Money Procurement Adjustment and Reliability

In the same way, here, we have to develop a math model to represent a curve of the customer's total cost with the cost of money procurement adjustment versus reliability (Fig. 6). From the above curve, the following four points are selected:

Failure Rate (λ)	Customer's Total Cost (C_C)
fr/10^6 hr.	Relative dollars
75	2.5
125	2.0
175	2.5
225	3.2

Substituting these values of λ and C_C in equation 3.1, we get

$$a + 75\,b + 5{,}625\,C = 2.5$$
$$a + 125\,b + 15{,}625\,c = 2.0$$
$$a + 175\,b + 30{,}625\,c = 2.5$$
$$a + 225\,b + 50{,}625\,c = 3.2$$

$$4\,a + 600\,b + 102{,}500\,c = 10.2 \qquad (3.6)$$

Next we multiply each equation by the coefficient of b in that equation and add; then we multiply each equation by the coefficient of c in that equation and add, as shown below:

$$
\begin{aligned}
75\,a + 5{,}625\,b + 320{,}625\,c &= 187.5 \\
125\,a + 15{,}625\,b + 1{,}953{,}125\,c &= 250.0 \\
175\,a + 30{,}625\,b + 5{,}359{,}375\,c &= 437.5 \\
225\,a + 50{,}625\,b + 11{,}390{,}625\,c &= 720.0 \\
\hline
600\,a + 102{,}500\,b + 19{,}023{,}750\,c &= 1{,}595.0 \qquad (3.7)
\end{aligned}
$$

and

$$
\begin{aligned}
5{,}625\,a + 320{,}625\,b + 31{,}640{,}625\,c &= 14{,}062.5 \\
15{,}625\,a + 1{,}953{,}125\,b + 244{,}140{,}625\,c &= 31{,}250.0 \\
30{,}625\,a + 5{,}359{,}375\,b + 937{,}890{,}625\,c &= 76{,}562.5 \\
50{,}625\,a + 11{,}390{,}750\,b + 2{,}562{,}890{,}625\,c &= 162{,}000.0 \\
\hline
102{,}500\,a + 19{,}023{,}750\,b + 3{,}776{,}562{,}500\,c &= 283{,}875.0 \qquad (3.8)
\end{aligned}
$$

Solving simultaneously these three equations, we get $a = 1.71$, $b = 0.0062$, $c = 0.0000034$, so that the desired equation is

$$C_C = 1.71 + 0.0062\,\lambda - 0.0000034\,\lambda^2 \qquad (3.9)$$

It is to be pointed out here that the above cost versus reliability math models are based on the pump life of 30,000 hours and with the assumption that the customer follows the preventive maintenance schedule suggested by the manufacturer. In the following sections the effect of change of life and maintenance schedule on optimum reliability is analyzed.

CHAPTER 4

MAINTENANCE COST OPTIMIZATION

4.1 Necessity of Preventive Maintenance

The costs of maintaining equipment usually constitute an important part of the total costs of operating the equipment, especially if the equipment is subject to frequent failure and if service interruption entails significant costs in addition to those involved in the actual repair. Maintenance policies are, therefore, getting more and more important and industries have to employ thousands of mechanics to maintain and repair the parts which have come to the end of their finite lives.

In some cases, it is possible to reduce the maintenance costs by establishing a preventive-maintenance policy consisting of periodic, scheduled replacement of parts prior to their wearout failure in operation. When the schedule for such preventive replacement is correctly chosen, considerable savings can result. However, if preventive replacement is performed on the wrong time schedule, maintenance costs can be even higher than those obtained when maintenance consists solely of repair of in-service failures.

The total cost to the user of the equipment consists of:

1. Initial cost of the system
2. Corrective and preventive maintenance costs
3. Operation costs (personnel and training, support and administration, transportation and supply, etc.)

The operation costs and other costs, such as installation and floor space, do not affect the optimum reliability; consequently, they are not considered in this study.

The object of this study is to minimize the total cost to the user so that the utilization of the available money to the customer is maximized. This total cost would tend to decrease with a decrease in system failures due to wearout until the increased cost required to obtain a system with fewer failures overwhelms the saving in total maintenance expenses. Thus, saving of dollars is directly concerned with the finding of the optimum level of reliability and scheduled maintenance policy which will bring the total cost of the pump to the user over its life to a minimum.

4.2 Types of Maintenance Actions

All repairable systems which are in operation for some time are subject, at one time or another, to maintenance. The importance of maintenance is understood when

one realizes the fact that "properly maintained equipment never really dies." When maintenance becomes a very costly affair, then the equipment is junked.

There are two basic types of components: those that upon failure or wearout can be repaired and those that cannot be repaired. Servicing is performed regularly during operation or at suitable intervals for components which require such attention as lubrication, refueling, cleaning, adjustment, alignment, etc. For all the components, there are two main types of maintenance action:

1. Corrective or repair or unscheduled maintenance, which takes place when the machinery fails to perform its function. Its purpose is to restore system operation as soon as possible by replacing or repairing the part or parts which cause the failure. Here the part usually fails by chance.

2. Preventive or scheduled maintenance which takes place at scheduled intervals. Here parts nearing wearout or fatigue are replaced or other necessary arrangements are made to avoid normal wearout or fatigue failures during equipment operation.

Demands for greater preventive maintenance effort are based generally on the belief that a high level of scheduled preventive maintenance will result in longer

failure-free operating periods, reduced unscheduled maintenance, and less unscheduled downtime. Preventive maintenance thus increases the operational reliability of equipment by eliminating a substantial portion of wear and fatigue failures. However, chance failures are not affected by preventive maintenance, since they are unpredictable and occur suddenly.

Therefore, by scheduling some system time for careful periodic inspection and testing of equipment to locate and replace weak components, clean certain surfaces, apply lubricants, and correct misadjustment, it is possible to eliminate the cause of many potential failures which otherwise would have produced unscheduled interruptions in productive operating time. Assuming that the most important preventive maintenance procedures would be handled first, a small amount of system time devoted to preventive maintenance would be expected to yield a worthwhile improvement in reliability by reducing the number of potential failures. Increasing amounts of system time devoted to preventive maintenance can be expected to yield further reductions of the remaining potential failures, but eventually the point of saturation will be reached where even all the system time devoted to preventive maintenance cannot detect all potential weaknesses nor can it prevent catastrophic failures.

Thus, one has to search for an optimum solution. The optimum solution can be one which maximizes reliability at an economically bearable maintenance cost or minimizes maintenance cost for an acceptable reliability level.

4.3 Types of Different Policies for Optimum Preventive Maintenance

There are two basic preventive maintenance policies.

Policy I

Perform preventive maintenance after T hours of continuous operation without failure. The possibility that T may be infinite, shows that in that case no preventive maintenance can be scheduled. If the system fails before T hours have elapsed, perform maintenance at the time of failure. Preventive maintenance is then rescheduled. In other words, the component is preventively replaced always after it has been in operation for T hours and is correctively replaced when it fails. Also, in this policy it is assumed that the system is as good as new after any type of maintenance (or replacement) is performed.

Policy II

Perform preventive maintenance on the system after it has been operating a total of T hours regardless of the number of intervening failures. Again the possibility that T may be infinite shows that there will be some failures and it is assumed that after each failure only minimal repair is made and that the system failure rate is not disturbed after performing minimal repair.

For less complex equipment, repair or replacement at the time of failure may actually correspond to general overhaul and, therefore, Policy I may be used. However, for more complex systems, preventive maintenance is commonly scheduled after a certain number of operating hours have accumulated and, therefore, Policy II may be used.

Because a centrifugal pump is a complex system containing many components, Policy II will be employed to find out the optimum preventive maintenance time.

4.4 Determination of Scheduled Overhaul or Replacement Time

The main function of a scheduled overhaul is to prevent the component to enter the wearout portion of its life. An extension of this overhaul time will thus depend upon the equipment's mean wearout life and its standard deviation.

When the equipment is subject to wearout failures, as is the case for the pump under consideration, then the scheduled replacement time, T_o, may be obtained from

$$T_o = M - k\sigma \tag{4.1}$$

where

M = mean wearout life

σ = standard deviation

k = the value read from normal tables depending upon the maximum allowable percent of failures between two regular overhauls.

Table VII gives the assumed value of the mean and standard deviation of some of the main centrifugal pump components. Ninety-five percent confidence level, failures not exceeding one percent, and a sample size of nine are assumed for all components.

The replacement time, T_o, for the pump casing is obtained as follows: Lower confidence limit of the mean wearout life, L, is given by (23, p. 198)

$$L = \hat{M} - t_{\alpha,n-1}\frac{s}{\sqrt{n}} \tag{4.2}$$

where percent confidence level = 95% = 100 $(1-\alpha)$ %, estimate of mean wearout life = $\hat{M}$ = 60,000 hours, estimate of standard deviation = s = 6,000 hours. Number of samples = n = 9. $t_{0.05,8} = 1.86$ from 't' tables.

Therefore,

$$L = 60,000 - 1.86 \frac{6,000}{3} = 56,280 \text{ hours.}$$

Upper one-sided confidence limit for component standard deviation, S_u, from Chi square tables is given by (23, p. 233)

$$S_u = s\sqrt{\frac{n-1}{X^2_{1-\alpha,n-1}}} \quad \text{where } X^2_{0.9,8} = 3.49 \qquad (4.3)$$

$$= 6,000\sqrt{\frac{8}{3.49}} = 6,000 \times 1.513$$

$$= 9.078 \text{ hours.}$$

TABLE VII

MEAN WEAROUT LIFE AND STANDARD DEVIATION OF THE MAIN COMPONENTS OF 5x4 SK AND KSK CENTRIFUGAL PUMPS BASED ON NINE SAMPLES

Component	Mean Wearout Life	Standard Deviation
	Hours	Hours
1. Casing	60,000	6,000
2. Impeller	20,000	2,500
3. Shaft	12,000	1,500
4. Shaft Sleeve	8,000	1,000
5. Ball Bearing	12,000	1,833

The pump casing replacement time, T_o, with 95% confidence is given by (23, p. 233)

$T_o = L - k\, S_u$ (14) where k = 2.34 from normal tables for failures not exceeding 1 percent

$= 56,280 - 2.34 \times 9078$

$= 35,040$ hours.

