STUDIES IN MAINTENANCE OPTIMIZATION OF SUBSYSTEMS IN A LARGE PRODUCTION UNIT

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

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PILANI (RAJASTHAN)

1981

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CERTIFICATE

This is to certify that the thesis entitled "STUDIES IN MAINTENANCE OPTIMIZATION OF SUBSYSTEMS IN A LARGE PRODUCTION UNIT", submitted by Mr. Ram Prakash Arora for the award of the Ph.D. degree of the Institute embodies original work done by him under my supervision.

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ACKNOWLEDGEMENTS

I wish to express my deep sense of gratitude to Dr. R. Bandyopadhyay, Adjunct Faculty, B.I.T.S. and Professor, National Institute of Bank Management, Bombay for agreeing to be my guide inspite of his busy schedule and for providing help and encouragement at all stages of the work. I am also thankful to Dr. C.R. Mitra, Director B.I.T.S. for kindly helping me in making this association possible in the first instance. I am no less grateful to Dr. V. Krishnamurthy, Prof. T.S.K.V. Iyer and Prof. N.K.N. Murthy for their encouragement from time to time.

The help received from the Management of the Aluminum Corporation from where the data was collected is sincerely appreciated. I am particularly indebted to the personnel of the Alumina Plant Operation, Maintenance, and Technical Departments and of Stores, Boiler House, Workshop, Laboratory and Design units for making available all the data at their command and for sparing a lot of their busy time for discussion on many occasions.

I am thankful to Prof. K.V. Ramanan, Prof. I.J. Nagrath, Dr. V.K. Tewary, Dr. V. Mandke, Prof. K.M. Dholakia, Dr. M.P. Kakar, Dr. R.K. Saksena, Dr. S.K. Sachdeva, Dr. R.P. Jain, Prof. J.R. Handa and many others who helped and encouraged me from time to time. I am particularly thankful to Mr. R.K. Mittal for his help throughout the project and his critical comments and suggestions at many occasions. Thanks are also due to Mr. Neeraj Varma for his help in data analysis.

I express my sincere appreciation to my children Sangeeta, Seema and Sumeet for their help in tabulation, and checking and to my wife Kamlesh for her patience, understanding and encouragement without which it would have been impossible to complete the work.

I thank Mr. Prem Kumar Kashyap and Mr. K.N. Sharma for their help in typing and drawing work.

R P Arora

(R.P. ARORA) 2.8.81

ABSTRACT

The maintenance function accounts for a substantial part of the total running cost of any large production unit. Increased complexity of equipment, higher production rates, tighter delivery schedules and rising inventory costs have forced industrial management during last thirty years to have a more objective view of the role of maintenance in reducing production costs. Maintenance, however, is still an area of industrial activity in which the gap between theory and practice is extremely wide. The application of operations research and mathematical techniques to optimization of maintenance policies in actual situations is lagging far behind their development. The need for optimal maintenance management is all the more imperative in developing countries.

In the present investigation, first an exhaustive literature survey has been carried out to bring into focus the essential nature of the maintenance models proposed to-date and their relevance to industry. The survey brings together at one place the total state-of-the-art, its thrusts, limitations and future directions. It also brings out the reasons for the poor application of the results of theoretical research in industry. It is shown that the reasons for this are both theoretical and psychological. Most theoretical models make over-simplifying assumptions regarding the nature

of the maintenance work or are too complex. The data required for the purpose is not available in many cases. There is also an inherent hesitancy on the part of the maintenance decision makers to venture into newer areas.

Three subsystems of an alumina plant are then studied for maintenance optimization. The subsystems include evaporators, slurry injection pumps and spent liquor heaters. Prescriptive models have been developed for the evaporators and spent liquor heaters while a descriptive model is used for the slurry injection pumps.

The evaporation subsystem is used to increase the concentration of spent liquor recovered in the precipitation area. This is done by heating and flashing the liquor in multi-effect evaporator units. As the liquor passes through the tubes of the heat exchangers scale formation occurs inside the tubes due to deposition of salts. This increases the amount of steam required in the live-steam heaters and hence the annual operating cost for the subsystem. The scales are removed by periodically cleaning the subsystem by circulating concentrated caustic solution through the tubes. A mathematical model has been proposed to find the optimal frequency of caustic cleaning for the subsystem so that the total annual steam cost plus caustic cleaning cost is minimized. It has been shown that a saving of Rs.2.64 lakhs per year can be obtained by changing the cleaning cycle time from the present 90 days to optimal 47 days. A sensitivity analysis has been carried out to find the effect of model parameters on optimal maintenance policy.

The slurry injection subsystem uses three pumps in the old unit and two in the new unit. The performance of the pumps has been studied over a period of 6 months to establish the failure characteristics of the pumps and the causes for charging loss in the subsystem. The possibility of preventively scheduling pump changeover so that switching losses due to standby unit not being ready, are minimized is also investigated. It has been found that the optimal maintenance policy for the pumps is to run them upto failure. Scheduling pump changeover preventively is not expected to yield any increase in plant availability. Increasing steam availability and checking erosion leakage in the old unit appear to be the most promising avenues for increasing plant uptime.

The third subsystem is used to preheat the spent liquor in stages before feeding it to the disgesters. As in the case of evaporators, continuousoperation of the spent liquor heaters causes scale build-up in the heater tubes with a consequent increase in steam required in the digesters. It also results in a reduction of flow due to plugging of the tubes. A mathematical model is proposed for finding the optimal cleaning frequency for the heaters to give minimum total increase in steam cost plus cleaning cost per year.

A brief discussion of the basic considerations in effective maintenance management and the practices usually followed in the industry is also included. The activities of the alumina plant mechanical maintenance (digestion) group are then reviewed in the light of these observations.

Maintenance investigations of the type carried out here evaluate the effect of operating parameters on plant availability and production cost, give theoretical support to existing policies based on trial and error, suggest desirable policy changes when necessary and effect considerable savings by optimization. It is for the first time that a systematic effort of this kind is being made in Indian situation.

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SYMBOLS AND ABBREVIATIONS

a constant

A_o heat transfer area based on outside diameter, m^2

b constant

C cost of a maintenance action, rupees

$C(t)$ steam cost per unit time as a function of time, rupees

$C_d(t)$ increase in operating cost per day as a result of scale deposition over t days, rupees/day

$C_p(t)$ net cost of production lost per day due to plugging of heater tubes over t days, rupees/day

$C_s(t)$ increase in steam cost per day due to reduction in heater outlet temperature over t days, rupees/day

C_{SL} specific heat of spent liquor, kcal/kg^{o}C

C_T total steam and caustic cleaning cost in interval (0,T), rupees

$C_T(90)$ annual steam and caustic cleaning cost for evaporation subsystem with 90 day cleaning interval, rupees

C_{TL} specific heat of thick liquor, kcal/kg^{o}C

C_0 cost of each caustic or acid cleaning operation, rupees

C_1 cost of steam, rupees/tonne

C_2 cost of lost production due to each lpm drop in flow, rupees/day lpm

$f(t)$ failure density function

f_{ei} expected frequency in class i

f_{oi} observed frequency in class i

F	spent liquor flow, lpm
F(t)	cumulative density function
F_s	slurry flow, lpm
g	mass, grams
gpl	concentration, grams per litre
h_F	enthalpy of vapours at T_o, kcal/kg
k	number of repair channels or service rates
k_i	cost of a unit of idle time per component
k_p	average cost of planned replacement per component
L	latent heat of steam, kcal/kg
m	mass flow rate, kg/hr
m(t)	steam consumption rate in live steam heaters as a function of time, tpd
m_C	mass of vapours flashed from the condensate, kg/hr
m_{CI}	mass flow rate of condensate into the evaporator, kg/hr
m_{CO}	mass flow rate of condensate out of the evaporator, kg/hr
m_F	mass of vapours flashed from thick liquor, kg/hr
m_{FS}	mass flow rate of flash steam into spent liquor heater, kg/hr
m_S	total amount of vapours present in the heater, kg/hr
m_{SL}	mass flow rate of spent liquor, kg/hr

m_{TLI}	mass flow rate of thick liquor into the flash chamber, kg/hr
m_{TLO}	mass flow rate of thick liquor out of the flash chamber, kg/hr
M	average cost of inspection plus minor repairs per unit time, rupees
MTBF	mean-time-between-failures
n	number of states, degrees of freedom, inspections per unit time etc.
N	number of components, machines or stages
p	probability of failure
p_{opt}	probability of failure for optimal inspection
P	value of out-put per unit time, rupees
q	hazard rate
Q	replacement cost, rupees
R	average repair cost per unit time, rupees
R(t)	probability of survival beyond time t, reliability
R_s	transfer rate between stages
s	slope of the Z_T versus t plot
S	amount of steam supplied per hour, kg/hr
t	time span, mass in tonnes
tpd	tonnes per day
tph	tonnes per hour
t_{ci}	interval between caustic cleanings, days
t_{ci}^*	optimal interval between caustic cleanings when steam consumption rate increases exponentially and

	maintenance time is not negligible, days
t^{**}_{C1}	optimal interval between caustic cleanings when steam consumption rate increases exponentially and maintenance time is negligible, days
t^{*}_{C2}	same as t^{*}_{C1} but with linear increase in steam consumption rate
t^{**}_{C2}	same as t^{**}_{C1} but with linear increase in steam consumption rate
t_h	interval between consecutive spent liquor heater acid cleanings, days
t^{*}_{h}	optimal heater cleaning interval, days
t_m	time taken for each caustic cleaning, days
T	time span, days
T_{CI}	inlet temperature of condensate, ^{o}C
T_{CO}	outlet temperature of condensate, ^{o}C
T_m	log mean temperature difference, ^{o}C
T_S	saturation temperature of steam in the heater shell side, ^{o}C
T_{SD}	saturation temperature of steam supplied to digester, ^{o}C
T_{SLI}	inlet temperature of spent liquor, ^{o}C
T_{SLO}	outlet temperature of spent liquor, ^{o}C
T_{TLI}	inlet temperature of thick liquor, ^{o}C
T_{TLO}	outlet temperature of thick liquor, ^{o}C

T_0	temperature of vapours flashed in the flash chamber, °C
T_0'	temperature of thick liquor in the flash chamber considering boiling point rise, °C
U	overall heat transfer coefficient, kcal/hr. m^2, °C
V	variance of a population
X	repair limit
Z_T	total increase in operating cost plus cleaning cost for the interval (0,T)
α	incremental change in steam consumption rate due to drop in heater outlet temperature, tpd/°C
β	incremental change in spent liquor flow rate due to plugging, lpm/day
ρ	density of spent liquor, gm/cc
λ	break down or arrival rate
μ	average service rate, expected value of time-to-failure
σ	standard deviation of a population

1 INTRODUCTION AND PROBLEM STATEMENT

1.1 INTRODUCTION

The importance of the maintenance function in industry can hardly be over emphasized. According to one estimate (14) about 40 percent of the unutilized industrial capacity in India is due to the absence of proper maintenance of plant and machinery. An investment in production effort presupposes the existence of necessary maintenance to keep the assets in working order. Neglected maintenance results in a reduction of productive capacity and hence amounts to capital erosion and that too at a fast rate as deterioration in the productive capacity increases with each year of neglected maintenance.

This neglect of maintenance duties is not peculiar to India alone. Maintenance was given a low priority all over the world till very recently. The reasons for this neglect of maintenance are not difficult to pinpoint. The maintenance function has neither the glamour of marketing or research function nor the visible importance of the production function so long as the equipment is working properly. Maintenance was, therefore, considered a necessary evil that must be tolerated - like taxes and fringe benefits. Expenditure on maintenance was kept at a minimum rather than an optimum level.

Increased complexity of equipment, higher production rates, tighter delivery schedules and rising inventory costs have forced the industrial management to take a more objective view of the role of maintenance in the last thirty years. These factors have tended to sharply increase the down-time penalties thereby emphasizing the importance of the maintenance activity. Enlightened top management has discovered that the maintenance function is an integral part of the total operation of a facility and there are substantial cost-reduction possibilities which have been over looked (71). The emphasis has, thus shifted towards optimizing maintenance costs rather than holding them to a minimum. The maintenance engineer is no longer expected to somehow cope with the break down problem, he is required to continuously operate in an optimal way. The decisions regarding inspection, overhauling or replacement of equipment are expected to be taken in quantitative terms based on mathematical models rather than by trial and error or individual preference.

This awareness of the importance of the maintenance function and the potential for extensive industrial application has stimulated active theoretical interest in maintenance research. A number of maintenance models have been proposed some of which are theoretically very challenging and innovative. A wide range of mathematical and operational research techniques have been used in developing these models.

Surveys of maintenance literature (15, 59, 90), however, reveal that maintenance is one area of industrial activity in which the gap between theory and practice is extremely wide. The increase in use of operation research techniques in maintenance activity is much slower than in other areas of manufacture. The theoreticians and the practitioners continue to talk in different languages even in the industrially advanced countries. This gap between the theoretical research worker and the practical decision maker must be narrowed if maintenance research has to significantly contribute to reducing production costs. Two things need to be done in this respect. Firstly, it is necessary that the present state-of-the-art in maintenance research be looked into critically to pin-point the differences in the theoretical and practical approach to the problem. Secondly, efforts should be made to apply more and more maintenance models in real life industrial situations to demonstrate their effectiveness and make them acceptable to the practical decision maker. The present investigation is an attempt in both these directions in Indian context.

1.2 THE NEED FOR MAINTENANCE

An equipment is said to need maintenance when it fails to perform its intended function effectively. For the equipment that deteriorates with use, the capability of the equipment to perform its function is progressively reduced resulting in increased maintenance costs and lower production. The equipment thus becomes progressively less profitable as its age advances. It may also have several stages of service, being relegated from more important to secondary type of service after some years. Finally when the equipment fails, it may be brought back to 'as new' condition by a major overhaul or replacement.

In the case of items that fail in service the units have a 'terminal life' after which they are subject to sudden failure. They can render no further service and must be replaced. They also generally have no salvage value.

Repair of equipment may be carried out at the time of failure called 'failure maintenance' or preventively before failure occurs, called 'preventive maintenance'. Preventive maintenance is preferable to failure maintenance because failure maintenance being unscheduled usually takes longer time and causes higher production loss compared to preventive maintenance. Failure of one component may result in failure of a related component due to increased stresses or cause substantial loss to in-process material. Failure maintenance costs may also increase due to non-availability of the requisite materials, spare parts or man-power for carrying out unscheduled repairs. Preventive maintenance, however, is economical only when the equipment failure rate is increasing and the cost of a failure maintenance action is more than that of preventive maintenance action(44).

Equipment replacement may also be similarly done at the time of failure or preventively before failure occurs. Preventive replacement may be individual or group replacement and may be done after fixed time or fixed age of the equipment with or without replacement of items that fail in between scheduled preventive replacements.