Similarly, the replacement time for the impeller is obtained from

$$L = \hat{M} - t_{\alpha,n-1} \frac{s}{\sqrt{n}}$$

$$= 20,000 - 1.86 \frac{2,500}{3}$$

$$= 18,450 \text{ hours}$$

$$S_u = S \sqrt{\frac{n-1}{X^2_{1-\alpha,n-1}}}$$

$$= 2.500 \times 1.513$$

$$= 3782 \text{ hours}$$

$$T_o = L - k\, S_u$$

$$= 18,450 - 2.34 \times 3782$$

$$= 9,607 \text{ hours}$$

The replacement time for the shaft is obtained from

$$L = \hat{M} - t_{\alpha,n-1} \frac{s}{\sqrt{n}}$$

$$= 12,000 - 1.86 \frac{1,500}{3}$$

$$= 11,070 \text{ hours}$$

$$S_u = S \sqrt{\frac{n-1}{\chi^2_{1-\alpha,n-1}}}$$

$$= 1,500 \times 1.513$$

$$= 2,269 \text{ hours}$$

$$T_o = L - k S_u$$

$$= 11,070 - 2.34 \times 2,269$$

$$= 5,761 \text{ hours}$$

The replacement time for the shaft sleeve is obtained from

$$L = \hat{M} - t_{\alpha,n-1} \frac{s}{\sqrt{n}}$$

$$= 8,000 - 1.86 \frac{1,000}{3}$$

$$= 7,380 \text{ hours}$$

$$S_u = s\sqrt{\frac{n-1}{X^2_{1-\alpha,n-1}}}$$

$$= 1{,}000 \times 1.513$$

$$= 1{,}513 \text{ hours}$$

$$T_o = L - k\,S_u$$

$$= 7{,}380 - 2.34 \times 1{,}513$$

$$= 3{,}840 \text{ hours}$$

Finally, the replacement time for the bearings is obtained from

$$L = \hat{M} - t_{\alpha,n-1}\frac{s}{\sqrt{n}}$$

$$= 12{,}000 - 1.86 \times \frac{1{,}833}{3}$$

$$= 10{,}864 \text{ hours}$$

$$S_u = s\sqrt{\frac{n-1}{X^2_{1-\alpha,n-1}}}$$

$$= 1{,}833 \times 1.513$$

$$= 2{,}773 \text{ hours}$$

$$T_o = L - k\,S_u$$

$$= 10{,}864 - 2.34 \times 2{,}773$$

$$= 3{,}959 \text{ hours}$$

4.5 Grouping of Various Pump Components According to Their Scheduled Replacement Time under the Policy of Performing Preventive Maintenance after Every T Hours Regardless of the Number of Intervening Failures

Centrifugal pump is a complex mechanical system and there is the possibility of many types and degrees of failure. If the system fails because the i^{th} component has failed, then the system is said to have failed in the i^{th} mode and the probability of failure in the i^{th} mode is the probability that i^{th} component fails before any of the other components.

Therefore, for this complex system, we have to adopt the preventive maintenance policy in which the schedule of preventive replacements does not alter after a failure has been replaced. Thus, under this policy there is no need to keep intensive records of the in-service failures of all the components.

To effect such a preventive maintenance policy, it is necessary to categorize all the pump components into groups according to their scheduled replacement times and accessibility. Here, all the components will be divided into three groups according to their scheduled replacement time, and the effect of accessibility of different components will be considered at the end of this chapter.

Let the categorizing of different pump components be represented as:

Group 1 - Those having scheduled replacement times over 12,000 hours

Group 2 - Those having scheduled replacement times between 6,000 hours and 12,000 hours

Group 3 - Those having scheduled replacement times under 6,000 hours.

Table VIII gives a list of all components used in 5x4 SK and KSK centrifugal pumps distributed under these three groups. The scheduled replacement time of some of the major components is already discussed in the previous section. As the wearout failure data of other components are not presently available, assumption is made that all other minor components have higher wearout life resulting in scheduled replacement time of over 12,000 hours. Therefore, all these components are categorized under Group 1. In practice, however, as indicated before, while performing the preventive maintenance for Group 2 or Group 3, some of the components under Group 1 are readily accessible and they may also be preventively replaced.

Table VIII also gives the approximate cost which is arrived at by discussions with Roy C. Hughes

TABLE VIII

COST AND MEAN GENERIC FAILURE RATE OF ALL COMPONENTS OF 5x4 SK AND KSK CENTRIFUGAL PUMPS

Group 1

Item No.	Component Name	Cost (dollars)	Mean Generic Failure Rate ($fr/10^6$ hr.)
3	Shaft Nut R. H.	1.0	0.0042
4	Shaft Nut L. H.	1.0	0.0042
5	Casing Ring (2)*	5.0	0.10
6	Casing Bushing (2)	10.0	0.1084
7	Ball Bearing Adapter (O.E.)	5.0	0.137
8	Adapter Cap (O.E.)	2.0	0.012
9	Spacer Sleeve (O.E.)	5.0	0.050
11	Bearing End Plate Style #1	5.0	0.088
12	Bearing Lock Washer (O.E.)	0.50	0.002
13	Bearing Lock Nut (O.E.)	1.0	0.002
14	Ball Bearing Adapter (C.E.)	5.0	0.137
15	Adapter Cap (C.E.)	2.0	0.012
16	Spacer Sleeve (C.E.)	5.0	0.050
18	Bearing Lock Washer (C.E.)	0.50	0.002
19	Bearing Lock Nut (C.E.)	1.0	0.002
20	Alemite Fitting (2)	1.0	0.055
21	Straight Key	5.0	0.14
22	Step Key	1.0	0.09
23	"O" Ring	1.0	0.04
25	Impeller Ring	5.0	0.1
26	Machine Screw (12)	5.0	0.025
27	Lock Washer (12)	5.0	0.025
29	Casing (Upper Half)	300.0	-
30	Casing (Lower Half)	425.0	-
31	Bearing End Plate Style #2	5.0	0.088
32	Gland (4 Halves)	20.0	0.125
33	Gland Bolts (4)	2.0	0.034
34	Seal Cage (4 Halves)	15.0	0.05

Note: Rotating Assembly (28) is mainly made of the following components: 1, 2, 3, 4, 8, 9, 10, 11, 12, 13, 15, 17, 18, 19, 20, 21, 24.

TABLE VIII

(Contd)

COST AND MEAN GENERIC FAILURE RATE OF ALL COMPONENTS OF 5x4 SK AND KSK CENTRIFUGAL PUMPS

Group 1

(Contd)

Item No.	Component Name	Cost (dollars)	Mean Generic Failure Rate (fr/10^6 hr.)
35	Oil Hole Cover (2)	1.0	0.0000
36	Alemite Collar (2)	2.0	0.0000
37	Valve Stem (2)	5.0	0.336
38	Packing	2.0	0.70
39	Gasket Suction	5.0	0.138
40	Gasket Discharge	5.0	0.138
41	Straight Dowel (2)	10.0	0.008
42	Pipe Plug	2.0	0.0000
43	Aircock Tee Handle	2.0	0.084
44	S. F.Hexagonal Nut (4)	2.0	0.016
45	Drive Screw (20)	4.0	0.04
46	Casing Gasket	5.0	0.138
47	Hex. Set Screw (2)	1.0	0.0084
48	Crankcase Sealer	5.0	0.01
49	Bearing Cap	2.0	0.2666
50	#0 Taper Dowel	3.0	0.016
51	#1 Taper Dowel	3.0	0.008
52	Cap Screw	1.0	0.044
53	Coupling Lock Nut	1.0	0.04
	Group 2		
24	Impeller	100.0	0.15
	Group 3		
1	Shaft	50.0	0.35
2	Shaft Sleeves (2)	50.0	0.30
10	Ball Bearing (O.E.)	50.0	1.570
17	Ball Bearing (C.E.)	50.0	1.340

* The number in parentheses indicates the number required. The cost and failure rate given in the columns are multiplied by the number.

(co-author, Ref. 15). The mean generic failure rates are taken from Table VI, Ref. 15.

As Group 1 components have high scheduled replacement time, let us assume that these components are replaced correctively if and when they fail; whereas, let Group 2 components be preventively replaced after every T_1 hours and Group 3 components be preventively replaced after every T_2 hours where T_1 will be greater than T_2.

4.6 Maintenance Cost Optimization

The calculations for numerical reliability evaluation are based on the long-term average failure rates of the parts. The stabilized average failure rate of the machine is approximately

$$\lambda_M = \sum_{h=1}^{n-k-s} \frac{1}{M_h} + \sum_{i=1}^{k} \frac{1}{M_i(T_1)} + \sum_{j=1}^{s} \frac{1}{M_j(T_2)} \qquad (4.5)$$

(Ref. 16, p. 43)

where

M_h = mean time to failure of the h^{th} component from Group 1

M_i = mean time to failure of the i^{th} component from Group 2 which is preventively replaced after every T_1 hours

M_j = mean time to failure of the j^{th} component from Group 3 which is preventively replaced after every T_2 hours.