1.3 MAINTENANCE OF LARGE PRODUCTION UNITS

The optimal maintenance policy for any large production unit is a function of a number of parameters. These include the age and condition of the equipment, the cost and penalties of failure, availability of labour and materials for maintenance, cost structure of the plant, management policies and contingencies of production. The optimal policy for a large plant can be worked out by first optimizing the maintenance of its subsystems individually and then synthesizing these subsystem optimal policies into total plant policies.

The techniques used to analyze maintenance problems belong to the methodology associated with decision making under uncertainity. The development of optimal policy models has relied heavily on principles of renewal theory, reliability engineering, net-work analysis, Monte Carlo simulation and linear and dynamic programming. Model solutions can generally be obtained analytically but it is not uncommon to use graphical solutions. The latter have an advantage in that, in addition to giving the optimal value desired, they provide the decision maker with a visual picture of the effect of deviating from the optimal solution if necessary. This may quite often be useful in making important management decisions. For example, if the total cost-maintenance-age plot for an equipment is fairly flat around the optimal, it is not really crucial for the management to schedule the maintenance action exactly at the optimal point. If the exigencies of production so dictate or a lean demand period is expected in near future the maintenance action might as well be delayed for some time without unduly increasing the over all cost.

1.4 MAINTENANCE MANAGEMENT IN DEVELOPING COUNTRIES

The situation regarding maintenance management is much worse in developing countries like India. Inadequate repair facilities, poor technological base, less than up-to-date repair methods, low level of specialization, absence of mechanization of time consuming maintenance operations and non-availability of spare parts and replacements are some of the common deficiencies of maintenance systems in these countries. Very often new industrial plants and facilities are built and utilized without an adequate maintenance infrastructure. The maintenance function is given a very low priority and status by the management and hence receives very little attention.

There are also certain fundamental differences in the maintenance situations in the developed and the developing countries. In developed countries, equipment is replaced much faster because of fierce competition and rapid technological obsolescence. Funds for replacement are more easily available and equipment procurement is much easier and cheaper. Labour being costlier, any technological development resulting in labour saving or increased productivity has to be immediately taken advantage of. On the other hand, in developing countries replacements may not be easily available because of insufficient funds, long lead periods or import restrictions. Cost-benefit ratios are not the same in the two situations. Much higher spare parts and raw materials inventories are also to be maintained in developing countries because of uncertain supply positions.

1.5 SCOPE OF THE PRESENT INVESTIGATION

In the present investigation, first an exhaustive literature survey has been carried out to bring in-to focus the essential nature of the maintenance optimization models proposed to-date and their relevance to industry. The survey brings together at one place the total state-of-the-art, its thrusts, limitations, and future directions. It also brings out the reasons for the poor application of the results of theoretical research in industrial maintenance.

Three subsystems of a large production unit are then studied for maintenance optimization. The sub-systems are a major part of a continuous production line and comprise of a number of reaction vessels, evaporators, heat exchangers, flash tanks and slurry injection pumps. The operating and breakdown characteristics of these subsystems have been studied in detail to establish their maintenance requirements and costs. Prescriptive optimal maintenance policy models have been developed for two of the subsystems.

The units included in the investigation being typical of most chemical plants, the results of this investigation are expected to be both of specific and general interest.

1.6 ALUMINA EXTRACTION PROCESS AND THE SUBSYSTEMS

The subsystems included in this investigation are parts of the Alumina plant of a large Aluminum Corporation. The plant uses Bayer process for extraction of alumina from bauxite. Almost 95 percent of the alumina produced in the world today is extracted by this process (51). The process is carried out entirely in the aqueous phase taking advantage of the solubility equilibria of the hydrates of alumina in caustic soda solution. A flow diagram for the process is given in Fig.1.1. The essential steps in the process are as follows:

1.6.1 Dissolution of Alumina by Digestion with Caustic Soda

Bauxite as received from the mines is first crushed in cone crushers and hammer mills to about 12 mm size. It is then wet ground in ball mills till about 80 percent passes through 200 mesh screen. Wet grinding is preferred to dry grinding because it requires lesser power, reduces abrasive action of bauxite and causes lesser dusting problems. The slurry coming from ball mills contains 50 - 60 percent solids. It is stored in slurry holding tanks for homogenizing its composition.

From the slurry holding tanks the slurry is charged to large cylinderical vessels called digesters. The pressure

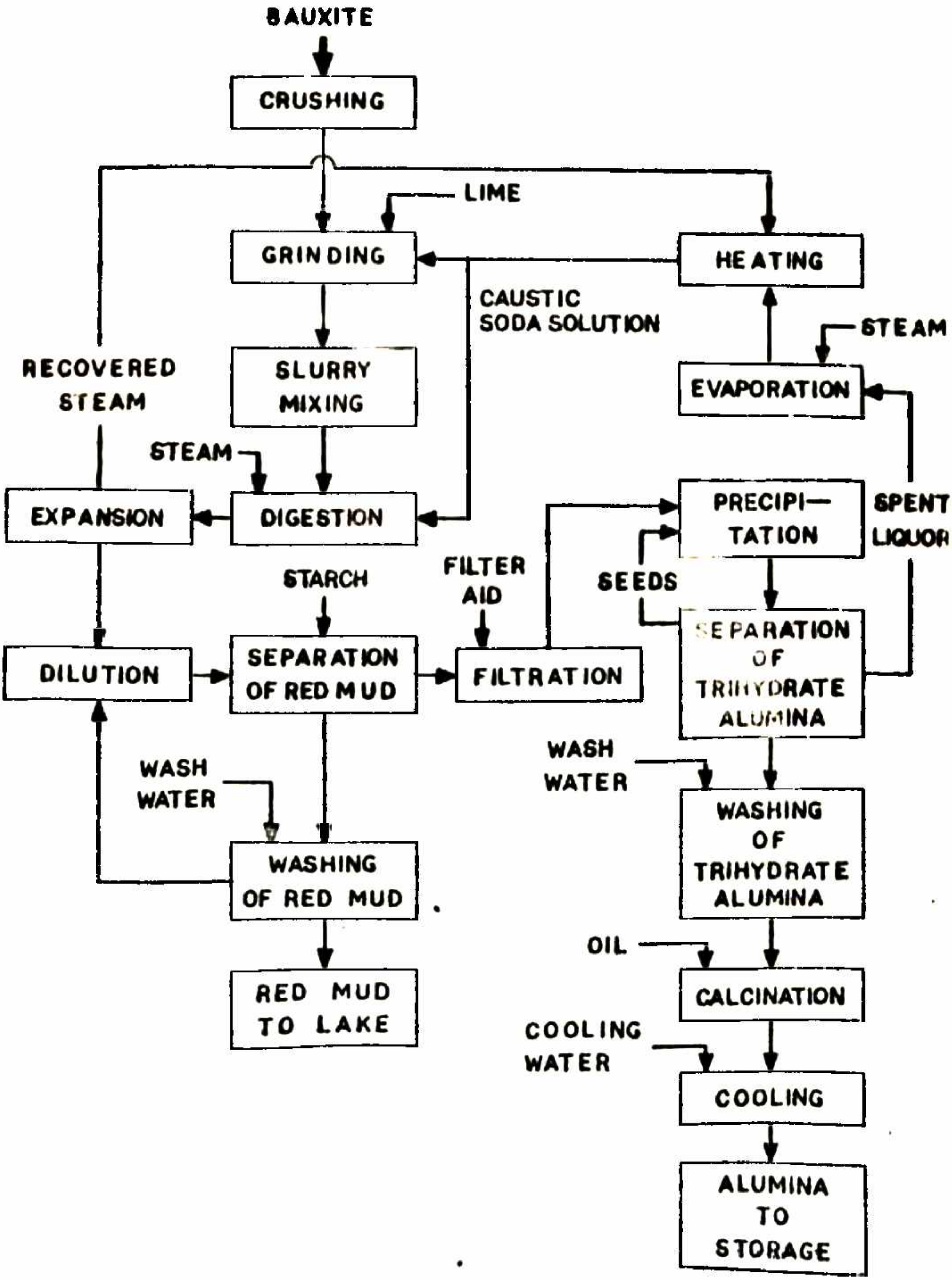

Fig 1.1 FLOW DIAGRAM OF BAYER PROCESS

and temperature in the digesters are maintained at $35\ kgf/cm^2$ and $243\,^oC$ respectively by injecting steam. Caustic soda solution with a concentration of 195 gpl is supplied to the digesters after being preheated to $210 - 212\,^oC$ in the spent liquor heaters. Preheating is done with the help of steam flashed in the expansion units. During the digestion process the alumina in the bauxite is extracted as soluble sodium aluminate while the impurities form an insoluble residue called red mud. The temperature, pressure, and the concentration of caustic used in the digesters depend upon the composition of bauxite. As seen from Table 1.1 bauxite may contain both trihydrate alumina and monohydrate alumina along with silica and other impurities.

Table 1.1 Typical composition of bauxite used in the Alumina Plant

Constituent		Percent
Total Alumina		49.50
Silica	(SiO_2)	3.00
Iron Oxide	(Fe_2O_3)	11.60
Titania	(TiO_2)	9.80
Calcium Oxide	(CaO)	0.61
Vanadium Pentoxide	(V_2O_5)	0.25
Combined water		25.24
Phosphorus Pentoxide	(P_2O_5)	Traces
		100.00
Total Available Alumina	(TAA)	46.00
Trihydrate Alumina	$(Al_2O_3 \cdot 3H_2O)$	37.00
Monohydrate Alumina	$(Al_2O_3 \cdot H_2O)$	9.00

Trihydrate alumina is digested completely in a dilute caustic solution of 150 gpl at a temperature of 150°C in about 30 minutes. Monohydrate alumina, on the other hand, can be extracted only above 220°C with higher caustic concentration of above 200 gpl and longer digestion periods of upto 8 hours. Silica combined as clay and other silicates dissolves easily in the extraction process while silica present as quartz is generally not attacked during extraction at lower temperatures and caustic concentrations. The attack on quartz increases as temperature and caustic concentration is increased. Since the amount of desilication products and the loss of alumina and caustic used in forming the desilication products increase with the increase of temperature, the choice of extraction conditions is made by balancing the extraction efficiency with the loss due to desilication products.

The high pressure pregnant liquorstream coming from the digestion units is brought to atmospheric pressure by passing it through a series of flash tanks and the blow off tank. As mentioned earlier, the steam generated in the flash tanks is utilized in the spent liquor heaters.

1.6.2 Separation and Washing of the Red Mud

The undigested residue from the digesters generally appears as very fine particles, reddish brown in colour, sometimes less than a micron in size. They include iron oxide, alumina, sodium aluminium silicate, titanium oxide and various other metal oxide impurities. Because of their size they are difficult to separate and wash. These operations are performed by first settling the particles in settlers and then washing them by continuous counter-current decantion. Starch is added in the settlers to aid the settling process. It acts like a flocculent lumping the sand particles and causing them to settle due to gravitly. The underflow of the last washing stage is sent for disposal to the red mud lake while the wash water is used for diluting the flash effluent stream.

1.6.3 Precipitation of Hydrated Alumina

After a final filtration to remove the last traces of insoluble mud, the pregnant liquor is sent to the precipitators where seeds of aluminium trihydrate are added from previously precipitated crystals and the mixture is agitated. The sodium aluminate solution hydrolyses in the presence of these crystaline seeds. As this reaction is carried out at around 50°C, it yields only alumina trihydrate which is the stable solid phase at this temperatute. The seeding is done for two reasons: Firstly, the aluminate liquors are metastable at the temperatures used in precipitation so that the reaction is slow and has to be primed. Secondly, if due caution is not exercised, the precipitation yields very fine alumina particles which can neither be filtered nor washed. The seeding serves to support the precipitating hydrate and makes it settle in the form of small agglomerates of well crystallized alumina trihydrate. The precipitation reaction is slow and it takes 50 to 80 hours to obtain the desired amount of precipitation.

1.6.4 Calcination

The precipitated alumina trihydrate is separated and washed in rotary filters. These filters feed large rotary kilns where the alumina is calcined at above $1100^{o}C$. This operation is done for the purpose of eliminating the 45 percent of water (which includes about 30 percent combined water) present in the hydrated material. It converts the trihydrate alumina into nonhygroscopic α - alumina which is the most suitable form for electrolysis.

1.6.5 Regeneration of the spent liquor

The circulating aluminate solution, diluted by the water used to wash the red mud prior to precipitation, is reconcentrated in multi-stage evaporation units.

1.6.6 Chemical Representation of the Bayer Process

Chemically, the Bayer process may be represented by the following equations:

Extraction in digesters:

$$Al_2O_3 \cdot 3H_2O + 2NaOH = 2Na\,AlO_2 + 4H_2O \qquad (1.1)$$

$$Al_2O_3 \cdot H_2O + 2NaOH = 2NaAlO_2 + 2H_2O \quad (1.2)$$

Desilication

$$3Al_2O_3 \cdot 3H_2O + 6NaOH + 5SiO_2 = 3Na_2O.3Al_2O_3.5SiO_2.5H_2O + H_2O \quad (1.3)$$

$$3Al_2O_3 \cdot H_2O + 6NaOH + 5SiO_2 + H_2O = 3Na_2O.3Al_2O_3.5SiO_2.5H_2O \quad (1.4)$$

Precipitation

$$2\ NaAl_2O + 4\ H_2O = Al_2O_3.3H_2O + 2NaOH \quad (1.5)$$

Calcination

$$Al_2O_3.3H_2O = Al_2O_3 + 3H_2O \quad (1.6)$$

Fig 1.2 gives a schematic arrangement of the plant

The plant has a total capacity of 535 tonnes of alumina dissolved per day in two units namely the old unit and the new unit. The old unit has a capacity of 160 tonnes per day while the new unit can dissolve 375 tonnes of alumina per day.