This is a general equation when n-k-s parts given in Group 1 are only correctively replaced, k parts given in Group 2 are replaced preventively after every T_1 hours, and s parts given in Group 3 are replaced preventively after every T_2 hours.

Mean time to failure of the part

$$M_h = \int_0^\infty R_h (t)\, dt \tag{4.6}$$

for the h^{th} part of the n-k-s parts.

Assuming that early failures caused by deficient materials or poor workmanship are preventively eliminated, reliability of each component is then the product of the exponential probability of surviving, R_c (t), and the nonexponential probability of surviving wearout, R_w (t).

$$R (t) = R_c (t) \times R_w (t) \tag{4.7}$$

$$= e^{-\lambda_c t} \times \int_t^\infty f (t)\, dt \tag{4.8}$$

Assuming that wearout failures of well-designed long-life mechanical parts can be approximately represented by a normal, Gaussian distribution,

$$M = \int_0^{\infty} e^{-\lambda_c t} \left[\int_t^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-M}{\sigma}\right)^2} dt \right] dt \qquad (4.9)$$

Let

$$T = \frac{t-M}{\sigma}$$

$$dt = \sigma dT$$

When

$$t = t \qquad T = \frac{t-M}{\sigma}$$

$$t = \infty \qquad T = \infty$$

Therefore

$$M = \int_0^{\infty} e^{-\lambda_c t} \left[\int_{\frac{t-M}{\sigma}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{T^2}{2}} dT \right] dt \qquad (4.10)$$

For example, if one of the components given in Group 1 has mean wearout life (M) equal to 120,000 hours, a standard deviation (σ) equal to 15,000 hours and a chance failure rate (λ_c) equal to 0.09 fr/10^6 hours, then, by substitution in equation 4.10, we get,

$$M = \int_0^{\infty} e^{-0.09\times10^{-6}t} \left[\int_{\frac{t-120,000}{15,000}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{\frac{-T^2}{2}} dT \right] dt$$

The value of the integral inside the brackets can be found by taking different values of t and finding the corresponding areas under the normal curve from normal tables. Then by plotting different values of t as the abcissa and the product of exponential term and the area found from normal tables at those values of t as the ordinate, the value of the whole integral can be found as the area under this plot from t = o to t = ∞.

Table IX gives the value of exponential term and Table X gives the area under normal curve for different values of t. Table XI gives the product of these two terms for various values of t. Figure 7 shows the effect of t on the product of exponential term and the area under normal curve. From this figure, the area under the curve is found to be approximately 120,000 hours which is the value of the whole integral.

Similarly, the value of M_h (mean time to failure) for other components given in Group 1 can be found.

As the components given in Group 2 are preventively replaced, the procedure to obtain their failure rate is different than for Group 1, and is as follows (Ref. 16, p. 41):

TABLE IX

CHANCE RELIABILITY $\left[R_c\ (t)\right]$

VALUE OF EXPONENTIAL TERM $e^{-\lambda_c t}$ FOR DIFFERENT VALUES OF t

FOR A PARTICULAR COMPONENT UNDER GROUP 1

Value of t (hours)	$R_c\ (t)$ Corresponding Value of $e^{-\lambda_c t}$ (λ_c = 0.09 fr/10^6 hours)
0	1.0000
1,000	0.9999
5,000	0.9995
10,000	0.9991
20,000	0 9982
30,000	0 9973
40,000	0.9964
50,000	0 9955
60,000	0.9946
70,000	0.9937
80,000	0.9928
90,000	0.9919
100,000	0.9910
110,000	0.9901
120,000	0.9892
130,000	0.9883
140,000	0.9874
150,000	0.9865
160,000	0.9856
170,000	0.9847
180,000	0.9838
190,000	0.9829

TABLE X

WEAROUT RELIABILITY (R_w) FOR DIFFERENT VALUES OF t FOR A PARTICULAR COMPONENT UNDER GROUP 1

M = 120,000 hours and σ = 15,000 hours.

$$R_w(t) = \int_{\frac{t-120,000}{15,000}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{T^2}{2}} dT$$

Value of t (Hours)	Area under Normal Curve
0	1.0
1,000	1.0
5,000	1.0
10,000	1.0
20,000	1.0
30,000	1.0
40,000	1.0
50,000	1.0
60,000	1.0
70,000	0.9996
80,000	0.9962
90,000	0.9773
100,000	0.9088
110,000	0.7475
120,000	0.5000
130,000	0.2525
140,000	0.0912
150,000	0.0227
160,000	0.0038
170,000	0.0004
180,000	0.0000
190,000	0.0000

TABLE XI

PRODUCT OF CHANCE AND WEAROUT RELIABILITIES FOR DIFFERENT VALUES OF t FOR A PARTICULAR COMPONENT UNDER GROUP 1

Value of t (hours)	$R_c(t) \times R_w(t)$ $e^{-\lambda_c t} \times \int_{\frac{t-120,000}{15,000}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{\frac{-T^2}{2}} dT$
0	1.0000
1,000	0.9999
5,000	0.9995
10,000	0.9991
20,000	0.9982
30,000	0.9973
40,000	0.9964
50,000	0.9955
60,000	0.9946
70,000	0.9933
80,000	0.9890
90,000	0.9694
100,000	0.9006
110,000	0.7401
120,000	0.4946
130,000	0.2495
140,000	0.0901
150,000	0.0224
160,000	0.0037
170,000	0.0004
180,000	0.0000
190,000	0.0000

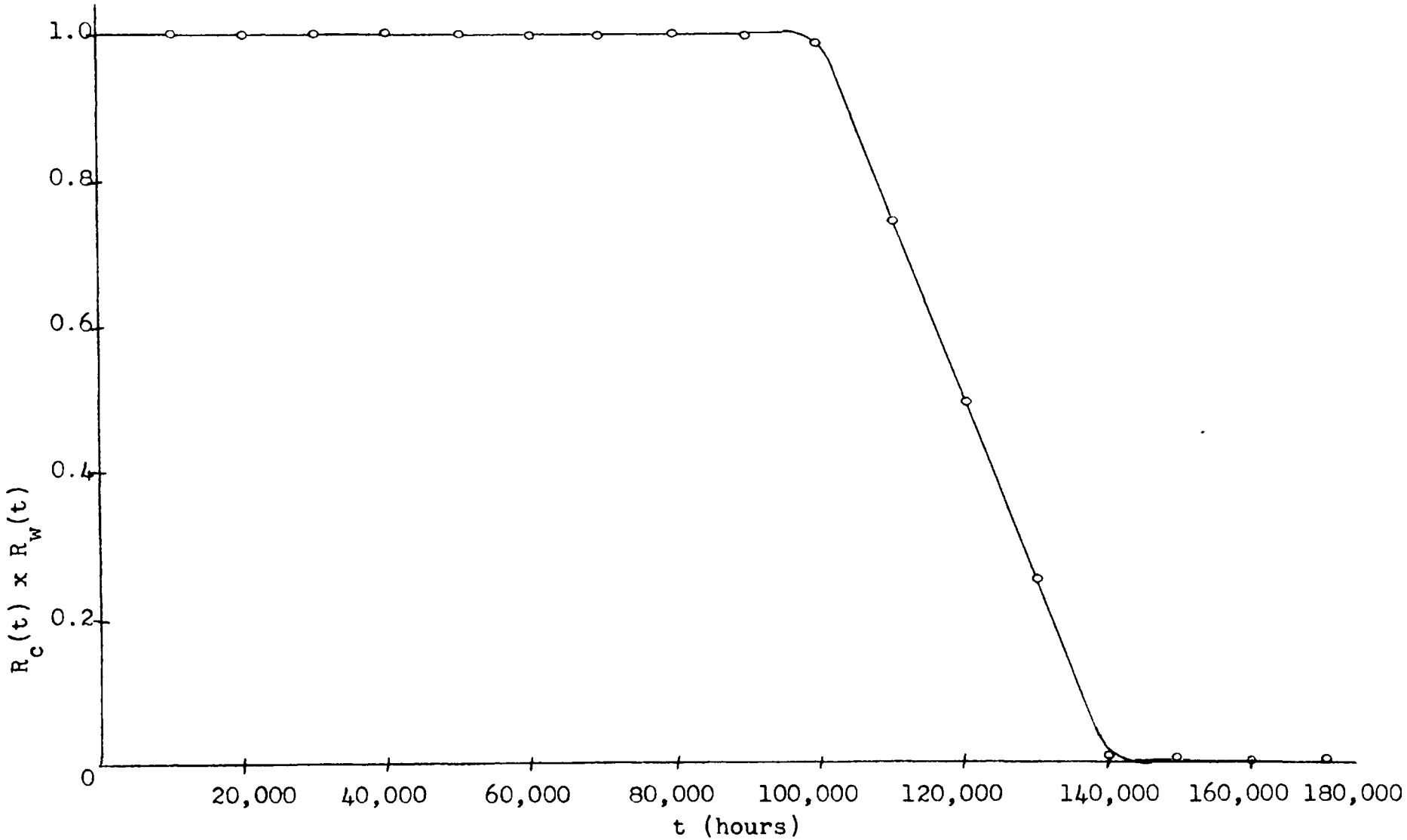


Fig. 7 Product of Chance and Wearout Reliabilities Versus Time for a Particular Component Under Group 1

$$\frac{1}{M_i\ (T_1)} = \frac{\int_0^{T_1} Q\ (t)\ dt}{T_1 \int_0^{T_1} R\ (t)\ dt} \tag{4.11}$$

$$= \frac{T_1 - \int_0^{T_1} R\ (t)\ dt}{T_1 \int_0^{T_1} R\ (t)\ dt} \tag{4.12}$$

where

T_1 = Preventive replacement time

$Q\ (t)$ = Unreliability

$R\ (t)$ = Reliability

t = Operating time

Where the value of R (t) is determined in the same way as shown before. Tables XII, XIII, XIV and XV give the chance reliability, wearout reliability, and their product for the impeller, shaft, shaft sleeve and bearing, considering different values of preventive maintenance time. While calculating the chance reliability for any component, its mean generic failure rate has been multiplied by ten (Ref. 15, Table XII). This figure is

TABLE XII

CHANCE AND WEAROUT RELIABILITY OF THE IMPELLER FOR DIFFERENT VALUES OF PREVENTIVE MAINTENANCE TIME (T_1)

Preventive Maintenance Time (T_1) (hours)	Chance Reliability R_c (t)	Wearout Reliability R_w (t)	Product of Chance and Wearout Reliability R_c (t)$\times R_w$ (t)
0	1.0	1.0	1.0
5,000	0.9925	1.0	0.9925
10,000	0.9850	1.0	0.9850
15,000	0.9775	0.9772	0.9552
20,000	0.9700	0.5000	0.4850
25,000	0.9625	0.0227	0.0219
30,000	0.9550	0.0000	0.0000

TABLE XIII

CHANCE AND WEAROUT RELIABILITY OF SHAFT FOR DIFFERENT VALUES OF PREVENTIVE MAINTENANCE TIME (T_2)

Preventive Maintenance Time (T_2)	Chance Reliability $R_c(t)$	Wearout Reliability $R_w(t)$	Product of Chance and Wearout Reliability $R_c(t) \times R_w(t)$
0	1.0	1.0	1.0
1,000	0.9965	1.0	0.9965
2,000	0.9930	1.0	0.9930
3,000	0.9895	1.0	0.9895
4,000	0.9860	1.0	0.9860
5,000	0.9825	1.0	0.9825
6,000	0.9790	1.0	0.9790
7,000	0.9755	0.9996	0.9752
8,000	0.9720	0.9962	0.9685
9,000	0.9685	0.9773	0.9464
10,000	0.9650	0.9098	0.8720
11,000	0.9615	0.7486	0.7191
12,000	0.9580	0.5000	0.4790
13,000	0.9545	0.2514	0.2400
14,000	0.9510	0.0901	0.0857
15,000	0.9475	0.0227	0.0215
16,000	0.9440	0.0038	0.0036
17,000	0.9405	0.0004	0.0004
18,000	0.9370	0.0000	0.0000

TABLE XIV

CHANCE AND WEAROUT RELIABILITY OF SHAFT SLEEVE FOR VARIOUS VALUES OF PREVENTIVE MAINTENANCE TIME (T_2)

Preventive Maintenance Time (T_2)	Chance Reliability $R_c(t)$	Wearout Reliability $R_w(t)$	Product of Chance and Wearout Reliability $R_c(t) \times R_w(t)$
0	1.0	1.0	1.0
1,000	0.9970	1.0	0.9970
2,000	0.9940	1.0	0.9940
3,000	0.9910	1.0	0.9910
4,000	0.9880	1.0	0.9880
5,000	0.9850	0.9986	0.9835
6,000	0.9820	0.9772	0.9596
7,000	0.9790	0.8413	0.7513
8,000	0.9760	0.5000	0.4880
9,000	0.9730	0.1587	0.1545
10,000	0.9700	0.0227	0.0220
11,000	0.9670	0.0013	0.0013
12,000	0.9640	0.0000	0.0000
13,000	0.9610	0.0000	0.0000

TABLE XV

CHANCE AND WEAROUT RELIABILITY OF BEARING FOR VARIOUS VALUES OF PREVENTIVE MAINTENANCE TIME (T_2)

Preventive Maintenance Time (T_2)	Chance Reliability R_c (t)	Wearout Reliability R_w (t)	Product of Chance and Wearout Reliability R_c (t) x R_w (t)
0	1.0	1.0	1.0
1,000	0.9843	1.0	0.9843
2,000	0.9686	1.0	0.9686
3,000	0.9529	1.0	0.9529
4,000	0.9372	1.0	0.9372
5,000	0.9215	0.9999	0.9214
6,000	0.9058	0.9995	0.9053
7,000	0.8901	0.9968	0.8873
8,000	0.8744	0.9854	0.8616
9,000	0.8587	0.9495	0.8153
10,000	0.8430	0.8621	0.7267
11,000	0.8273	0.7088	0.5864
12,000	0.8116	0.5000	0.4058
13,000	0.7459	0.2919	0.2323
14,000	0.7802	0.1379	0.1076
15,000	0.7645	0.0505	0.0386
16,000	0.7488	0.0150	0.0011

approximately the product of the application factor (k_A), the operating factor (k_{op}), and the design factor (k_G). Figure 8 gives the picture of reliability versus preventive maintenance time for these components.

The cost equation for minimizing maintenance costs of these parts is given by (Ref. 16, p. 43)

$$C_M = \sum_{h=1}^{n-k-s} \frac{C_h F}{M_h} + \sum^{k} \left(\frac{C_i P}{T_1} + \frac{C_i F}{M_i(T_1)}\right) + \sum^{s} \left(\frac{C_j P}{T_2} \quad \frac{C_j F}{M_j(T_2)}\right) \tag{4.13}$$

where

C_P = Preventive replacement cost

C_F = Corrective replacement cost

To determine the repair time and the repair labor cost, it is necessary to know how long it takes to reach each component and which components must be removed to reach a given one. This information is conveniently obtained with the help of an accessibility tree. An accessibility tree is a display of information which tells both the approximate time to reach and remove a given part or parts, and which part might be conveniently preventively maintained at the same time. It is assumed that disassembly times are the same as assembly times and, therefore, total time required to preventively replace any component will be twice the disassembly time of that component as given in Fig. 9.

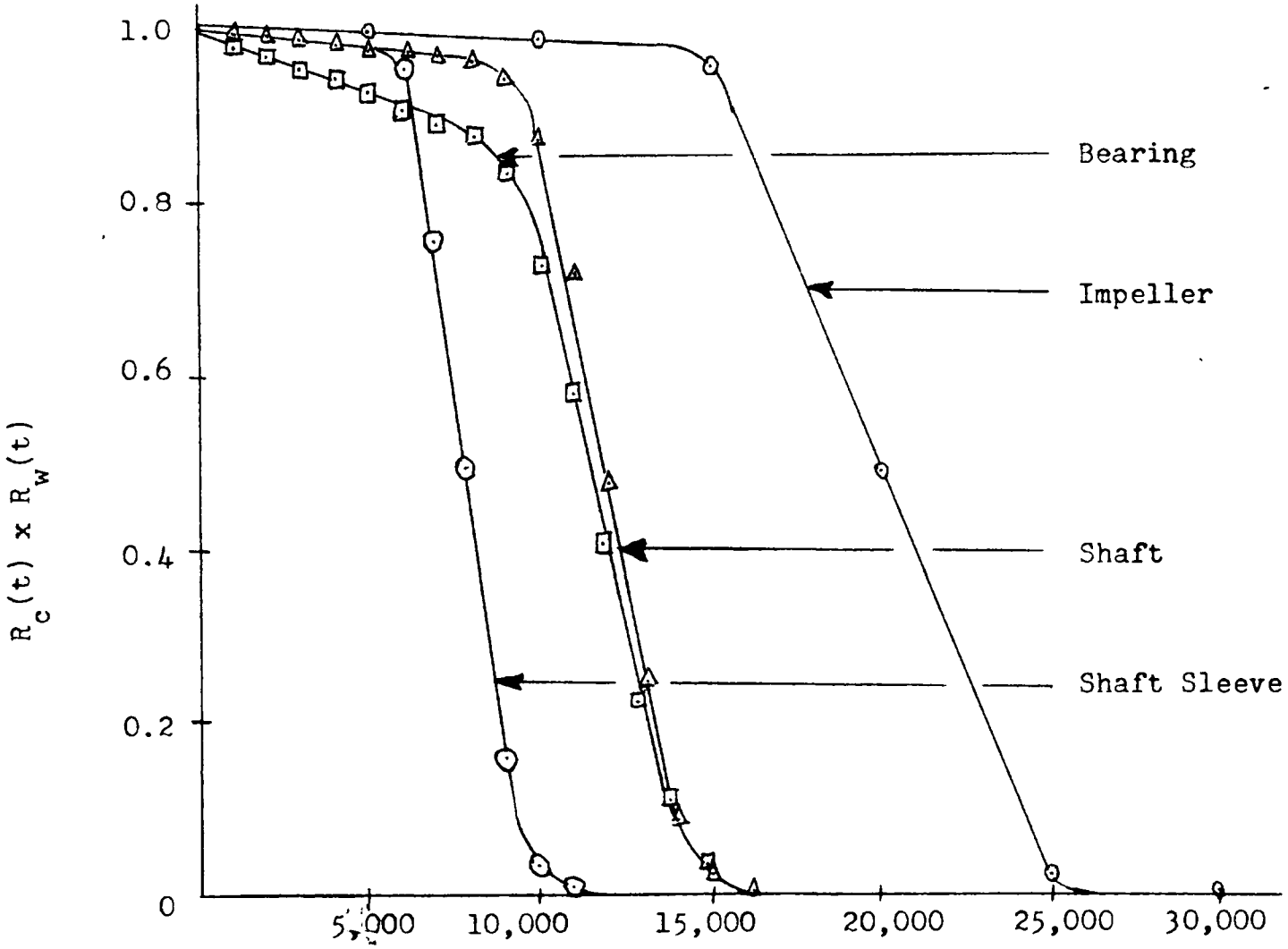
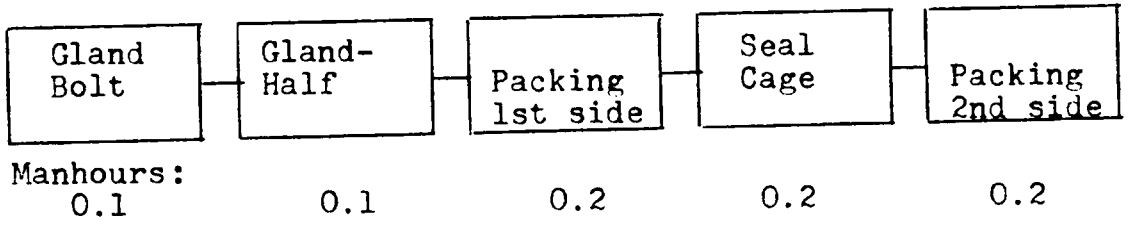
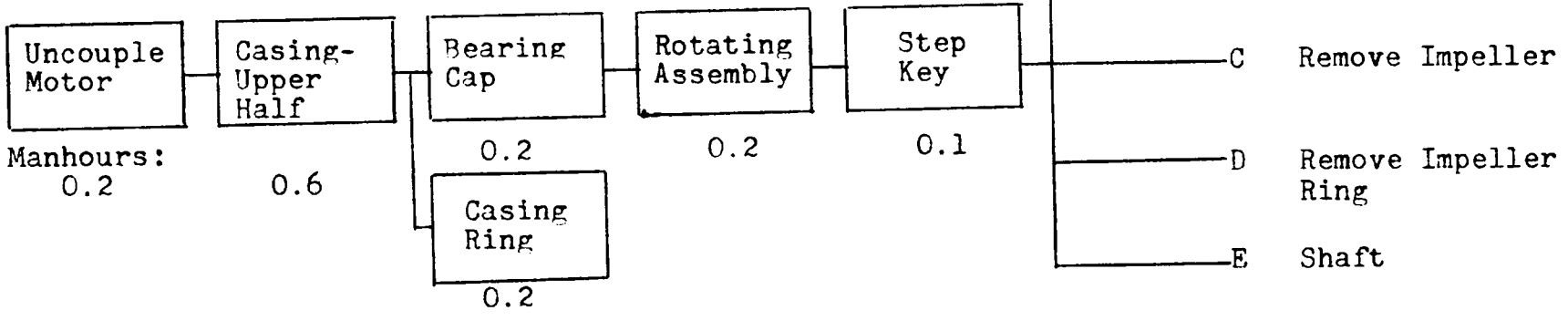