The three subsystems of the plant selected for study are:

1. Evaporators
2. Slurry injection pumps
3. Spent liquor heaters

The two units of the plant have only these three subsystems

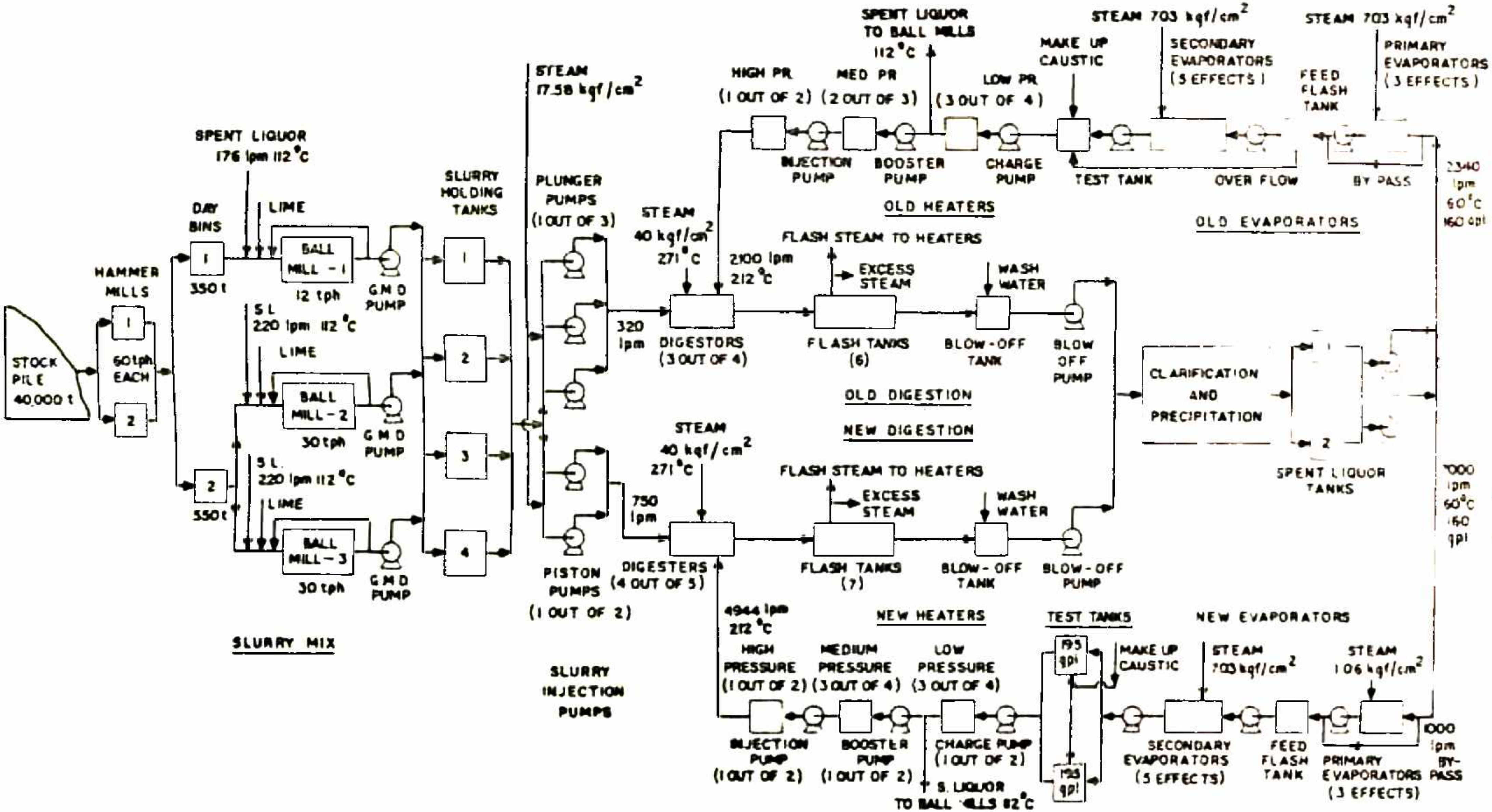

Fig 12 SCHEMATIC ARRANGEMENT OF THE SLURRY MIX, DIGESTION, SPENT LIQUOR HEATERS AND EVAPORATION AREAS OF THE ALUMINA PLANT

separate for each unit. The rest of the subsystems are common to both the units.

1.7 MAINTENANCE REQUIREMENTS FOR THE SUBSYSTEMS

The maintenance requirements and the conflicts involved in selecting optimal maintenance policies for the subsystems are discussed below:

1.7.1 Evaporators

The spent liquor recovered in the precipitation area has a caustic concentration of 160 gpl. Before this liquor can be reused in the digesters, it is necessary to concentrate it to 195 gpl. This concentration is done by heating and flashing the liquor in multi-effect evaporator units. Each effect in these units consists of a vertical shell and tube type heat exchanger with a flash chamber at the top. The liquor is first heated in the heat exchangers, then in a live steam heater and then flashed in the flash chambers of the successive effects. Since each effect is maintained at a pressure lower than the preceding one, the excess water in spent liquor gets evaporated as the liquor is flashed through these effects.

The recovered spent liquor contains certain amount of hydrates of alumina and traces of vanadium and dialuminium sodium silicate. As the liquor passes through the tubes of the heaters of the various effects, scale formation takes place inside the tubes due to deposition of the above compounds. This scale formation results in a decrease of the overall heat transfer coefficient of the heat-exchangers and a reduction in temperature pick up by the spent liquor in each effect. Consequently, liquor enters the live steam heater at a lower temperature. Since the outlet temperature of the liquor from the live steam heater must be kept constant to maintain the desired rate of evaporation, the quantity of steam supplied to the heater increases with increase in scale formation. This increases the operating cost of the evaporation system with time.

In order to keep the operating cost within reasonable limits, scales are removed from the heating surfaces periodically by chemical and mechanical methods. Chemical cleaning is done by circulating concentrated caustic solution through the tubes while mechanical cleaning involves physical scraping of the tube walls with suitable tools.

The present interval between chemical and mechanical cleaning cycles has been fixed by trial and error. As can easily be visualized an increase in the interval between cleanings will result in less number of cleanings per year and hence a reduction in annual cleaning cost.

On the other hand the cost of steam consumed by the heaters in each cycle will increase thereby increasing the running cost. A mathematical model is sought to be developed for determining the optimal frequency of cleaning which yields the minimum overall total cost per year.

1.7.2 SLURRY INJECTION PUMPS

This subsystem has five pumps in total, three in the old unit and two in the new unit. At any time only one pump is sufficient to meet the requirement of slurry in either unit. The other pumps are provided as cold standby.

Slurry being a chemically active abrasive substance pump failures occur frequently. When a pump fails it is immediately replaced by a standby unit but if the failures occur very frequently or the maintenance is not properly scheduled, the standby unit may not be ready when the operating pump fails. This results in a delay in change over with a consequent loss in the amount of slurry charged to the digesters and a reduction in alumina produced.

From an analysis of the alumina plant records over many months it is found that the number of changeovers and the charging loss per month is considerably higher for the old unit pumps compared to the new unit pumps. It is desired to study the operation of all the pumps in detail to establish their failure characteristics and identify the units causing maximum charging loss. The possibility of preventively scheduling pump change over so that switching losses due to standby units not being ready are reduced, is also to be investigated.

1.7.3 Spent Liquor Heaters

The spent liquor heaters are used to raise the temperature of the spent liquor in stages from 85°C to 212°C with the help of flash steam. The old unit uses six heaters arranged in series for this purpose while the new unit has seven heaters.

Just as in the case of evaporator heat-exchangers continuous operation of the spent liquor heaters causes scale build-up on the tubes. This reduces transfer of heat from the tube walls to the liquor flowing through the tubes. It also frequently results in reduction in flow due to blocking of tube passages. For efficient operation, the heaters are periodically isolated and their tubes cleaned by circulating a weak solution of sulphuric acid through the tubes. As the rate of scale build-up is a function of temperature, the frequency of cleaning required for each heater will be different. The variation in performance of the heaters is to be studied and a mathematical model developed for finding the optimal cleaning frequency. The cost conflicts are similar to those for the evaporators.

It may be mentioned here, that the heater maintenance crew is required to look after a total of 42 heat exchanger bodies as given in Table 1.2 Maintenance of auxiliary units like condensate receivers, pumps, tanks, piping etc. is also the responsibility of the same crew.

Table 1.2 Heat exchanger bodies in Evaporation and Heater areas

	Old unit	New unit
Evaporators	10	10
Live steam heaters	1	2
Spent liquor heaters	9	10
Total	20	22

1.8 SCHEME OF ANALYSIS AND PRESENTATION

The following scheme of analysis and presentation is followed in the thesis:

A review of the maintenance optimization models proposed in the last three decades is presented in chapter 2. After giving a broad classification of the models, major contributions in each area are reviewed with particular reference to the type of model proposed, methodology used in developing the model, shortcomings of the model and its relevance to industry.

Chapters 3, 4 and 5 deal respectively with the maintenance optimization studies of the three subsystems namely the evaporators, slurry injection pumps and the spent liquor heaters. In each case the details of the subsystem are first presented along with a discussion of the nature of maintenance required, maintenance costs, down-time penalties and the existing maintenance policy. A mathematical model is then formulated for finding optimal maintenance policy for the subsystem. Pefformance data taken from alumina plant logbooks and maintenance department records is then presented for many months and analyzed statistically to establish behavioural patterns and find model parameters. This data is substituted in the model to obtain numerical results, wherever possible. Sensitivity analysis has also been carried out for the models.

Chapter 6 gives details of the maintenance work carried out by the alumina plant mechanical maintenance(Digestion) group and the existing organizational set-up. Some observations regarding effectiveness of the present maintenance work based on analysis of plant records are also presented in this chapter.

Conclusions of the study and recommendations for the three subsystems are given in chapter 7. This chapter also includes suggestions for further work in the area.

Contents of various chapters and their linkages are indicated in a summarized form in Fig.1.3.

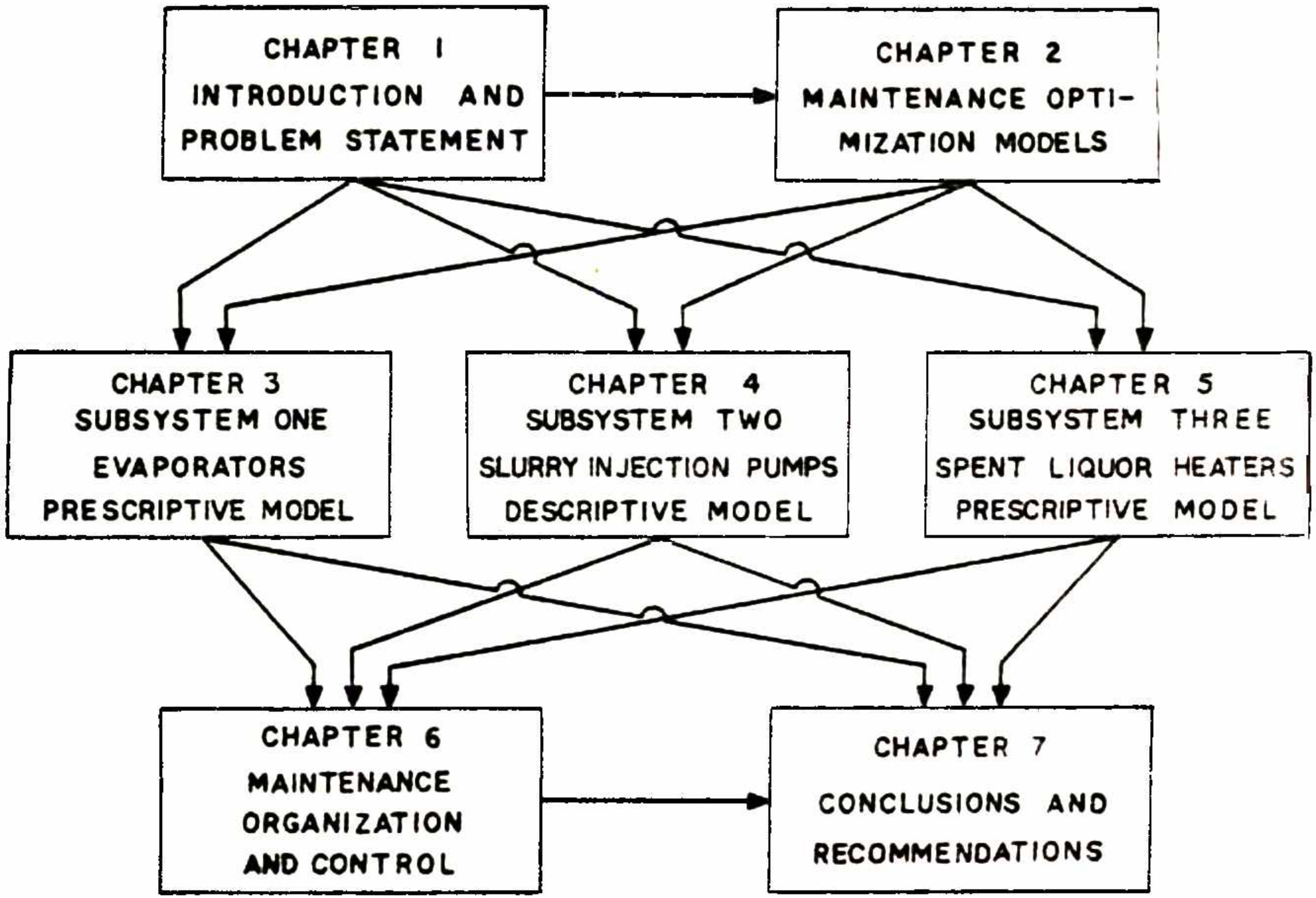

Fig 1.3 THESIS OUTLINE

2 MAINTENANCE OPTIMIZATION MODELS

2.1 INTRODUCTION

As mentioned in chapter 1, there has been a considerable influx of technical literature related to maintenance activity in the last three decades or so. A review of major maintenance optimization models proposed during this period is presented below. The models have first been divided into two categories namely those related to maintenance of equipment for which the time-to-failure distribution is known and those for which this information is not available. These main categories have then been further subdivided as follows:

1. Models for equipment with known distribution of time-to-failure
   - (a) Periodic maintenance policy models
   - (b) Opportunistic maintenance policy models
   - (c) Models for equipment with several states of operation
   - (d) Multi-stage maintenance policy models
   - (e) Repair-limit replacement policy models
   - (f) Optimal maintenance man-power requirement models

2. Models for equipment with uncertain distribution of time-to-failure
   - (a) Minimax policy models
   - (b) Models using bounding techniques

(c) Adaptive policy models

(d) Co-efficient of variation models

Within each subcategory the models are presented in the following order:

(a) Inspection policy models

(b) Repair and overhaul policy models

(c) Replacement policy models

(d) Other models

It may be pointed out, however, that this last classification is not very rigid. In many cases, where single comprehensive models have been proposed for taking inspection, repair or replacement decisions, the models could have been classified under more than one category. In this review, such models have been listed under repair and overhaul category

2.2 MODELS FOR EQUIPMENT WITH KNOWN DISTRIBUTION OF TIME-TO-FAILURE

2.2.1 Periodic Maintenance Policy Models

The simplest and best known maintenance policies are periodic policies. These policies are characterized by a simple decision parameter in that the equipment is inspected, repaired or replaced as the case may be at the time of failure or at a specified age whichever occurs earlier. The equipment is assumed to be in one of the two states - good or bad and the overhauls or replacements bring the equipment back to 'as new' condition.