Fig. 8 Product of Chance and Wearout Reliability Versus Time for Different Components of 5x4 SK and KSK Pumps.

Case I - Remove packing (assume reverse for replacing packing)



Case II - General Pump Repair (assume reverse for replacement)



Branch A

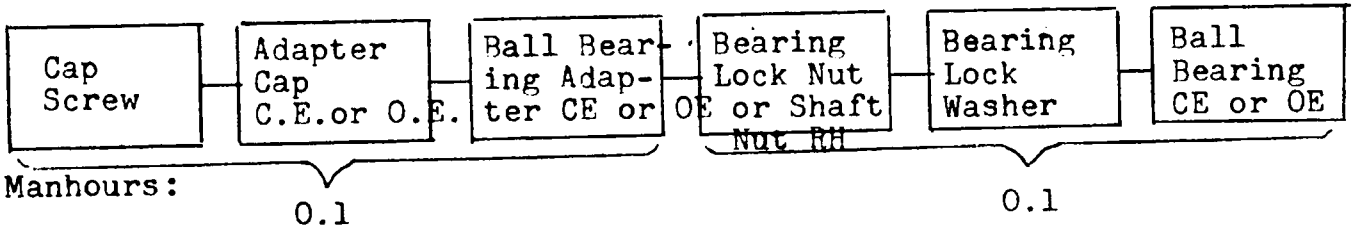
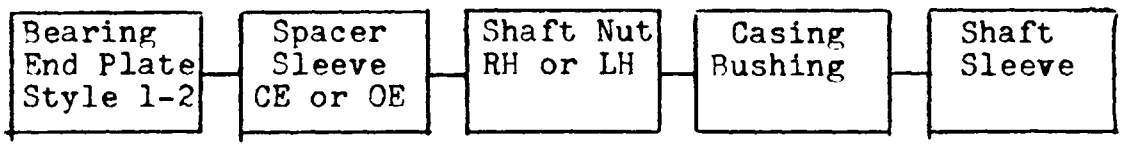
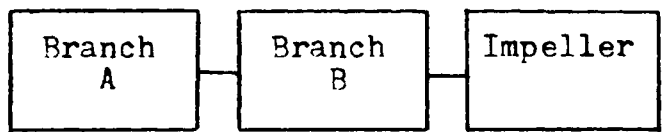


Fig. 9 Manhours Required for the Disassembly of the Different Parts of the Pump Given in the Form of an Accessibility Tree

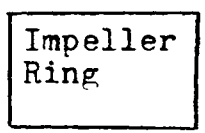
Branch B



Branch C



Branch D



Branch E

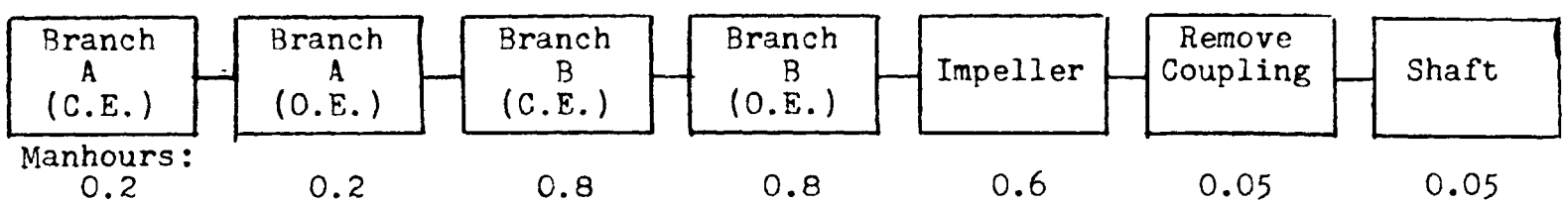


Fig. 9 (Contd) Manhours Required for the Disassembly of the Different Parts of the Pump Given in the Form of an Accessibility Tree

Note: C.E. = Coupling End; O.E. = Other End

This figure considers the following main components of the pump: packing, bearing, shaft sleeve, impeller, impeller ring and shaft.

Assuming pump remains bolted to floor and to piping and drainage pipes are not taken into account, the general disassembly of the pump requires manhours as follows:

Step	Manhours Required
Uncouple motor	0.2
Unbolt and remove top half of casing	0.6
Remove packing glands and packing	0.2
Remove bearing caps	0.2
Lift out rotating assembly	0.2
Remove coupling	0.05
Remove bearings (assembly)	0.2
Remove shaft sleeves	0.8
Remove impeller	0.6
Remove impeller ring	0.3
Remove casing ring	0.2

With this basic information, the manhours required for the diassembly of different parts of the pump are worked out as shown in Fig. 9.

As packing could be replaced without removing the casing, it is treated separately to calculate the total manhours required for its disassembly. This is given

under Case I of the above figure. Replacement of all other components first requires the removal of the upper half of the casing and is, therefore, given under Case II of the figure.

Case II is further divided into four branches:

Branch A - to remove <u>one</u> bearing

Branch B - to remove <u>one</u> shaft sleeve

Branch C - to remove impeller

Branch D - to remove impeller ring

The manhours required to disassemble each branch are given separately in the figure.

After having the above information, the cost equation for the pump can be numerically evaluated. As there is 1 component to be preventively replaced after every T_1 hours, and 5 components to be preventively replaced after every T_2 hours, and remaining 106 components are to be correctively replaced, from equation 4.13, we get

$$C_M = \sum_{h=1}^{106} \frac{C_h F}{M_h} + \sum_{i=1}^{1} \frac{C_i P}{T_1} + \frac{C_i F}{M_i(T_1)} + \sum_{j=1}^{5} \frac{C_j P}{T_2} + \frac{C_j F}{M_j(T_2)} \tag{4.14}$$

where the impeller is to be preventively replaced after every T_1 hours. The shaft, 2 bearings, and 2 shaft sleeves are to be preventively replaced after every T_2 hours. Remaining 106 components of the pump are to be correctively replaced.