Periodic policies may be further subdivided into simple periodic policies and sequential policies. Simple periodic policies have a constant maintenance interval which is calculated only once for the equipment. These policies are optimal only for an infinite time span. Sequential maintenance policies differ from simple maintenance policies in that the maintenance interval is recalculated at each maintenance action. This is done to minimize the expected cost of operating the equipment over the remaining finite time span. Barlow and Proschan (6) have shown that the expected cost when following an optimal sequential policy during an interval (0,t) is always less than or equal to the expected cost of the corresponding optimal simple periodic policy

(a) Inspection policy models

Signorini (86) gave a procedure for determining optimal frequency of inspection for 128 medium pressure steam traps installed in a chemical plant using steam for heating. It was shown that the optimal frequency of inspection of the traps (and repairing the ones found defective) can be expressed as a function of total number of steam traps, total number of defects observed, effective number of defects, cost of inspection, cost of repairs and hourly loss per trap when the trap is out of order.

Pritskar (75,76) gave a model for determining the boundaries on the characteristics of a system beyond which the system should be subjected to a maintenance action. He assumed that the system can be characterized by a continuous valued control variable. This variable is measured at equal intervals and a maintenance action is taken if the measured value exceeds the control limit specified.

White (94) used dynamic programming to solve the same problems with a considerably reduced computational effort.

White, Donaldson and Lawrie (95) and Jardine (44) developed a model for determining optimal inspection frequency for an equipment which is inspected at regular intervals. It was assumed that major breakdowns occur according to negative exponential distribution, the time to repair is small compared to mean time-to-failure, and repairtimes and inspections are negative - exponentially distributed. Under these conditions, the maximum profit per unit time is obtained when the parameters of the system satisfy the relationship

$$\frac{d(\lambda(n))}{dn} = -\frac{\mu}{t_o}\left(\frac{P+M}{P+R}\right) \tag{2.1}$$

where

n = Number of inspections and minor repairs carried out per unit time.

$\lambda(n)$ - Break down rate (assumed to vary with inspection frequency)

P = Value of output per unit time
= Selling price of the product minus material and production costs per unit time

M = Average cost of inspections and minor repairs per unit time.

R = Average repair cost per unit time.

μ = Average repair rate

t_o = Mean time required for each inspection

If it is assumed that break down rate varies inversely with respect to the inspection frequency,

$$\lambda(n) = \frac{\lambda}{n} \qquad (2.2)$$

and
$$n = \sqrt{\frac{\lambda . t_o}{\mu} \left(\frac{P+R}{P+M}\right)} \qquad (2.3)$$

A basic difficulty in using this model is to relate the failure rate of the equipment to the frequency of inspection. Two alternative approahces are possible. First, to experiment with one's own equipment and the second, to collaborate with other companies using similar equipment and doing same type of work. The first approach gives results which are more reliable and truly representative of conditions within one's own plant but the process is time consuming and does not lead to immediate solution. The second approach may not give correct results because except in very simple cases, it is impossible to maintain exactly the same environmental and operational parameters or upkeep procedures in any two plants even when they use similar equipment and are apparently involved in the same type of work.

White et al also showed that if the objective function of the maintenance policy is to minimize total down time Eq.(2.3) takes the form

$$n = \sqrt{\frac{\lambda t_o}{\mu}} \tag{2.4}$$

Munford and Shahni (65,66) developed a model for determining optimal frequency of inspection of an equipment for which failure can only be detected by inspection. A one parameter type inspection policy was suggested according to which the optimal inspection interval t_i is such that

$$\text{Prob (system fails in } t_{i-1}, t_i \mid \text{working at } t_{i-1}) = p_{opt}$$

$$i = 1, 2, 3 \ldots \tag{2.5}$$

The optimal value of probability was chosen so as to give minimum total expected cost of inspection and undetected failure state. A nomograph was presented for finding p_{opt}

for Weibull distribution of failure time.

Luss and Kander (53) developed models for finding optimal inspection policies when time taken for inspection is not negligible compared to mean time-to-failure of the equipment. Optimal inspection intervals were worked out on the basis of expected loss per cycle, per unit time and per unit good time. The models were analyzed by differentiation and by dynamic programming for exponential, Erlang and uniform life-time distributions. It was shown that when the equipment has an increasing failure rate, the interval between successive inspections should decrease but the difference is significant only for the first two intervals.

(b) Repair and overhaul policy models

Barlow and Hunter (4) used renewal theory to obtain optimal maintenance intervals for two types of preventive maintenance policies. In policy 1 a preventive maintenance is performed after the equipment has been in continuous operation for a period of t_1 hours without failure. If the system fails before t_1 hours maintenance is performed at the time of failure and preventive maintenance is rescheduled. In policy 2 the preventive maintenance is performed after a constant t_2 hours regardless of the number of intervening failures. Whenever a failure occurs a minimal failure maintenance is carried out and it is assumed that this minimal repair does not affect the system failure rate. The policies were evaluated on the basis of maximum limiting efficiency i.e. fractional amount of uptime over long intervals. It was shown that for the case where both types of policies are feasible and the expected time to perform emergency maintenance is equal to the expected time to perform scheduled maintenance, policy 1 is superior to policy 2 when

$$\frac{\text{Expected time to perform minimal maintenance}}{\text{Expected time to perform scheduled maintenance}} > \frac{1}{t_m q} \qquad (2.6)$$

where t_m is the main time to failure and q is the hazard rate.

Holl and McLean (41) used the models developed by Barlow and Hunter for obtaining optimal maintenance policies for equipment at the Nuclear Division of the Union Carbide Corporation, U.S.A.

Noonan and Fain (73) developed a model for finding preventive maintenance interval for optimal system performance when the failure cannot be detected immediately or the repair is not carried out due to some reason. The system availability was used as the criterion for optimality. The maintenance policy was to reschedule the preventive maintenance every time a repair was carried out. It was shown that under these conditions optimal preventive maintenance schedules exist even for exponential failure distributions.

Queuing Theory principles were used by Morse (63) to establish the conditions under which preventive maintenance is justified and to obtain expressions for the average availability of machines and utilization of crews. Graphical results were presented to show the variation of fraction of time a machine is available for operation, under repair or under preventive maintenance for different failure time and service time distributions. Optimal policy decisions were derived from these graphical solutions.

Srinivasan (89) derived expressions for the expected time-to-failure of a two-unit redundant system subject to intermittent usage and repair maintenance. Two models were proposed. In the first model the system failure distribution was evaluated without consideration of the demand pattern for the system. In the second model the demand pattern was also considered. Numerical results showed that when the system is not continuously in use, working out reliability on the basis of its failure time distribution alone may be considerably biased. This is due to the fact that a failure of the system may occur and be rectified when the system is not in demand.

Abbott (1) proposed a model for deciding whether a vital component of a system which fails on inspection when received should be repaired or replaced in order to maximize the probability of system success. The study was related to an unmanned space system in which there is no chance of maintenance once the system is put in operation. Each repair of the failed component reduces the probability of successful performance of the component by a constant factor. The probability of successful operation of the system is thus a function of the number of repairs done on the component before it is finally accepted. This number was optimized to give maximum probability of system success when launched.

Roll and Naor (82) proposed models for determining optimal preventive maintenance and replacement policies for equipment subject to both a continuous deterioration and random break down. The level of deterioration with time was assumed to be known and controllable with maintenance. It was shown that when both preventive maintenance and replacement are applied to equipment subject to degradation and failure, direct optimization of the cost equation is not possible. A numerical approach can be used in such cases to obtain near optimal policies and to carry out sensitivity analysis.

Thompson (92) and Arora and Lele (3) discussed models for finding optimal maintenance policy and economic life of equipment based on maximum present worth concept. The approach essentially consists of finding an optimal policy and an optimal life to maximize the present worth of the machine.

Davidson (21) developed models for determination of optimal overhauling policy for the air heaters of coal-fired, high pressure boilers in an electric supply company. The performance of the boilers deteriorates between statutory maintenance intervals, called surveys, due to deposition of solids in the air heaters. This increases the cost of fuel per unit time. The maintenance policy proposed was to overhaul the heater tubes at specified intervals so that the total cost of overhauls and excess fuel is minimized. Two cases were considered, first with a constant interval between the overhauls and the second in which this interval could vary. The second approach is considered more realistic because the excess fuel cost between overhauls increases with operation due to deterioration of boiler parts other than the air heater. A dynamic programming approach is necessary in this case.

Watson (93) presented a case study for determining optimal preventive maintenance frequency of components to maximize the percentage availability of equipment in a sintering plant. An important aspect of this case study is the fact that the data obtained from the plant showed a significant difference in the average life of components after preventive maintenance and after break down maintenance. The improvement factor defined as the ratio of the planned maintenance repair life to break down maintenance repair life varied from 1.5 to 2.7 depending on the type of the job. This is contrary to the classical assumption that all maintenance actions whether preventive or break down are statistically similar in nature. Two possible reasons were suggested for this difference. Firstly, the state of the plant at the time of maintenance is different in the two cases. Preventive maintenance being prescheduled, the maintenance area and the various units are thoroughly cleaned of all material, spillage etc. making the components more accessible and any damage more apparent. Secondly, planned maintenance is done in a specified time with no apparent hurry and pressure from the production department to put the unit back in operation in the least amount of time which is a characteristic of the breakdown maintenance. The superivision and inspection are thus better during planned maintenance leading to a more comprehensive and careful repair work.

The improvement in life was found to exist onlyupto the first breakdown after preventive maintenance and subsequent breakdowns were not affected.

Srinivasan and Gopalan (87,88) and Gopalan and D'Souza (32,33) developed expressionsfor the availability of a two unit standby system subjected to preventive maintenance and /or repair with a single repair facility.

The failure, repair and preventive maintenance time distributions were assumed to be known. Both cold and warm standby redundancies with similar or dissimilar units were considered.

Nakagawa and Osaki (69) discussed optimal preventive maintenance policies to maximize the availability of a two unit standby redundant system. Regeneration point technique was modified to obtain Laplace-Stieltjes transform of the point wise steady state availability. Optimal preventive maintenance time was obtained as a unique solution of the equation under certain conditions.

Crabill (17) discussed the case of a production system in which the service rate can be changed. The system considered had (N + n) production units out of which only N were required for production at any time. The remaining n units could be in repair, waiting for repair or waiting for being used. The time-to-failure distributions for the units were considered to be independent and exponential. A single service facility was available with First Come First Served (FCFS) type of service discipline and exponential service time distribution. The service rate could be changed to k different values with corresponding cost rates. Long range expected average costs were minimized to find the optimal service rate as a function of the system state.

It was observed by Kay (48) that the availability or percentage up time is not always the best criterion for judging the effectiveness of a preventive maintenance policy for production equipment. He showed that effective cost per unit time or effective profit per unit time may give optimal values that do not maximize availability but yield better percentage increase in revenue or decrease in maintenance cost. A decision model for determining the optimal criterion for many types of distributions was presented. An approximate method was suggested for finding optimum maintenance interval when the failure times follow a Weibull distribution.

Goheen (31) considered an N out of (N + n) cold standby redundant system with k repair channels. The costs considered included a repair cost and a penalty cost when the number of machines operating falls below N. The failure and repair times were assumed to have Erlang distributions. It was shown that the problem of assigning the failed machines to repair facilities so as to minimize the long run average cost can be expressed in terms of a simple non-linear programme which has an optimal solution.

Winstor (96) also considered a case in which the repair facility could be operated at several rates. The maintenance system consisted of a finite number of machines with a single service repair facility. The costs incurred were taken to be function of the production loss and the rate at which the repair facility was operated. Conditions were developed for finding optimal repair rate.

Handlarski (37) showed that the conventional two function approach of trying to obtain improvement in machine utilization by maximizing machine availability and minimizing cost invariably results in suboptimization. He proposed a single function optimization namely maximization of profit which incorporates both availability and cost functions. This approach makes it possible to compare effectiveness of various maintenance policies on the basis of one function. Using this approach it was shown that age replacement is always more profitable than block replacement.

(c) Replacement Models

According to Dean (23), Terborgh (91) was the first to develop a theory for equipment replacement based on the assumption of time-dependent linear operating cost function. He considered obsolescence by extrapolating the historical rate of obsolescence into the future on the assumption of a uniform rate of technological discovery. It was shown that for optimal replacement, the average increase in cost due to operating inferiority should be equal to the average annual depreciation in capital.

Clapham (16) discussed a simple model for determining the economic replacement age of an equipment based on the minimum average annaul depreciation plus maintenance cost. Straight line depreciation was assumed with no salvage value. The maintenance cost was taken to be an increasing function of age of the equipment. Under these conditions it was found that the optimum occurs when the current rate of maintenance cost is equal to the average total cost to date.

Crookes (19), Blanning (9) and Woodman (97) compared five different strategies for replacement of equipment that fails in use. These strategies were defined as follows:

A Make service replacements only

B Make a planned replacement every t units of time regardless of the age of the component then in use. Make service replacements whenever required.

C Make a planned replacement when the component has reached an age t. When a failure occurs make service replacement.

D Make planned replacement every t units of time as in strategy B. Make service replacements only upto a time $(t-t')$ in each interval $(t'<t)$. If a failure occurs in the interval $(t-t',t)$ the system is to be left idle upto time t.

E Make only planned replacements every t units of time. If a failure occurs in the interval $(0,t)$ leave the system idle upto time t.

It was shown that if,

k_p = Average cost of planned replacement per component

k_i = Cost of a unit of idle time per component.

μ = Expected value of time-to-failure

V = Variance of time-to-failure

$f(t)$ = Failure density function and

$F(t)$ = Cumulative distribution function

1. Strategy B is preferrable to strategy A if

$$k_p < 1/2\,(1 - \frac{V^2}{\mu^2}) \qquad (2.7)$$

2. Strategy C is preferrable to strategy A if

$$\mu\, \phi\,(\infty) > \frac{1}{1 - k_p} \qquad (2.8)$$

where $\phi(\infty)$ is the value of the age-specific failure rate

$$\phi(t) = \frac{f(t)}{1-F(t)} \quad \text{as} \quad t \to \infty. \qquad (2.9)$$

3. Strategy D is always profitable and the optimal value

of t' is given by the equation

$$k_i t' \, (1 - F(t')) = 1 \qquad (2.10)$$

4. Strategy E does not lead to any optimal value of t

The costs k_p and k_i used in this analysis were normalized so that the cost of service replacement per component becomes unity.

A comparison of age and block replacement policies was given by Barlow and Proschan (7). It was assumed that units failed independently with monotonically increasing or decreasing failure rates and that time required to make replacements was negligible. It was shown that if the failure rate is increasing, the number of failures in interval (0,t) is larger with an age replacement policy compared to a block replacement policy. The number of planned replacements and the total number of removals-sum of failure replacements and planned replacements - is, however, smaller with the age replacement policy.

Ghare and Torgerson (30) considered the effect of inflation and increased productivity on machine replacement using sunk cost method. It was shown that the effect of inflation is to increase the taxable income at a rate faster than the increase in the rate of inflation. The sunk cost (difference between the cost of the new machine and the sum of resale value and accumulated depreciation for the old machine) decreases with time resulting in more frequent replacements. The effect of increased productivity is opposite to that of inflation. Under favourable conditions increased productivity can neutralize the effect of inflation completely resulting in less frequent replacements.

The model proposed by Ghare et al is valid for a constant inflation rate only.

Eilon, King and Hutchinson (27) were probably the first to propose replacement models taking into account tax concessions available on investment of capital for equipment replacement. They presented two models for replacement of trucks in a fleet of fork lift trucks. The first of these models was based on minimum average cost per truck per year and the second on discounted cash flow approach. The discounted cash flow model gives increasingly larger replacement intervals compared to those obtained from average cost considerations, as the interest rate increases. The discounted cost function, however, becomes less and less sensitive to interest rate and almost becomes constant at high interest rates. Tax allowances result in shorter replacement intervals compared to those obtained without consideration of these allowances.

In their discussion of the above paper Mortimore(64), Allen (2) and Jones (46) pointed out that the models proposed by the authors could be made more realistic by including the penalty costs which arise due to non-availability of the trucks. Hackemer (36) gave a case study to illustrate the importance of such costs in optimal maintenance policy models.

It was shown by Schwitzer (85) that for systems with exponential and hyper exponential failure distributions block replacement policy is costlier than failure replacement. For rectangularly distributed times, block replacement is preferable to failure replacement only if the ratio of the cost of individual replacement with block replacement policy to that with failure replacement policy is less than 0.3862.

Jardine (45) discussed basic types of probability distribution functions used in replacement theory and developed models for deterministic and probabilistic replacement strategies. The models discussed included preventive replacement after fixed interval and after fixed age with or without consideration of time taken to make failure and preventive replacements. The total expected cost per unit time was used as the objective function for optimization.

Kent (50) discussed a method for determining approximately the effect of using discounted cash flow on the replacement age and the total annual cost of an equipment. According to simple replacement theory using undiscounted costs, the optimum replacement point occurs where the rate of growth of maintenance costs equals the rate of fall of capital depreciation costs. Expressions were developed to give approximately the delay in the replacement point and the saving in real costs that would accrue as a result of using discounted cash flow in the analysis.

Nicholson and Pullen (72) and Daniel (20) considered the problem of optimally phasing out a group of similar units of capital equipment over a specified time period so as to maximize the long-term compounded assets of the company. The former authors proposed a two-stage heuristic model for the problem. Daniel simplified the approach by transforming the problem into a transportation type of problem which can be solved by linear programming.

The decision problem concerning the replacement of units of a fleet of fork lift trucks during periods of inflation and economic uncertainity was discussed by Christer and Goodbody (18). The procedure adopted differs from the conventional net present value concept in that relatively short term estimates of costs and discount rates only can be used justifiably under such uncertain conditions. The alternative criterion function developed can be used for both constant and variable discount rates. It can also take care of factors like tax allowances, regional development grants and technology improvements.

(d) Miscellaneous Models

Graveley (35) gave a detailed comparison of failure maintenance and break down maintenance policies based on man-power requirement, records to be kept, spare parts needed, inspection procedures, job scheduling and cost control. It was pointed out that although usually preventive maintenance is less costly and better organized, there are situations where failure maintenance is more economical.

A dynamic programming model was proposed by Falkner (28) for finding the optimal spare part inventory level and maintenance policy to yield the minimum expected cost of operating an equipment for a finite planning horizon. A procedure was also given for deciding the reorder values for the spare parts.

An interesting application of theory of replacement of parts was presented by Kendal and Sheikh (49). These authors applied the time-to-failure probability models to the machining process. A procedure was developed for finding an optimal tool replacement interval and cutting speed to minimize expected cutting cost. The cost equations were developed by assuming variable cost per component to be a function of the tool replacement strategy and the cutting speed. The replacement strategy called for a preventive replacement after an optimal time and a failure replacement at the time of failure.

2.2.2 Opportunistic Maintenance Policy Models

Opportunistic maintenance policies relate to maintenance of equipment with several parts or to large multicomponent plants. When a plant is subjected to intensive continuous or semicontinuous operation, opportunities for preventive maintenance of its equipment are limited because of the cost involved in stopping the entire production line. Such an equipment may, however, occasionally cease to operate not because of its own failure but because of failure of other equipment, scheduled overhauls, periodic inspection or production breaks between batches. When this occurs, an opportunity arises for performing a preventive maintenance of equipment that has not reached a failed state. A decision must be made whether to take advantage of this opportunity to maintain the equipment or to wait till next such opportunity arises. Because the replacement of equipment at each such opportunity is optional, replacement policies of this type have been termed Optional Replacement Policies by Woodman(98).

Fairly simple opportunistic policies can be developed by assuming that though the system contains many components the failure rate and the costs associated with failure and replacement are independent of the failure of the other components. This assumption is, however, often not strictly valid in industrial situations. Failure of a component may cause unduly high stresses on the remaining system or change the operating environment sufficiently to alter the failure rate of other components. Again, the cost of replacement of a component is generally reduced when more components are to be replaced at the same time. Opportunistic policies have also been used to exploit these economies of scale (83, 24, 80, 59).

Sasieni (83) and Dreyfus (24) considered a bladder replacement problem occuring in the rubber tyre manufacturing industry. Two such bladders are used on a machine for producing two tyres simultaneously one on each bladder. If a bladder fails in service a faulty tyre is produced and a cost C_1 is incurred. Replacement of the bladder involves a cost C_2 as the cost of the new bladder and a cost C_3 as the labour cost for stripping the machine for effecting the replacement. There is also a cost C_4 for lost production time if the bladder has to be replaced during a production shift. Economy of scale arises from the fact that once the machine is stripped for replacement of one bladder, the second bladder can be replaced at the cost of bladder alone.

Sasieni represented the problem as a Markov chain process while Dreyfus used dynamic programming for its solution. The dynamic programming approach results in an optimal sequence of decisions at each stage yielding a lower overall cost compared to Sasieni's model.

McCall (59) discussed opportunistic policies for a system composed of two parts 1 and 2. Part 1 has an increasing failure rate and the cost of replacing the component before failure C_1 is less than the cost of replacing after failure C_1^*. Part 2 is assumed to fail exponentially with a replacement cost C_2 when the part is replaced alone but if both parts are replaced together the cost is only C_{12}. The inequality

$$C_{12} < (C_1 + C_2) \tag{2.11}$$

signifies economy of scale possible in this case.

The optimal maintenance policy model was developed by assuming the parts to have stochastic independence as far as their failure patterns were concerned.

It was suggested by McCall that the above analysis can easily be extended to include part 1 and N exponentially failing parts. The calculation of the (N + 1) decision parameters of the general model can easily be handled by dynamic programming.

Woodman (98) used dynamic programming to show that for any block replacement policy, regular or random, there is always an optional policy which is cheaper and that for components having increasing failure rate the best optional policy at each opportunity is to replace the component if it has reached a critical age otherwise to wait for the next opportunity. The critical age was found to be a function of the ratio of planned replacement cost to repair cost and was not influenced much by the choice of a distribution to represent the time-to-failure. For a given cost ratio, control limits were found to be lower when the opportunities for replacement arise at regular intervals as compared to the case when the interval between these opportunities is exponential.

Duncan and Scholnick (26) extended Woodman's model to include both optional replacements and interrupt replacements.

According to their model, replacement of items is effected at the time of production breaks as in Woodman's model. In addition, if the opportunities for replacement arise only sparsely and the time to the next opportunity is expected to be too long, a replacement is made by interrupting production instead of risking a failure replacement. It was shown that the optional interrupt - opportunistic replacement strategy is better than pure age replacement or pure opportunity replacement strategies. Also, as expected, the advantage to be gained by interrupt-opportunistic replacement policy is a function of the opportunity rate defined as:

$$\text{Opportunity rate} = \frac{\text{mean time to failure}}{\text{mean time between replacement opportunities}} \qquad (2.12)$$

As the opportunity rate increases, the advantage of using interrupt-opportunistic strategy over pure opportunistic strategy is reduced.

2.2.3 Models for Equipment with Several States of Operation

Just as the periodic maintenance policies can be generalized by permitting the equipment to have more than one component, a second generalization permits the equipment to occupy several states of deterioration between the good and failed states. The equipment having one or more components is assumed to move from one state to another stochastically. The exact state of the equipment can be determined by inspection at suitable intervals. A variety of repair actions may be possible at each of these inspections which return the equipment to a higher state of performance. A generalized policy statement for problems of this category is 'to make a decision $d_{sk}(i)$ at each inspection which transforms the equipment from its observed state i to state s and specifies the next inspection interval k periods hence'. Maintenance problems of this type may also be extended to include the possibility that inspection may be imperfect i.e. the inspection may not detect a failure or may call a good equipment as failed. Multi-state maintenance models have been considered by Mine and Kawai (61,62), Proctor and Wang (79), McCall (59) and Brown and Martz (11,12).

Mine and Kawai considered a two-unit parallel system with state degradations. The units were identical, with good, degraded or failed states. The transition rate from one state to the next was taken to be constant. The effect of degradation was to cause an increase in failure rate and repair maintenance rate and a decrease in income per unit time. The net profit per unit time was maximized. The method proposed requires a set of lengthy equations to be solved.

Proctor and Wang (79) presented a model for finding optimal preventive maintenance policy for a single unit system that can have (n + 1) states: 0(good), 1,2,,,,,(n-1), (degraded) and n (failed). The maintenance policy was to perform a preventive maintenance after t_{opt} hours of continuous operation without failure. Optimal maintenance interval was found on the basis of maximum availability of the system.

Mine and Kawai (61) discussed preventive replacement policy for a one unit system with three possible states: normal with constant hazard rate, wear out with monotonically increasing and unbounded failure rate and failed. Two models were presented: First with a fixed period for normal state operation and the second in which the constant hazard rate period is variable. In the first case the state of the equipment, good or wear out, can be identified by its age but in the second case an inspection is necessary to identify the state. For each model the expected total cost associated with inspection, preventive replacement and corrective replacement was minimized yielding optimal preventive replacement policies based on both age and state. Conditions under which the policies are effective were also discussed.

Brown and Martz Jr. (11,12) considered the replacement problem for a multi-component system. The replacement policy was to inspect the system at regular intervals and to replace its components, if necessary. The system was assumed to be composed of n components each of which could deteriorate to $(N + 1)$ different states. How many and which components to replace were determined by a two-phase algorithm using dynamic programming (11) and Monte Carlo simulation (12) so as to minimize the expected overall cost. The relative importance of each component to the system's performance was represented in terms of a 'weightage factor' for each component in each state.

2.2.4 Multi-Stage Maintenance Policy Models

Multi-stage maintenance policy models are related to replacement of equipment in systems containing a large number of similar units which can be divided into groups on the basis of their replacement costs. Consider, for example, a system containing N identical units of a certain item which fail in service at random and are required to be replaced when they fail. If some of these units are critical for the operation of other equipment in the system the replacement costs associated with these units may be much more than the replacement costs associated with other units which are not so critical. It has been shown by Bartholomew (8), Naik and Nair (67,68) and others, that for such systems, under certain conditions, a policy of multi-stage replacement may be more economical than simple replacement of individual units as they fail.

The multi-stage replacement policy consists of dividing the N units of the system into n stages containing N_1, N_2..N_n units such that the cost of replacement of each unit in stage 1 is C_1, that in stage 2 is C_2 and so on. Initially new units are installed in all stages. As failures occur in any stage, these failures are replaced not by new units but by units already operating in the previous stage. Thus failures in stage i are replaced by units operating in stage (i-1), failures in stage (i-1) as well as the units transferred to stage i are replaced by units operating in stage (i-2) and so on. New units are introduced only in stage 1. Such an arrangement obviously does not change the failure rate of the system as a whole but it does result in an overall saving because the higher failure rates are transferred to the stages where the cost of replacement per unit is lower.

Two rules for transferring units from one stage to the other have been considered:

1. Transfer of the oldest unit

2. Transfer at random

Rule 1 invariably results in lower costs compared to Rule 2 but in actual practice it may be difficult to distinguish between units of different ages and as such transfer at random may be the only choice. Moreover, the cost benefit obtained by transferring the oldest unit may not be high enough to justify the additional effort involved in recording the replacement of each unit separately.

Bartholomew (8) discussed the problem of multistage replacement considering only two stages. It was shown that a two-stage replacement policy is always cheaper than a single-stage policy if the failure rate of the items is monotonically increasing or decreasing. Specifically, if the failure rate of the items is monotonically increasing, two-stage replacement can be cheaper than simple replacement if $C_1 > C_2$. On the other hand if the failure rate is monotonically decreasing, two-stage replacement would be cheaper if $C_1 < C_2$. Further, if the cost of transferring an item from stage 1 to stage 2 is negligible, the condition for two stage replacement strategy to be cheaper than single stage replacement is given by

$$R_s \gtrless \frac{N_2}{N_1 \mu} \qquad (2.13)$$

depending upon whether the failure rate of the item is increasing or decreasing, where R_S is the transfer rate from stage 1 to stage 2 and μ is average life of each unit.

Naik and Nair (67) extended Bartholomew's 2-stage strategy to an n-stage replacement strategy. The conditions under which an n-stage replacement policy is more economical than a single stage replacement policy were discussed and it was shown that the savings obtained by using an n-stage policy increase with increase in number of stages. However as the number of stages increases the total transfer cost of all units from all stages becomes considerable even when the transfer cost of each unit from one stage to the next is small. This fact, actually determines the number of stages to be used. The number of stages may also be limited due to practical constraints.

As a further refinement of the n-stage failure replacement model, Naik and Nair (68) introduced the effect of finite time taken to transfer units between the stages and the probability of failures occuring during removal, transportation and insertion. It was suggested that if down time during transfer is to be completely eliminated interstage inventories should be established in the system. Replacement in the stages can be done from units in the inventories which can then be restored by transferring units from the preceding stages. In the equilibrium condition these inventories will be completely made up of units operating in the preceding stages and no additional cost on inventory stock will be incurred. The optimum size of these inventories can thus be established by balancing the additional cost of maintaining them against the reduction in lost benefits due to downtime during transfer.

Marathe and Nair (56,57) discussed some aspects of economy and ordering of stages in the n-stage failure replacement strategy given by Naik and Nair in the above two papers. They also proposed two multi-stage replacement strategies involving planned replacement of units between stages. The first strategy called multi-stage block replacement strategy involves replacement of all the units in a stage enbloc at regular intravels. All the units in stage 1 are replaced by new units at intervals of time t_1. Working units removed from stage 1 are used to replace units in stage 2 at intervals of time t_2 and so on. Failures occurring in any stage i during the time $(0 - t_i)$ are replaced by new units available at the stage. Units released from the nth stage at intervals of time t_n are removed from the system. Between replacements units are stored in interstage inventories. The second strategy called multi-stage planned replacement strategy by age involves replacement of components in any stage after a fixed age or failure whichever is earlier. In general, a unit entering a stage i will have an age x_{i-1} and will be operated in this stage until its age is x_i. If it fails in the stage before reaching age x_i, it is replaced by a unit having age x_{i-1}.