C_F = hours to repair (cost/hr downtime + cost/hr labor) + cost of component. For the impeller,

$C_F = 5.8\ (100 + 6) + 100$

$C_F = 714.8$ dollars

C_P = hours to repair (cost/hr labor) + cost of component. For the impeller,

$C_P = 5.8\ (6) + 100$

$C_P = 134.8$ dollars

Therefore, the total corrective and preventive maintenance cost for impeller is given by:

$$C_{impeller} = \frac{134.8}{T_1} + \frac{714.8}{M(T_1)} \quad \text{(dollars)} \qquad (4.15)$$

Table XVI gives this total cost of maintenance for the impeller for different values of preventive maintenance time T_1. The value of $\frac{1}{M(T_1)}$ is calculated from equation 4.12 as explained earlier. For example,

$$\frac{1}{M(1000)}\ (\text{Impeller}) = \frac{1000 - \int_0^{1000} R(t)\,dt}{1000 \int_0^{1000} R(t)\,dt}$$

The value of $\int_0^{1000} R(t)\,dt$ is found from Fig. 8 as 998, therefore,

TABLE XVI

TOTAL MAINTENANCE COST FOR THE IMPELLER FOR DIFFERENT VALUES OF PREVENTIVE MAINTENANCE TIME (T_1)

Preventive Maintenance Time (T_1) hours	Preventive Maintenance Cost/hr $	Corrective Maintenance Cost/hr $	Total Maintenance Cost/hr $
10,000	0.01348	0.00036	0.01384
11,000	0.01225	0.00045	0.01227
12,000	0.01123	0.00050	0.01173
13,000	0.01036	0.00053	0.01089
14,000	0.00962	0.00059	0.01021
15,000	0.00898	0.00064	0.00962
16,000	0.00842	0.00071	0.00913
17,000	0.00792	0.00110	0.00902
18,000	0.00748	0.00161	0.00909
19,000	0.00709	0.00222	0.00931
20,000	0.00674	0.00294	0.00968
21,000	0.00641	0.00370	0.01011
22,000	0.00612	0.00452	0.01064
23,000	0.00586	0.00545	0.01131
24,000	0.00561	0.00639	0.1200
25,000	0.00539	0.00740	0.01279

$$\frac{1}{M(1000)} = \frac{2}{998,000}$$

$$= 2 \times 10^{6} \text{ approximately.}$$

Therefore, the total cost of maintenance per hour (impeller)

$$= \frac{134.8}{1000} + \frac{714.8}{2.10^{6}}$$

$$= 0.01348 + 0.00036$$

$$= 0.01384 \text{ (dollars)}$$

For the shaft, the total cost of maintenance/hr

$$= \frac{C_1 P}{T_2} + \frac{C_1 F}{M(T_2)}$$

$$= \frac{8(6) + 50}{T_2} + \frac{8(6 + 106) + 50}{M(T_2)}$$

$$= \frac{98}{T_2} + \frac{898}{M(T_2)} \text{ (dollars)} \qquad (4.16)$$

Table XVII gives this total cost of maintenance for the shaft for different values of preventive maintenance time, T_2.

TABLE XVII

TOTAL MAINTENANCE COST FOR THE SHAFT FOR DIFFERENT VALUES OF PREVENTIVE MAINTENANCE (T_2)

Preventive Maintenance Time (T_2) hours	Preventive Maintenance Cost/hr $	Corrective Maintenance Cost/hr $	Total Maintenance Cost/hr $
6,000	0.01633	0.00100	0.01733
7,000	0.01400	0.00148	0.01548
8,000	0.01225	0.00170	0.01395
9,000	0.01088	0.00192	0.01280
10,000	0.00980	0.00240	0.01220
11,000	0.00890	0.00389	0.01279
12,000	0.00816	0.00755	0.1561

For the shaft sleeve, total cost of maintenance/hr

$$= \frac{C_2 P}{T_2} + \frac{C_2 F}{M(T_2)}$$

$$= \frac{4.2(6) + 25}{T_2} + \frac{4.2(6 + 100) + 25}{M(T_2)}$$

$$= \frac{50.2}{T_2} + \frac{470.2}{M(T_2)} \qquad (4.17)$$

Table XVIII gives this total cost of maintenance shaft sleeve for different values of preventive maintenance time, T_2.

TABLE XVIII

TOTAL MAINTENANCE COST FOR THE SHAFT SLEEVE FOR DIFFERENT VALUES OF PREVENTIVE MAINTENANCE TIME (T_2)

Preventive Maintenance Time (T_2) hours	Preventive Maintenance Cost/hr $	Corrective Maintenance Cost/hr $	Total Maintenance Cost/hr $
6,000	0.00836	0.00066	0.00902
7,000	0.00717	0.00198	0.00915
8,000	0.00627	0.00451	0.01078
9,000	0.00557	0.00843	0.01400
10,000	0.00502	0.01300	0.01802
11,000	0.00456	0.01719	0.02175
12,000	0.00418	0.02071	0.02489

For the bearing, total cost of maintenance/hr

$$= \frac{C_3 P}{T_2} + \frac{C_3 F}{M(T_2)}$$

$$= \frac{3.0(6) + 50}{T_2} + \frac{3.0\ (6 + 100) + 50}{M(T_2)}$$

$$= \frac{68}{T_2} + \frac{368}{M(T_2)} \qquad (4.18)$$

Table XIX gives the total cost of maintaining bearing for different values of preventive maintenance time, T_2.

TABLE XIX

TOTAL MAINTENANCE COST FOR BEARING FOR DIFFERENT VALUES OF PREVENTIVE MAINTENANCE TIME (T_2)

Preventive Maintenance Time (T_2) hour	Preventive Maintenance Cost/hr $	Corrective Maintenance Cost/hr $	Total Maintenance Cost/hr $
6,000	0.01133	0.00279	0.01412
7,000	0.00971	0.00285	0.01256
8,000	0.00850	0.00287	0.01137
9,000	0.00755	0.00297	0.01052
10,000	0.00680	0.00320	0.01000
11,000	0.00618	0.00372	0.00990
12,000	0.00566	0.00478	0.01044

Table XX gives the total cost of maintenance for all the components to be preventively replaced after every T_2 hours for different values of T_2.

From the equation 4.14, the sum of the total costs for all the components to be preventively replaced after every T_1 hours represented by $\sum^{k}$ is plotted in Fig. 10 as a function of a variable, T_1. As there is only one component (impeller) to be preventively replaced after every T_1 hours, the total cost of maintenance per hour is obtained from Table XVI, whereas, the sum of the total maintenance costs for other components to be preventively replaced after every T_2 hours represented by $\sum^{s}$ is

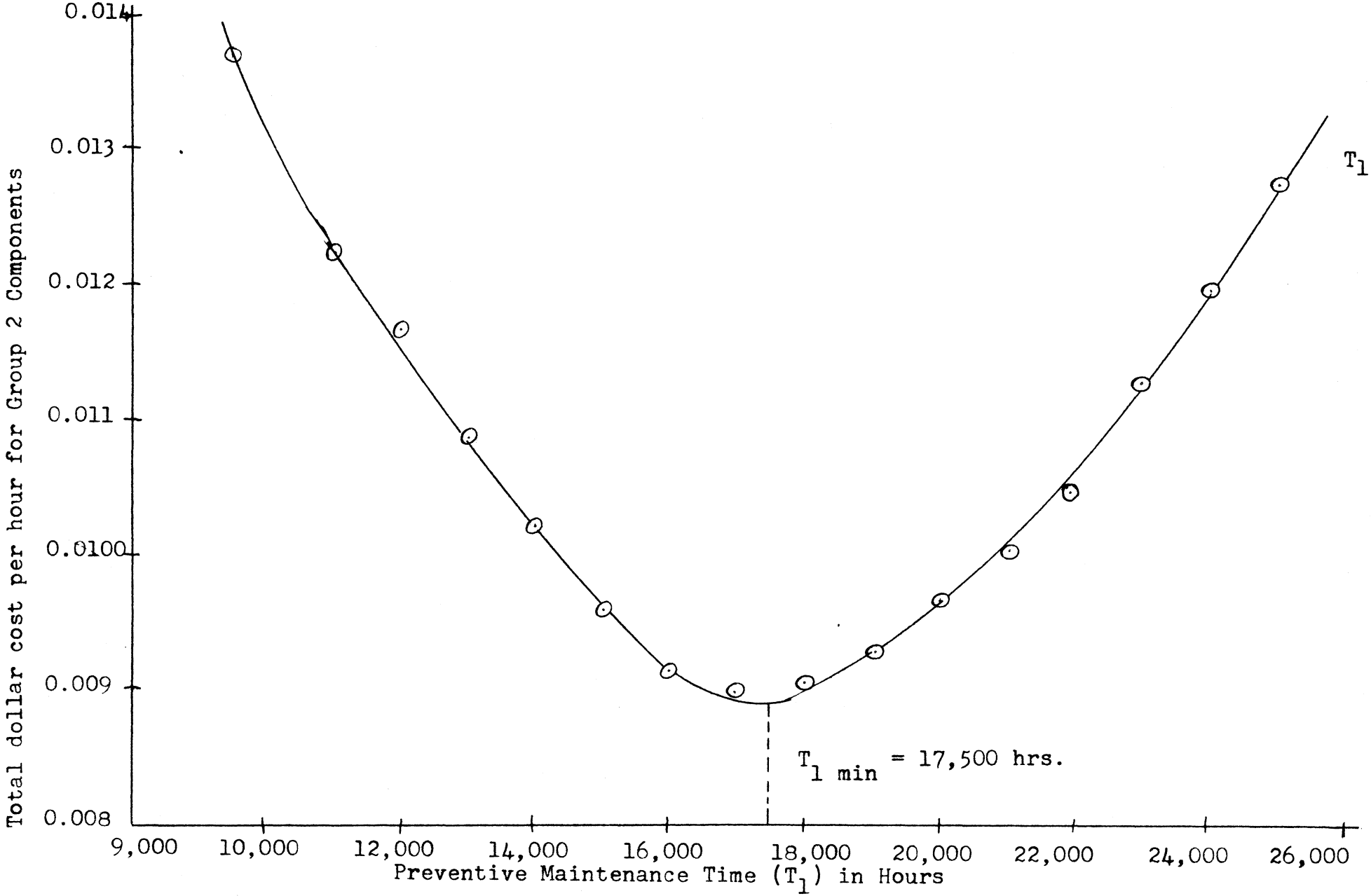


Fig. 10 Sum of Total Cost Per Hour of the Components to be Preventively Replaced After Every T_1 Hours Versus Preventive Maintenance Time T_1

TABLE XX

TOTAL MAINTENANCE COST/HOUR FOR ALL THE COMPONENTS TO BE REPLACED AFTER EVERY T_2 HOURS

Preventive Maintenance Time (T_2) hours	Maintenance Cost/Hr			Total Maintenance Cost/hr
	Shaft	2 Bearings	2 Shaft Sleeves	
6,000	0.01733	0.02824	0.01804	0.06361
7,000	0.01548	0.02512	0.1830	0.05890
8,000	0.01395	0.02274	0.02156	0.05825
9,000	0.01280	0.02104	0.02800	0.06184
10,000	0.01220	0.02000	0.03604	0.06824
11,000	0.01279	0.01980	0.4350	0.07609
12,000	0.01561	0.02088	0.04978	0.08627

plotted in Fig. 11 as a function of variable T_2. As there are five components to be preventively replaced after every T_2 hours, the total cost of maintenance per hour is obtained from Table XX.