Both planned replacement strategies result in a reduction in number of failures in the system compared to simple multi-stage strategies, but the requirement of new items increases. Replacement by age eliminates the possibility of replacing components much before failure as could occur with a block replacement strategy. But with this strategy it is necessary to record each new unit and schedule and reschedule its replacement in case of failure. If the cost of recording and scheduling is negligible, multi-stage planned replacement strategy by age is more economical than multi-stage block replacement strategy. If this cost is high or it is not considered desirable to distrub the system frequently for making replacements, multi-stage block replacement strategy proves cheaper. The latter strategy also permits bulk transfer of units between stages.

Jain and Nair (43) compared the n-stage failure replacement, n-stage block replacement and n-stage age replacement strategies with the corresponding single-stage replacement strategies for an item with monotonically increasing failure rate. Rate of failure replacement, rate of planned replacement and average cost per unit time were used as the basis for comparison. Following conclusions were drawn:

1. The n-stage replacement strategies are always cheaper than the corresponding single-stage strategies because of the transfer of failures from high-replacement cost stages to stages where these costs are lower.
2. If the inter-stage inventory costs are negligible, n-stage block replacement is cheaper than n-stage failure replacement because in n-stage block replacement some failures are eliminated.
3. If the cost of recording replacements in each stage is negligible, n-stage age replacement is cheaper than n-stage block replacement because more failures are transferred in the case of n-stage age replacement.
4. n-stage age replacement involves larger number of failure replacements than the n-stage block replacement but the number of planned replacementsis more

in the case of n-stage block replacement.

2.2.5 Repair Limit Replacement Policy Models

The policy of replacing equipment at predetermined intervals of time based on minimum average cost or maximum average production per unit time has a basic disadvantage which remains however accurately the replacement interval may be determined. If the equipment requires expensive repairs just before its replacement age, and it is not expected to have a resale value at the time of replacement, the expenditure on repairs may not be economically worthwhile. Even when the equipment does have a resale value there is a limit to the maximum maintenance expenditure beyond which it is advantageous to replace the equipment instead of repairing it. Equipment replacement strategies based on a repair limit upto which the equipment should be repaired and beyond which it should be replaced whatever,its physical age, are called Repair Limit Replacement Strategies.

The basic theory of the repair limit replacement strategies was given by Drinkwater and Hastings (25), Howard (42) and Woodman (99). In these strategies whenever a repair action is called for, the equipment is first inspected and an estimate prepared for carrying out the repairs. If this estimateis less than the repair limit, the equipment is repaired otherwise it is replaced. This approach is expected to result in a more economical operation of the equipment compared to that with replacement strategies based on economic life. It also provides a systematic policy for equipment replacement under which replacement decisions are taken whenever due without being delayed due to red tape or false sense of economy.

Hastings (38,39,40) used dynamic programming to establish repair limits under a variety of decision situations. It was shown that where repair/replacement decisions are to be made at regular intervals, say at the beginning of each time period repair limits can be determined from a simple recursive relationship of the following form:

$$C\ (i,r) = \min_{X} \Big[s(x) + P\ (x)\ C(1,r-1) + (1 - P(x))\ C\ (i+1,\ r-1) \Big] \qquad (2.14)$$

where

C(i,r) = Value of the state (i,r) defined as the mean total cost incurred when the system starts with an age i and operates under optimal maintenance policy for the remaining r years

X = Repair limit

$z(x)$ = Immediate expected cost given by the expression

$$z(x) = \int_{0}^{X} x \quad f(x) \, dx \quad + \quad Q.P \, (X) \tag{2.15}$$

$f(x)$ = Probability density function of the repair cost distribution

$$P \, (X) = \int_{X}^{\infty} f(x) \quad dx \tag{2.16}$$

Q = Replacement cost

The recursive relationship (2.14) can easily be modified to include random failure pattern, discounting, availability, obsolescence and so on.

In cases where planning horizon is finite, the resulting equations can be solved by value iteration procedure starting from a known final state and proceding backwards. When the planning horizon is infinite it is necessary to use approximations in policy space to obtain optimal policies.

As an illustration of the procedure suggested, Hastings solved the Army vehicle repair problem discussed by Drinkwater and Hastings (25).

Lambe (52) pointed out that the repair limit replacement method proposed by Hastings suffers from a limitation in that by this method it is possible to identify a machine having excessive expenditure on an individual repair but it is not possible to isolate a machine having consistently more frequent and higher repair costs than an average machine of its class. The method also requires a complete record of repairs for a fleet of similar machines. He proposed a repair-limit model based on the repair data of the particular machine and whatever prior knowledge is available about the repair characteristics of that class of machines. Baye's formula is used as basis for modifying the model parameters as information regarding the performance of the particular unit accumulates. Dynamic programming is avoided by assuming that, after being adjusted for inflation, repair costs do not change with age.

Dê Veroli (22) postulated that the optimal preventive replacement policy is a function of the optimal repair limit and developed a mathematical model for considering simultaneously the problem of preventive replacement and replacement in case of failure. It was shown that the optimal repair limit is the solution of an ordinary differential equation and its value determines the optimal preventive replacement policy. An algorithm for finding combined optimal policies was given in this paper.

The repair limit replacement models discussed so far use estimated cost of a repair operation to decide whether to repair or scrap a piece of equipment. Nakagawa and Osaki (70) proposed repair time as the controlling parameter for making such a decision. According to this approach the failed equipment is repaired if the repair time is short but if the repair is not completed upto a time called repair limit time the equipment is replaced.

The repair limit models based on this approach are particularly suitable in situations where it is difficult to estimate the expected cost of a repair. These models can also be used in situations where the outcome of an operation is not certainly known. A typical example of this type occurs when deciding the optimal time to be spent in searching for a lost item. The maximum search time in this case corresponds to the optimal repair limit time in the maintenance case.

Mahon and Bailey (54) proposed a modification of the repair limit model given by Drinkwater and Hastings (25) to take care of vehicles having exceptionally high or low mileage compared to average vehicles of their age. This was done by basing the repair limit on equivalent age which was a function of actual age and the mileage completed.

2.2.6 Optimal Maintenance Manpower Requirement Models

The optimal man-power requirement for the maintenance operation and its distribution trade-wise and skillwise is obtained by striking a balance between the cost of non-availability of the equipment for production due to lack of maintenance and the cost of maint-aining this equipment. The problem is generally more serious for equipment that is subjected to continuous or semi-continuousoperation. Standby equipment, in process inventories or excess capacity may be provided to reduce the impact of equipment break down in such situations.

As mentioned earlier, Morse (63) used queuing theory to develop models for finding optimal size of maintenance crews and their percentage utilization for maintenance work. Queuing theory was also used by Mann (55) to find optimal crew-size for maintaininga bank of compressors.

Reed Jr. (81) suggested that optimal man-power allocation for maintenance can be obtained by working out separately the man-power requirement for performing the regular or preventive maintenance work and for emergency operations. High man-power utilization can be planned for regular maintenance while percentage time utilization for emergency maintenance are generally much lower.

Goswami (34) discussed the importance of setting standard timings for repetitive activities in maintenance operation. An example was given to show how the maintenance man-power requirements and job schedules can be worked out with the help of standard timings and net-work analysis.

Carruthers et al (13) discussed the man-power requirement for the maintenance workshop of an open cast coal mine. The Workshop was responsible for the maintenance of large number of dump trucks, excavators, tractors, and bull dozers. The records of the plant were analyzed to determine the average failure rate, average repair rates and the average size of repair teams. Queuing theory was then used to calculate expected down time cost, idle time cost and the number of service, crews to be provided for each section of the workshop separately.

Yakkundi and Barat (100) similarly studied the man-power requirements for maintenance department of a large mechanized foundary. The man-power requirements were found by first sampling a large number of work orders to find the utilization of man-power while attending to breakdown work and average standard strength of each crew. The expected number of machines requiring service simultaneously in each section was then determined from the records of the maintenance department thus giving the man-power requirement for break down work. Man-power requirement for general maintenance could be calculated directly from standard time and manning requirements for the machines.

Classification of man-power required, into different wage groups was done on the basis of skill required, professional knowledge necessary, effort required, responsibility for men, machines and materials and environment of work site. Each listed job was given a weightage for each of these parameters. The wage group of the members of the squad was decided by the point value of the job and the number of people in the squad. The total daily man-hours of each wage group were then calculated and percentage of each class determined. The daily cumulative percentages were calculated till they became steady. These steady state percentages were then taken as the percentage of various wage groups in the total man-power for each section. Suitable adjustments were made for absenteism, overtime, deterioration of equipment and change of production level.

A case study for determination of maintenance man-power size was also presented by Boden (10).

2.3 MODELS FOR EQUIPMENT WITH UNCERTAIN DISTRIBUTION OF TIME-TO-FAILURE

The maintenance policies discussed so far relate only to systems for which the time-to-failure distributions for system components are known with certainity. Maintenance personnel quite frequently run into situations where such information is not available or is only partially available. The different approaches that have been tried in the literature to tide over this difficulty include the following:

1. Use of minimax policies
2. Use of bounding techniques
3. Adaptive policies
4. Use of coefficient of variation

2.3.1 Minimax Policy Models

Minimax policies are useful when the decision maker has no information at all regarding time-to-failure distribution of the equipment. These policies aim at finding the maintenance strategies that minimize the maximum possible loss.

It has been shown by McCall (59) that for an equipment that is continuously inspected and has an increasing failure rate, a strictly periodic minimax policy is to schedule no preventive maintenance i.e. optimal minimax policy is to set the replacement interval equal to infinity.

For an equipment that has to be inspected, if C_1 is the constant cost of each inspection and C_2 the constant cost per unit time the equipment failure is left undetected, the inspection strategy that minimizes the maximum possible loss is given by

$$t_i = ip \left(\frac{T}{np+1} + \frac{C_1}{2C_2} \left(\frac{n\sqrt{p(n+1)+2}}{np+1} - (i+1)\right)\right), \quad i = 0,1..n \qquad (2.17)$$

where n is the largest integer such that

$$C_1 p^2 n^2 + C_1 p(2 - p)n + 2(C_1 - p\, C_2 T) \leq 0 \qquad (2.18)$$

p is the probability that an inspection detects a failed equipment and T is the maximum time between inspections. A minimax strategy was also proposed by Fox (29) to find optimal replacement age with discounting.

2.3.2 Models Using Bounding Techniques

The bounding techniques are used to establish upper and lower bounds on the expected cost per unit time when at least some information regarding the stochastic behaviour of the equipment is known. The decision maker might, for example, know the expected value of the failure distribution and that the failure distribution is monotone increasing.

It has been shown by Barlow and Marshall (5) that if F is a failure distribution with an increasing failure rate and known mean (μ), the probability R(t) that the equipment has not failed by age t, is bounded from below by an exponential distribution with the same mean i.e.

$$R(t) \geq V(t) = \begin{cases} e^{-t/\mu} & , t < \mu \\ 0 & , \text{otherwise} \end{cases} \qquad (2.19)$$

Similarly, R(t) is bounded from above by the relation

$$R(t) \leq W(t) = 1 - x_o \qquad (2.20)$$

where x_o satisfies the condition

$$x_o = 1 - e^{-\left(\frac{x_o t}{\mu}\right)} \qquad (2.21)$$

These bounds have been expressed in terms of the cost per unit time and used to compare various preventive maintenance policies.

2.3.3 Adaptive Policy Models

Adaptive maintenance policies are used where the decision maker has atleast some subjective information about the failure distribution of the equipment and further statistical data is expected to accrue with time. The process starts by first assuming an initial policy based on whatever information is available. This policy is then progressively revised as more data becomes available.

The basic theory of this method was given by Jorgenson and McCall (47) and White (94). Sathe and Hancock (84) used the approach for determining minimum cost rate preventive maintenance schedules while Lambe (52) used the method for developing a repair limit replacement model.

Meisel (60) discussed a method for finding maintenance schedule for a complex equipment in order to get the desired MTBF without actually evaluating MTBF or knowing the probability distribution of failure. The technique consists of initially choosing a schedule of maintenance every t_1 units of time. After the i th failure at time t_i since the last failure a new schedule of maintenance every t_i units of time is instituted such that

$$t_i = t_{i-1} + a_{i-1}\,(t_{i-1} - \mu_0),\ i = 2,3.. \quad (2.22)$$

where a_i is a scaler quantity such that $a_i = \frac{a}{i}$ and μ_0 is the desired MTBF. It was shown that under reasonable assumptions the procedure converges to give the desired MTBF.

2.3.4 Models using Coefficient of variation

A somewhat different approach to obtaining reliability and optimal replacement policies was suggested by Pandit and Sheikh (75). They suggested that most of the commonly used life time distributions could be replaced by a dimensionless factor called 'coefficient of variation' defined as

$$K = \frac{\text{Standard deviation}}{\text{Mean}} \quad (2.23)$$

and a life parameter called 'characteristic life' which may be mean, median, mode or a given fractile. The coefficient of variation determines the shape and spread of a distribution around the mean value and usually remains constant or varies slowly with operating conditions. Characteristic life determines the location of the distribution and generally varies widely with operating conditions. The coefficient of variation provides a dimensionless format for the optimal replacement strategies and gives simple graphical solutions of the otherwise complicated optimal replacement equations. This approach is particularly helpful when the choice of a distribution is difficult because of inadequate knowledge of failure mechanism and/or insufficient failure data or the failure data is available at one operating conditions but replacement policies are needed at different conditions.

2.4 CONCLUSIONS

2.4.1 The State-of-the-art

From the above discussion it is clear that by far the maximum amount of work done in the maintenance optimization area relates to single component, two-state type of systems with known time-to-failure distributions. Both continuously inspected and preparedness types of situations have been studied. Dynamic programming has proved to be the most helpful technique particularly in situations where the planning horizon is limited due to fast process deterioration or technological obsolescence. Other techniques like Monte Carlo simulation, network analysis, linear programming, and queuing theory have also been used fairly widely.

Studies in multi-component and multi-state-types of systems have generally been simplified by assuming cost and failure independence. Use of multi-stage and repair limit strategies is not very popular because of the lengthy computations involved. Similarly models for multi-state systems with variable service rates are also not common because of their complex nature.

Of the various methods used for finding optimal maintenance strategies when the distributions of times-to-failure are not precisely known, Baysian adaptive approach appears most appealing because of its inherent ability to apply in-process corrections as further data becomes available.

Determination of optimal man-power requirement for maintenance work involves detailed investigation of break-down patterns, maintenance times, crew sizes and maintenance effectiveness. Time standards need to be developed for all repetitive type of work and reporting and analysis activity strengthened to continuously update the data base.

According to Chanin and Sphicals (15) the decision problems arising in maintenance management can be classified into following categories.