From the minimum of these two curves, the optimum values of T_1 and T_2 for the minimum total maintenance cost are obtained as

T_1 = 17,500 hours

T_2 = 7,500 hours

It may be possible to achieve a further saving by making T_1 an integer of T_2, so that T_1 becomes a major preventive overhaul, and T_2 a minor preventive overhaul.

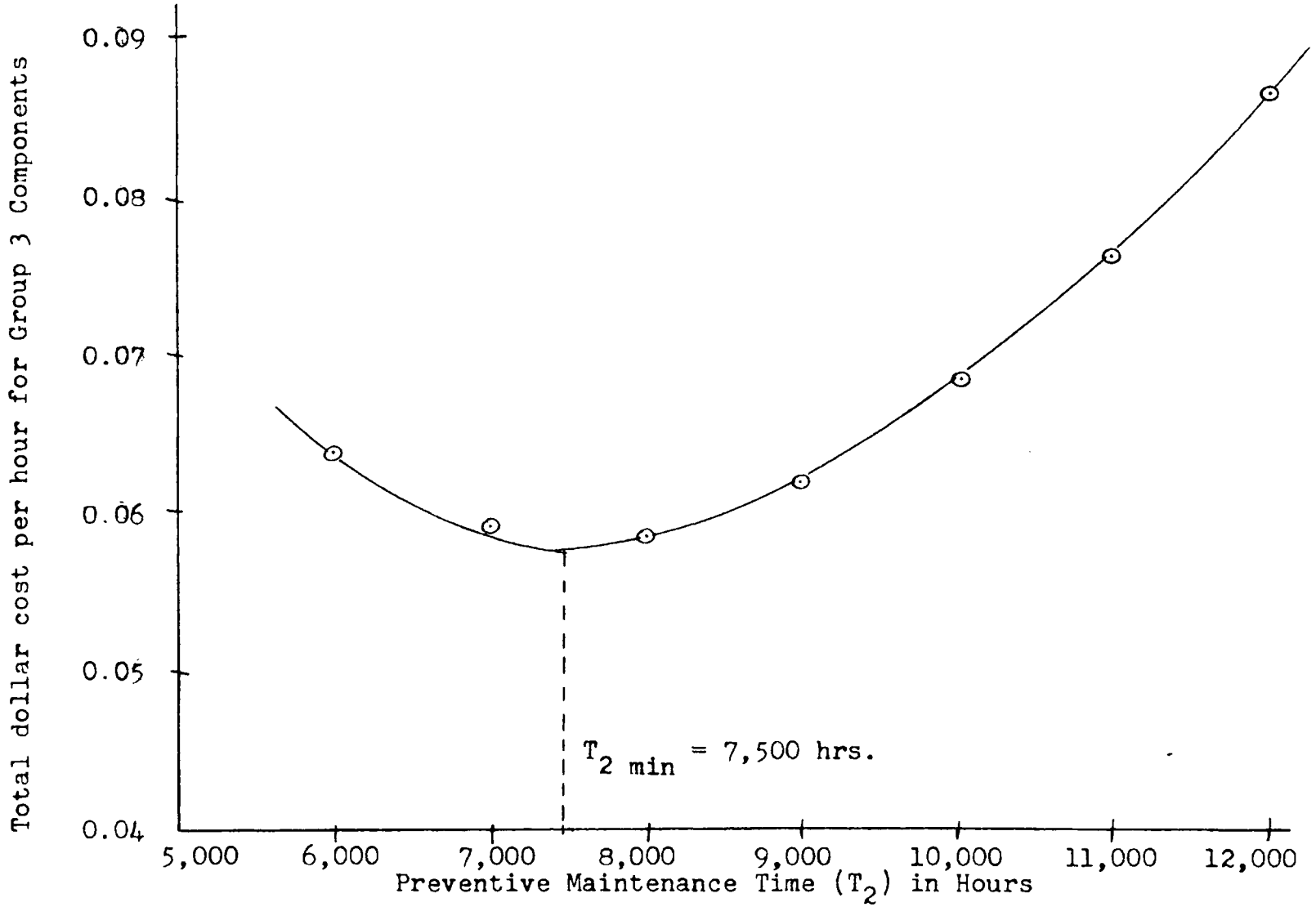


Fig. 11 Sum of Total Cost Per Hour of the Components to be Preventively Replaced After Every T_2 Hours Versus Preventive Maintenance Time T_2

Finally, as explained earlier, considering the accessibility of components, it will be worthwhile to replace the impeller ring along with the impeller after every T_1 hours and to replace the shaft nuts, straight key and step key along with the shaft, shaft sleeves and bearings after every T_2 hours.

CHAPTER 5

EFFECT OF VARIATION IN PUMP LIFE ON OPTIMUM RELIABILITY

5.1 Variation in Life of 5x4 SK and KSK Pumps Manufactured by Allis-Chalmers Mfg. Co.

The study by Kececioglu and Hughes (Ref. 15), which is used as the basis for this thesis, reveals that a pump life of 30,000 hours is assumed with the following reasoning:

> "A pump does not have a well-defined life. Parts can be readily replaced indefinitely and the pump will not reach a worn-out condition even though every part in the pump will probably have to be replaced to prevent it. Therefore, the pump's life is the period before its design or application becomes obsolete. Considering the pump application involved in the study, a life of 30,000 hours was chosen or about 10 years of average age (8 hours/day)."

Here two cases will be considered having life periods of 20,000 and 40,000 hours. It must be mentioned that with increase in equipment life, the total maintenance costs per 1000 hours of pump operation will normally increase. This is because the total maintenance costs increase with the number of years the pump is in operation. And, thus, when we vary the equipment life, the maintenance schedule as found out in the last chapter is also likely to change.

The manufacturer's total relative cost for the pump remains stationary even though there is some variation in the assumed pump life. And, thus, the manufacturer's optimum reliability also remains the same.

In the study by Kececioglu and Hughes (Ref. 15), adjusted customer's relative purchase price per 1000 hours of pump operation is obtained by dividing customer's purchase price by the one thousandth part of the assumed life. The same procedure is adapted to find out adjusted customer's purchase price per 1000 hours of pump operation for different pump lives.

The customer's relative costs are determined from the actual field data supplied by the customers. From these data, customer's scheduled and unscheduled maintenance costs per 1000 hours of pump operation are obtained as given in Table VI. So, in fact, these figures represent the stabilized customer's relative maintenance costs. Therefore, when we assume the change in pump life, we can also assume that in this particular case the customer's scheduled and unscheduled relative maintenance costs per 1000 hours of pump operation will not deviate from the stabilized customer's cost figures which have been determined from large-scale field data supplied by various customers.

The adjusted customer's relative costs per 1000 hours of pump operation for different pump lives are given in Table XXI.

Figure 6 is the original picture of reliability versus adjusted customer's relative costs for a pump life of 30,000 hours. The optimum reliability is found to be in the range of 120 to 140 fr/10^6 hours. Figures 12 and 13 give the same picture for the customer for pump life of 20,000 and 40,000 hours respectively. From these figures, the customer's optimum reliability is found to be in the same range of 120 to 140 fr/10^6 hours.

Therefore, it is concluded that in this particular case, a variation of 10,000 hours of pump life from the assumed pump life of 30,000 hours will have little effect on the optimum reliability of the pump from both manufacturer's and customer's point of view.

TABLE XXI

ADJUSTED CUSTOMER'S RELATIVE COSTS* FOR 5x4 SK AND KSK PUMPS

WITH PUMP LIFE OF 20,000 HOURS AND 40,000 HOURS

Cost	Item	Group No. I	II	III	IV	V	VI	VII	VIII
1a.	Purchase Price for Pump Life of 20,000 Hours	0.252	0.253	0.281	0.278	0.847	0.818	0.235	0.242
1b.	Purchase Price for Pump Life of 40,000 Hours	0.126	0.127	0.140	0.139	0.423	0.409	0.117	0.121
2.	Total Unscheduled Repair Costs	3.58	2.522	1.051	2.066	1.322	0.699	2.667	1.932
3.	Total Scheduled Repair Costs	0.396	0.398	0.434	0.433	1.114	1.054	0.376	0.385
4a.	Total Customer Cost for 20,000 Hours Pump Life	4.228	3.173	1.766	2.777	3.283	2.571	3.278	2.559
4b.	Total Customer Cost for 40,000 Hours Pump Life	4.102	3.047	1.625	2.639	2.859	2.162	3.160	2.438

* Relative Cost Per 1000 Hours of Pump Operating Including Cost of Money Procurement.

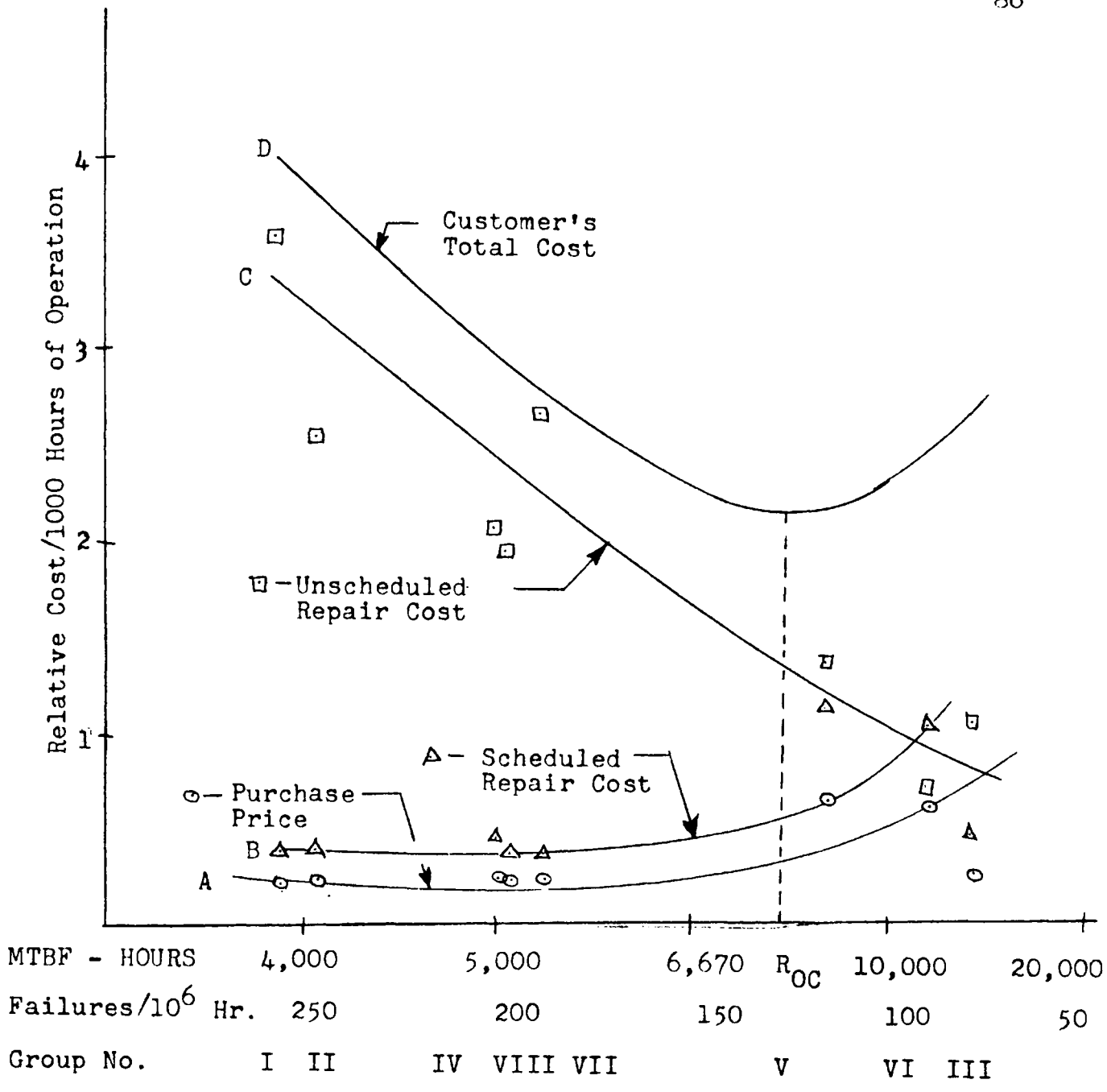


Fig. 12 Reliability and Customer's Cost for a 5x4 SK and KSK Pump and 20,000 Hours Life (Shipboard Saltwater Environment)

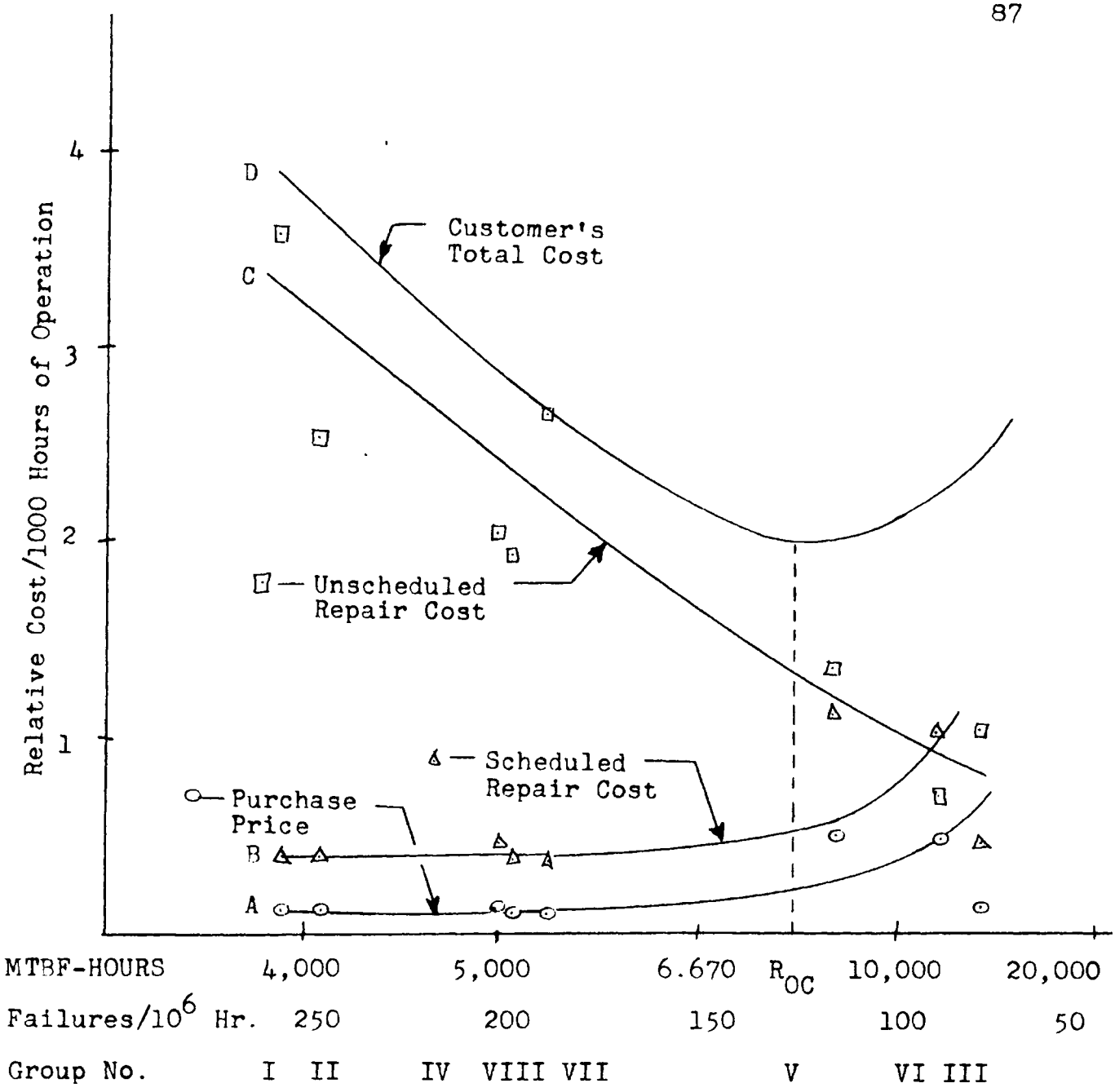


Fig. 13 Reliability and Customer's Cost for a 5x4 SK and KSK Pump and 40,000 Hours Life (Shipboard Salt-water Environment)

CHAPTER 6

CONCLUSIONS

The following conclusions are drawn from the results of this study:

1. For the manufacturer and the customer, the cost of money procurement has very little effect on optimum reliability of the pump. The reason for this is that the initial cost of the pump is substantially less than the total cost. As in the majority of cases, this is found to predominate inclusion of cost of money procurement in the optimization of reliability with respect to total cost and, therefore, will not significantly change the optimum reliability.

2. It is necessary for the manufacturer and the customer not only to optimize reliability with respect to cost but also to consider the optimum preventive maintenance schedule. In the case of the centrifugal pump it is found that the components can be divided into three groups. The first group needs to be replaced only correctively; however, the second group, consisting of the impeller,

should be preventively replaced every T_1 = 17,500 hours for minimum preventive maintenance cost and the group three components, consisting of the shaft, shaft sleeves, and bearings, should be preventively replaced every T_2 = 7,500 hours for their minimum preventive maintenance cost. Furthermore, as T_1 is very close to twice T_2, the preventive maintenance schedule can be conveniently made up so that when group three components are preventively replaced, every other time the impeller should also be replaced preventively. In addition, it is desirable to replace the impeller ring along with the impeller after every T_1 hours and to replace the shaft nuts, straight key and step key along with the shaft, shaft sleeves and bearings after every T_2 hours.

3. Manufacturer's and customer's optimum reliability remains the same even if there is variation of 10,000 hours on the assumed pump life of 30,000 hours. This is because unscheduled and scheduled repair costs are based on stabilized field cost data and would remain constant for different pump lives. Although the customer's purchase price per 1,000 hours of operation changes, this change is small in comparison to the total repair costs, consequently influencing the optimum reliability of the customer insignificantly.

CHAPTER 7

RECOMMENDATIONS

Special efforts should be made to collect the following data:

1. Component cost data
2. Component wearout failure data
3. Replacement time data
4. Failure analysis
5. Component availability data
6. Component replacement data

This will make it possible to accurately optimize total cost with respect to reliability and preventive maintenance period of the Type II kind.

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