1. Inspection frequencies.
2. Depth of inspection.
3. Overhaul intervals.
4. Whether or not to do repairs.
5. Replacement rules for components.
6. Replacement rules for capital equipment.
7. Whether or not an equipment modification should be made.
8. Reliability considerations.
9. Maintenance crew sizes.
10. Composition of machines in a workshop.
11. Spares provision rules.
12. Sequence rules for jobs requiring some form of maintenance effort.
13. Scheduling start times for constituent jobs of a maintenance project.
14. Maintenance performance monitoring.
15. Personnel management, training and development.
16. Payment, incentives and merit rating.
17. Organizational problems like location of maintenance groups, rationalization of interdepartmental relations, decentralized versus centralized control, facilities

planning for maintenance operation, prestige and status of maintenance employees and so on.

From the review it is clear that not all of these problems have the same appeal for the research worker. Mathematical tractability and possibility of using known operation research techniques for optimization seem to be the major factors influencing choice of problems.

The gap between the theoreticians in the maintenance field and the practical maintenance decision makers has arisen primarily due to the following reasons:

1. The theoreticians mainly concentrate on such problems as can be easily modelled and analyzed mathematically. Most of the models deal with one or two units, homogeneous groups of machines or crews, complete segregation of functions of maintenance groups, known distributions of failure and maintenance times, predictable effect of maintenance action on equipment state and so on. The practitioners on the other hand are faced with intricate complexities and interdependency of maintenance issues and are interested infinding solutions to the multi-machine and multi-crew types of problems.

2. Many of the assumptions made by the theoretical model makers to simplify the models do not appear valid to the practitioners. Assumptions like environmental, cost

and stochastic independence, negligible maintenance times, zero salvage value, immediate availability of tax concessions, ability of maintenance function to continuously return the equipment to 'as new' state and absence of technological obsolescence seem easily questionable. Faced with a large number of differences in his situation and that studied by the research worker, the maintenance decision maker tends to play safe.

3. Maintenance models need a considerable amount of data regarding the behaviour of the equipment, repair times, crew sizes and maintenance costs. Because maintenance has not been a focal business activity, little need has been seen for maintaining such data and as such none exists in most plants.

4. Maintenance models cover only a narrow range of activities of the maintenance manager. Maintenance management practice requires managers to solve many complex problems which do not appeal to the researcher or are not easily quantifiable. Hence the hesitation to be unduly obsessed by maintenance models.

5. There are many behavioural problems associated with implementing theoretical maintenance models. Maintenance managers feel threatened by the complexity of these

models and resist changes that the implementation of these models may bring. Absence of enough authentic case studies showing advantages to be gained by scientific maintenance management helps in continuing the status quo.

6. A need exists to deal with-maintenance problems not independently but in their totality and interdependency. Practical considerations and limited resources, particularly in developing countries, force maintenance management to take maintenance decisions in the overall interest of the plant rather than by sectional subsystem optimization considerations. No comprehensive studies of this nature have appeared in literature to help the practical maintenance engineer.

2.4.2 Future Directions

All these difficulties not-withstanding, the importance of the maintenance. optimization procedures has been amply demonstrated by the few case studies reported in literature. Properly managed maintenance reduces running and inventory costs, increases equipment availability, improves employee morale, increases production rate and, in general, leads to higher overall profits. Industrial enterprises exist in order to make profit and maintenance department must contribute to that objective. With the productivity in manufacturing processes appearing to be progressively approaching its asymptotic growth limit, maintenance is one of the last areas where cost economies are to be effected. The need for optimal maintenance management is all the more imperative in developing countries where maintenance must fight an unequal battle for allocation of scarce resources with more pressing demands of scarcity management, social development and national security.

Annual maintenance costs run into crores of rupees and the rate of increase of maintenance costs is known to be much higher than the comparable increase in production costs (90). Even minor improvemtns in maintenance effectiveness are bound to have significant impact on nation's economy. The task of future researchers is to study and develop procedures that will help in making scientific management more popular and acceptable to industry. The current practices of maintenance management have to be reviewed and improved. The theoretical models have to be made more practical and system oriented. More case studies have to be presented to demonstrate the use of maintenance models in real life situations. Data collection methods have to be standardized and popularized as source data for making maintenance decisions. The management must be convinced about the need to give the maintenance function its due status and improve its technological base. The task is by no means easy but there exists a wide potential and a very strong need for future research in these areas of maintenance management.

3. EVAPORATORS

3.1 SUBSYSTEM DETAILS

It was pointed out earlier that the evaporation subsystem is used to increase the concentration of spent liquor recovered in the precipitation area from 160 gpl to 195 gpl. This is achieved by evaporating the excess water in the spent liquor in primary evaporators, feed flash tank and secondary evaporators arranged in series as shown in Fig.3.1. The subsystem actually has four primary evaporators, one feed flash tank and six secondary evaporators in each unit but one primary evaporator and one secondary evaporator (along with a live steam heater in the secondary evaporation area) are kept out of circuit for maintenance work. In addition to the units mentioned above, the evaporation subsystem also includes condensers, intercondensers, steamjet ejectors, condensate receivers and circulating pumps as shown in the figure.

3.1.1 Primary Evaporators

Each primary evaporator consists of a vertical shell and tube type heat exchanger with a flash chamber at the top. The heat exchanger has 4 tube side passes and one shell side pass. The flash chamber is a cylinderical unit connected to the shell side of the heat exchanger at the top.

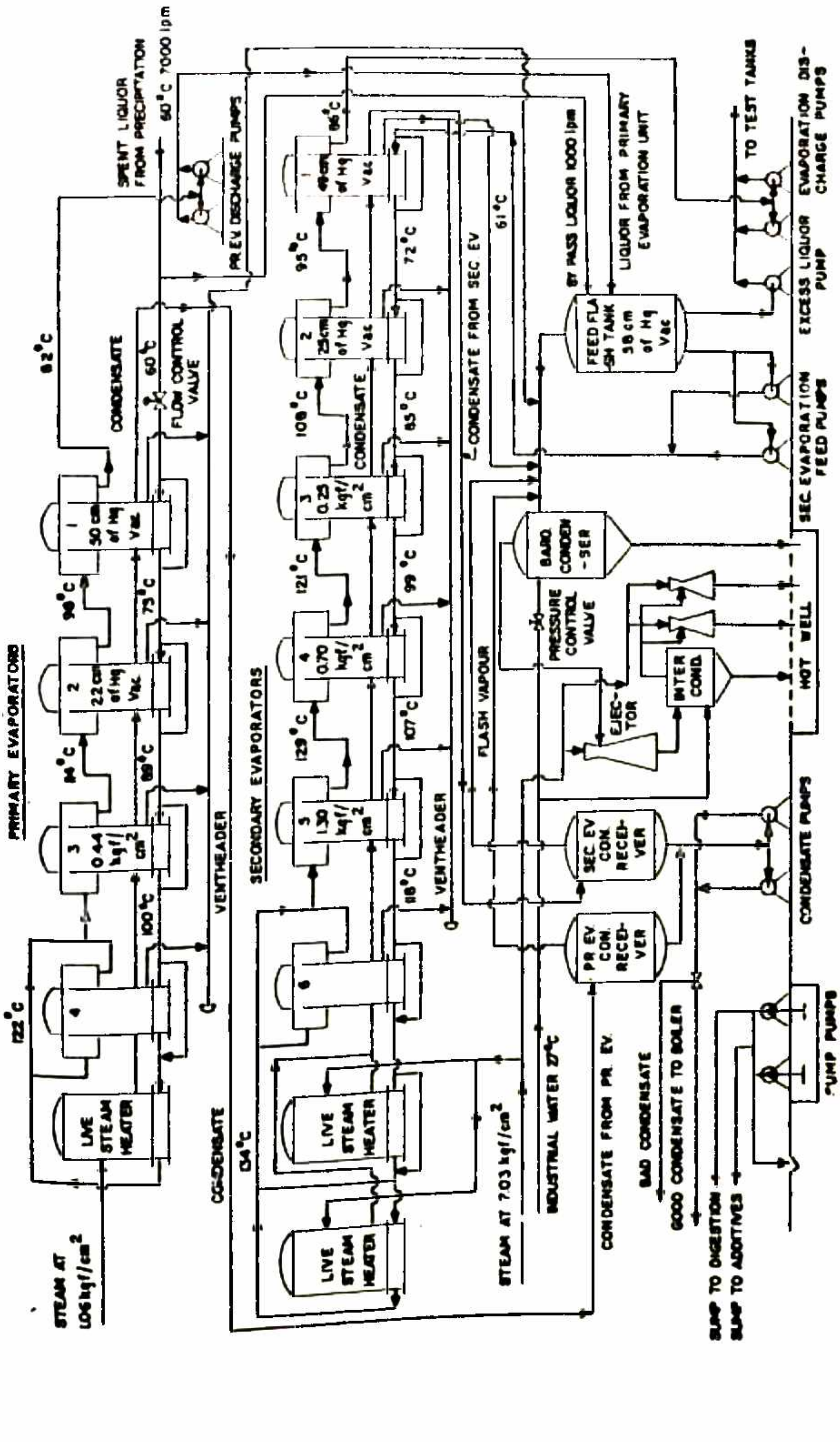

Fig 31 FLOW DIAGRAM FOR THE NEW UNIT EVAPORATORS

About 6000*litres of spent liquor at 60°C is pumped per minute from spent liquor tanks to the tube side of the first effect primary evaporator through a flow control valve. This liquor is heated to about 75°C by the vapours released in the flash chamber of this effect and the condensate from second effect. The vapoursget condensed and give their latent heat to the tube side liquor while the condensate gives its sensible heat. A part of the condensate also gets evaporated in entering the shell side of each effect because of the difference in pressures between the condensate and the shell side of the particular effect. Thevapours so formed also give their latent heat on recondensation.

The heated liquor from first effect enters the second and the third effects in succession and gets heated to 89°C and 100°C respectively in the same way as in effect 1.

The liquor coming out from the third effect enters the primary evaporation live steam heater where its temperature is raised to 122°C. The live steam heater has two tube side passes and one shell side pass. Heat is supplied in the live steam heater by steam at 1.06kgf/cm^2 (gauge) pressure condensing on the shell side. A part of this steam is obtained from excess steam produced in the digestion area

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*The numerical values given here are for the new unit.

a conductivity of less than 200 mhocm in order for it to be suitable as boiler feed. The conductivity of the condensate is a measure of its caustic contamination.

The shell side of each heat exchanger is connected to a common header through a vent line for removal of non-condensable vapours. These vapours, if not removed, will seriously reduce heat transfer between the tube walls and the condensing vapours.

About 27.2 tonnes of water is evaporated per hour in primary evaporators. The steam consumption is around 16 tonnes per hour.

3.1.2 Feed Flash Tank

Feed flash tank is a cylinderical vessel maintained at a vacuum of 58 cm of mercury. This tank receives about 1000 lpm of spent liquor directly from the primary evapotation by-pass line and the rest from the flash chamber of the first effect primary evaporator. Because of the low pressure in the feed flash tank further flashing of liquor takes place in this tank and about 13.2 tonnes of water is evaporated per hour. The flashed vapours are removed by the barometeric condenser and are condensed by direct contact with industrial water. The outgoing liquor from the feed flash tank is at a temperature of 61^{o}C and has a caustic concentration of 176 gpl.

3.1.3 Secondary Evaporators

The construction and working of the secondary evaporators and the live steam heaters is similar to that of the corresponding primary evaporator bodies. About 6400 lpm of thick liquor is supplied to the secondary evaporators from the feed flash tank with the help of evaporation feed pumps. The liquor enters the tube side of the first effect and gets heated by the vapours released in the flash chamber of the same effect and condensate from the next effect in the same way as in the primary evaporator effects. The outlet temperature of the liquor from heat exchanger and the pressure in the flash chamber of each effect are given in Table 3.1.

Table 3.1 Heat exchanger outlet temperature and flash chamber pressure in different effects of the secondary evaporation unit.

Effect No.	Outlet temperature °C	Flash chamber pressure
1	72	49 cm of Hg. Vacuum
2	85	25 cm of Hg. Vacuum
3	99	0.25 kgf/cm^2 gauge
4	107	0.70 kgf/cm^2 gauge
5	118	1.30 kgf/cm^2 gauge

Liquor from the last effect enters the live steam heater where it is heated by 7.03 kgf/cm^2 steam to 134°C. About 13.5 tonnes of steam is supplied per hour to the live steam heater. The quantity of steam supplied is controlled in such a way that the out-let temperature from the live steam heater remains constant. The high temperature thick liquor coming from the live steam heater then enters the flash chambers of various effects where flashing takes place and water is evaporated.

The condensate from the live steam heater goes to the shell side of the fifth effect, that from the fifth effect to the shell side of the fourth effect and so on in succession. The condensate from the last effect is collected in the condensate receiver from where it is sent to the boiler house.

The water evaporated in the secondary evaporators is about 35.1 tonnes per hour bringing the total evaporation in the new unit to 75.5 tonnes per hour.

The liquor coming out of the evaporation system has a concentration of 195 gpl. It is pumped to the test tanks with the help of the secondary evaporation discharge pumps.

3.1.4 <u>Barometric Condenser, Intercondenser and Ejectors</u>

The vapours generated in the feed flash tank and the condensate receivers as well as the non-condensable vapours from the evaporator bodies go to the barometric condenser. Vacuum is created in the barometric condenser with the help of a steam jet ejector using steam at 7.03 kgf/cm^2. Industrial water at 27°C is injected into the barometric condenser to condense the vapours. The quantity of water supplied is regulated by a pressure control valve.

The uncondensed vapours from the barometric condenser are sent to the barometric intercondenser. Vacuum is maintained in the barometric intercondenser by means of two second stage ejectors. About 1 tonne of steam is required per hour for the three ejectors.

Steam jet ejectors are preferred as air pumps because of their simple design and absence of moving parts. Multistage ejectors are more economical than reciprocating pumps for producing vacuum down to 1 to 2 millimetres of mercury.

Feed flash tank, barometric condenser and condensate receivers are interconnected closed vessels. Because of physical connection, the vacuum in all these bodies should be same under steady state operating conditions. The barometric condenser can be looked upon as a constant pressure source and this pressure is maintained in the other units also.

The arrangement in the evaporation system of the old unit is similar to that described above for the new unit. The only difference is that in the old unit primary evaporation live steam heater is supplied with steam at 7.03 kgf/cm^2 instead of 1.06 kgf/cm^2 as is done in the new unit heater. The spent liquor flow in the old unit is 2340 lpm. The total evaporation is 25.3 tph with a steam consumption of about 12 tph.

3.1.5 Test Tanks

Test tanks are vertical cylinderical vessels provided with side entering agitators. They are used to give surge capacity in the system for planned and emergency flow adjustment. The agitation provided in the tanks helps in proper blending of the liquor so that a uniform concentration is assured. Make-up caustic may be added in the tanks, when necessary.

During normal operation, attention has to be given to maintain constant liquor level and alumina-to-caustic ratio in the test tanks.

3.2 THE CAUSTIC CLEANING PROCESS

The heat transfer surfaces of the evaporators are periodically caustic cleaned to remove the scales deposited on the inside of the tubes. The current practice is to isolate the entire evaporation system and clean all the units simultaneously by circulating hot concentrated caustic through them for about 16 hours. The caustic cleaning time is also used to take in line any evaporation effects that have been mechanically cleaned and to isolate new effects for this purpose. The entire operation of isolation, cleaning and line up takes about 40 hours for each caustic cleaning cycle.

It has been found experimentally that a caustic solution with a concentration of 350 gpl, and heated to about 93 ^{o}C gives best results for caustic cleaning. Higher caustic concentration and temperature are very corrosive to mild steel while the use of lower concentration and temperature prolongs the cleaning time.

3.2.1 Caustic Cleaning Procedure

The concentrated caustic required for caustic cleaning is supplied to the evaporation bodies through a 101.6 mm diameter common header to which all units are connected. The liquor from a caustic cleaning tank is pumped to the first primary evaporator effect from where it passes to subsequent effects through main liquor line. The liquor coming out of primary evaporation live steam heater is passed through the secondary evaporation live steam heater and then progressively backwards through all the secondary evaporator effects. The liquor coming out of the first secondary evaporator effect is stored and fed into the main system when necessary. Before taking shut down of the evaporation system for caustic cleaning the following conditions must be ensured in the plant:

1. There should be enough condensate in the condensate receiver to ensure continuoussupply of feed water to the boilers during caustic cleaning period.
2. The extra make-up caustic required in the test tank for increasing the concentration of spent liquor directly coming from precipitation area should be available.
3. The level in the spent liquor tank should be low enough so that the excess quantity of liquor available during the shut down of the evaporator units can be stored.

After taking shut down, the unit is handed over to the maintenance department for making the closed circuit for circulating cleaning caustic. Following operations are done by the maintenance department before starting caustic flow:

1. The spectacle blinds in the 254 mm diameter inlet lines of the first effects and outlet lines of the

live steam heaters in both the evaporator units are closed while those in the 101.6 mm diameter caustic cleaning inlet line of the first effects and outlet line of live steam heaters are opened.

2. The caustic - cleaning inlet linesof the first effects and outlet linesof the live steam heaters are rolled down, cleaned and fitted back in position.
3. One mechanically cleaned body is taken into line in each evaporation unit. For these bodies the spectacle blinds in the inlet and outlet lines of heaters and flash chambers are opened while the spectacle blinds in the respective by-pass lines are closed. The spectacle blinds in the condensate lines are also opened.
4. One effect from each of the evaporation units is taken out of line. For these effects, the spectacle blinds in the inlet and outlet lines to heaters and flash chambers are closed and the spectacle blinds in the respective by-pass lines are opened. The blinds in the condensate lines are also rotated. Patches are cut on both sides of by-pass line valves for inspecting the line. If the line is choked it is rolled down, cleaned and welded back in position.
5. All leaky gaskets are replaced.

The above preparations, on an average, take 12 hours for 14 workers. During this period the operation personnel prepare caustic solution of required concentration and temperature using caustic of 800 gpl.

During caustic cleaning, the maintenance department attends to barometeric condenser, feed flash tank, and other units.

When caustic cleaning is over, all the blinds are rotated to the original position.

3.2.2 Cost of Caustic Cleaning

The following costs are associated with the caustic cleaning operation:

1. Cost of lost alumina production due to lower concentration of caustic supplied to digesters.
2. Cost of extra caustic lost with red mud.
3. Cost of work done by the maintenance department.

1. Cost of lost alumina production

When the evaporation subsystem is shut-down for caustic cleaning, the spent liquor from the precipitation area is by-passed to test tanks directly. Fresh caustic of 800 gpl concentration is added in this tank to increase the concentration of spent liquor before feeding it to digesters. Since only a maximum of 65 lpm of 800 gpl caustic can be supplied to the test tanks due to physical limitations of the plant a lower concentration liquor is fed to the digesters during the caustic cleaning interval. This results in a reduction of alumina dissolved and hence a loss of plant income.

2. Cost of caustic lost with red mud

The red mud coming from the digestion area is washed in the washers to recover caustic before it is sent to mud lake for disposal. The wash water is sent to the blow off tanks as dilutant. During normal plant operation about 2.5 gpl of soda is lost with red mud even after washing. When the evaporation subsystem is being caustic cleaned, the amount of caustic coming with the flash effluent being lower, less water is used to wash the red mud. This is done in order to maintain the concentration of caustic going to precipitation area. This results in an increase of soda with red mud to 5 gpl and hence a loss of caustic due to caustic cleaning.

3. Cost of work done by the maintenance department

This includes the labour cost for the maintenance staff and the material cost for carrying out the caustic cleaning operation.

The cost of caustic used for cleaning is not considered since the caustic after cleaning is fed to the system as make-up caustic.

A part of these costs is neutralized by the saving in the cost of bauxite fed to the plant as a result of reduced digestion. When the caustic concentration in test-tank liquor goes down, it is necessary to reduce the supply of bauxite slurry to the digesters in order to maintain a constant alumina-to-caustic ratio in the flash effluent. This results in some saving of the bauxite charged during each caustic cleaning cycle.

The net cost of each caustic cleaning operation is therefore given by the following expression:

Net cost of caustic cleaning

= Cost of lost alumina production

+ Cost of extra caustic lost with redmud

+ Cost of work done by the maintenance department

- Cost of bauxite saved (3.1)

3.2.3 The Optimal Cleaning Frequency

The optimal maintenance policy desired for the sub-system is to find the interval between consecutive caustic cleaning operations so that the total annual cost of the caustic cleaning operations and the steam used in the live steam heaters in minimized. Assuming cost of each caustic cleaning operation to be constant, the annual caustic cleaning cost depends on the number of caustic cleaning operations done in the year which is inversely proportional to the caustic cleaning interval. The steam cost depends on the number of caustic cleanings as well as the rise in steam consumption rate with time, due to scale deposits.

3.3 OPTIMAL CLEANING FREQUENCY MODELS

Let the maintenance policy be to perform n equally spaced caustic cleanings in an interval (0,T) as illustrated in Fig.3.2 Let

t_c = Interval between consecutive caustic cleanings, days

t_m = Time taken for each caustic cleaning, days

C_o = Cost of each caustic cleaning, (assumed constant), rupees.

$C(t)$ = Steam cost per unit time as a function of time , rupees

C_T = Total steam and caustic cleaning cost in the interval (0,T), rupees

Then

$$C_T = n\,C_o + n \int_0^{t_c} C(t)\,dt$$

$$= n\,(C_o + \int_0^{t_c} C(t)\,dt) \tag{3.2}$$

But $\quad n\,(t_c + t_m) = T$

$$\text{or} \quad n = \frac{T}{t_c + t_m} \tag{3.3}$$

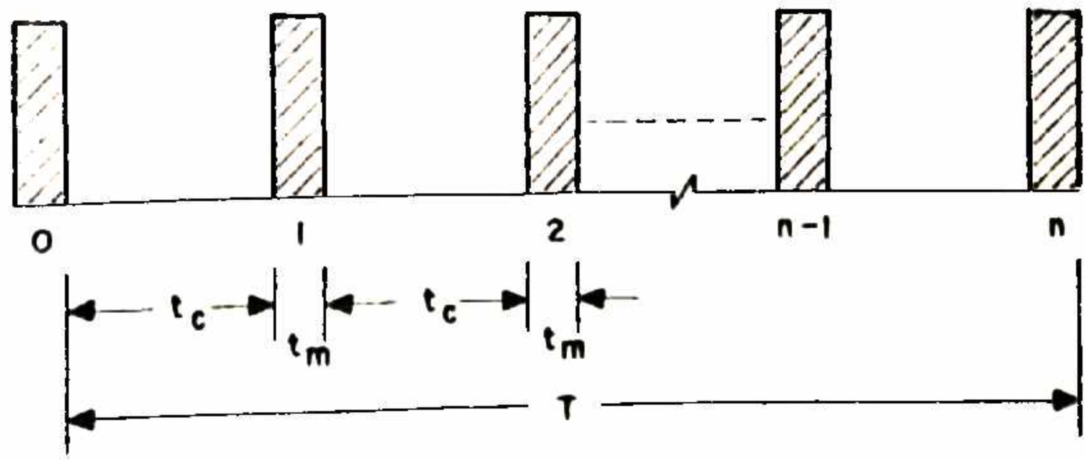

Fig 3.2 MAINTENANCE POLICY FOR THE EVAPORATORS

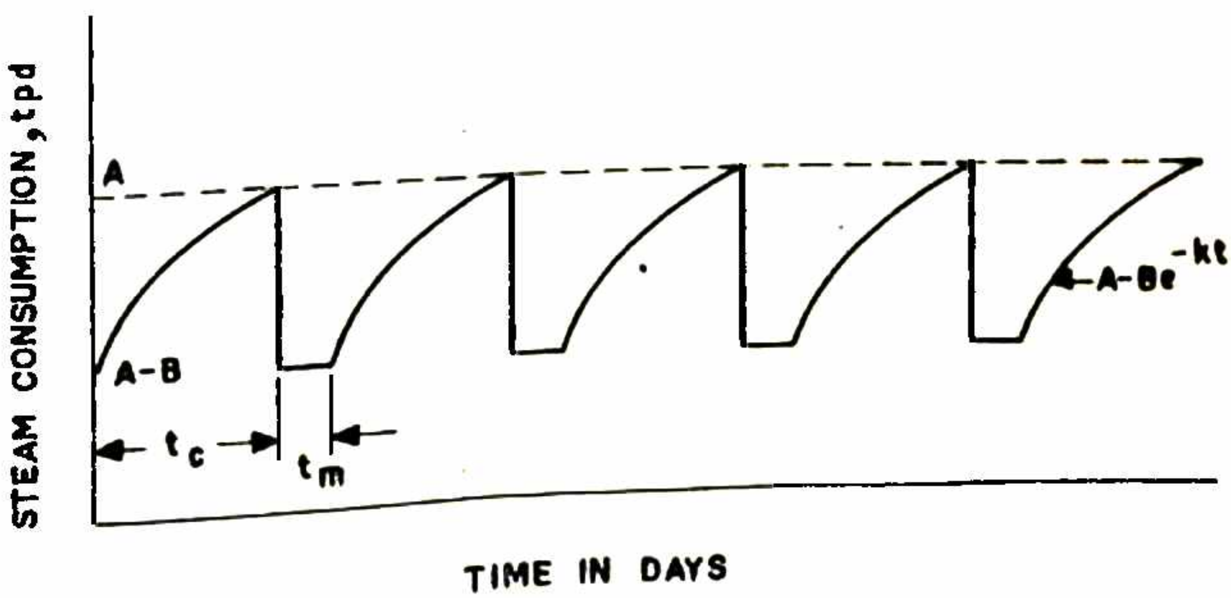

Fig 3.3 VARIATION OF STEAM CONSUMPTION RATE WITH TIME

and $C(t) = C_1 \, m(t)$ (3.4)

where C_1 = Cost of steam, rupees per tonne

$m(t)$ = Steam consumption rate tonnes per day as a function of time

Thus $$C_T = \frac{T}{t_c + t_m} \left(C_o + C_1 \int_0^{t_c} m(t)\, dt \right) \qquad (3.5)$$

It has been shown by Davidson (21), Jardine (44) and Perry (76) that variation in performance of deteriorating heat transfer surfaces can be represented by exponential curves of the type shown in Fig.3.3. Thus steam consumption rate t days after caustic cleaning may be written as

$$m(t) = A - B \exp(-kt) \qquad (3.6)$$

where A, B and k are constants

Substituting this value of m(t) in Eq 3.5, the total cost of steam and maintenance for the period (0,T) is given by

$$C_T = \frac{T}{t_c + t_m} \left(C_o + C_1 \int_0^{t_c} (A - B\, e^{-kt})\, dt \right)$$

$$= \frac{T}{t_c + t_m} \left(C_o + C_1 A t_c + \frac{C_1 B\, e^{-kt_c}}{k} - \frac{C_1 B}{k} \right) \qquad (3.7)$$

Differentiating with respect to t_c and equating to zero yields

$$C_1 B\, e^{-kt^*_{c1}} \left(t^*_{c1} + t_m + \frac{1}{k} \right) + C_o - \frac{C_1 B}{k} - t_m C_1 A = 0 \qquad (3.3)$$

where t^*_{c1} is the optimal interval between caustic cleanings when steam consumption rate increases exponentially

If $t_m << t_c$, we may write

$$T = n\, t_c \tag{3.9}$$

and $$C_1 B\, e^{-k\, t^{**}_{c1}} (k\, t^{**}_{c1} + 1) + C_o k - C_1 B = 0 \tag{3.10}$$

If changes in heat transfer coefficients due to scale deposition are small, steam consumption rate may be approximated by a straight line variation instead of an exponential variation without much error. In such a case, let $m(t)$ be represented by the expression

$$m(t) = a + bt \tag{3.11}$$

Then

$$C_T = \frac{T}{t_c + t_m} \left(C_o + C_1 \int_o^{t_c} (a + bt)\, dt\right)$$

$$= \frac{T}{t_c + t_m} \left(C_o + C_1\, at_c + \frac{C_1\, b\, t_c^2}{2}\right) \tag{3.12}$$

Differentiating with respect to t_c and equating to zero gives

$$t^{*2}_{c2} + 2\, t^*_{c2}\, t_m - \frac{2(C_o - a\, C_1\, t_m)}{bC_1} = 0 \tag{3.13}$$

where t^*_{c2} is the optimum value of t_c when steam consumption increases linearly.

Once again, if $t_m << t_c$ we may write $T = nt_c$ which yields

$$t_{c2}^{**^2} = \frac{2C_o}{bC_1} \qquad (3.14)$$

and $$C_T^{**} = T\left(\sqrt{2bC_oC_1} + C_1 a\right) \qquad (3.15)$$

3.4 PERFORMANCE ANALYSIS AND CALCULATION OF MODEL PARAMETERS

3.4.1 Theoretical Background

Fig.3.4 shows a schematic diagram of a typical evaporator effect.

Let

m_{SL} = Mass flow rate of spent liquor, kg/hr

C_{SL} = Specific heat of spent liquor, kcal/kg^{o}C

T_{SLI} = Inlet temperature of spent liquor, ^{o}C

T_{SLO} = Outlet temperature of spent liquor, ^{o}C

m_{CI} = Mass flow rate of condensate into the evaporator, kg/hr

m_{CO} = Mass flow rate of condensate out of evaporator, kg/hr

T_{CI} = Inlet temperature of condensate, ^{o}C

T_{CO} = Outlet temperature of condensate, ^{o}C

m_{TLI} = Mass flow rate of thick liquor into the flash chamber, kg/hr

m_{TLO} = Mass flow rate of thick liquor out of the flash chamber, kg/hr

C_{TL} = Specific heat of thick liquor, kcal/kg^{o}C

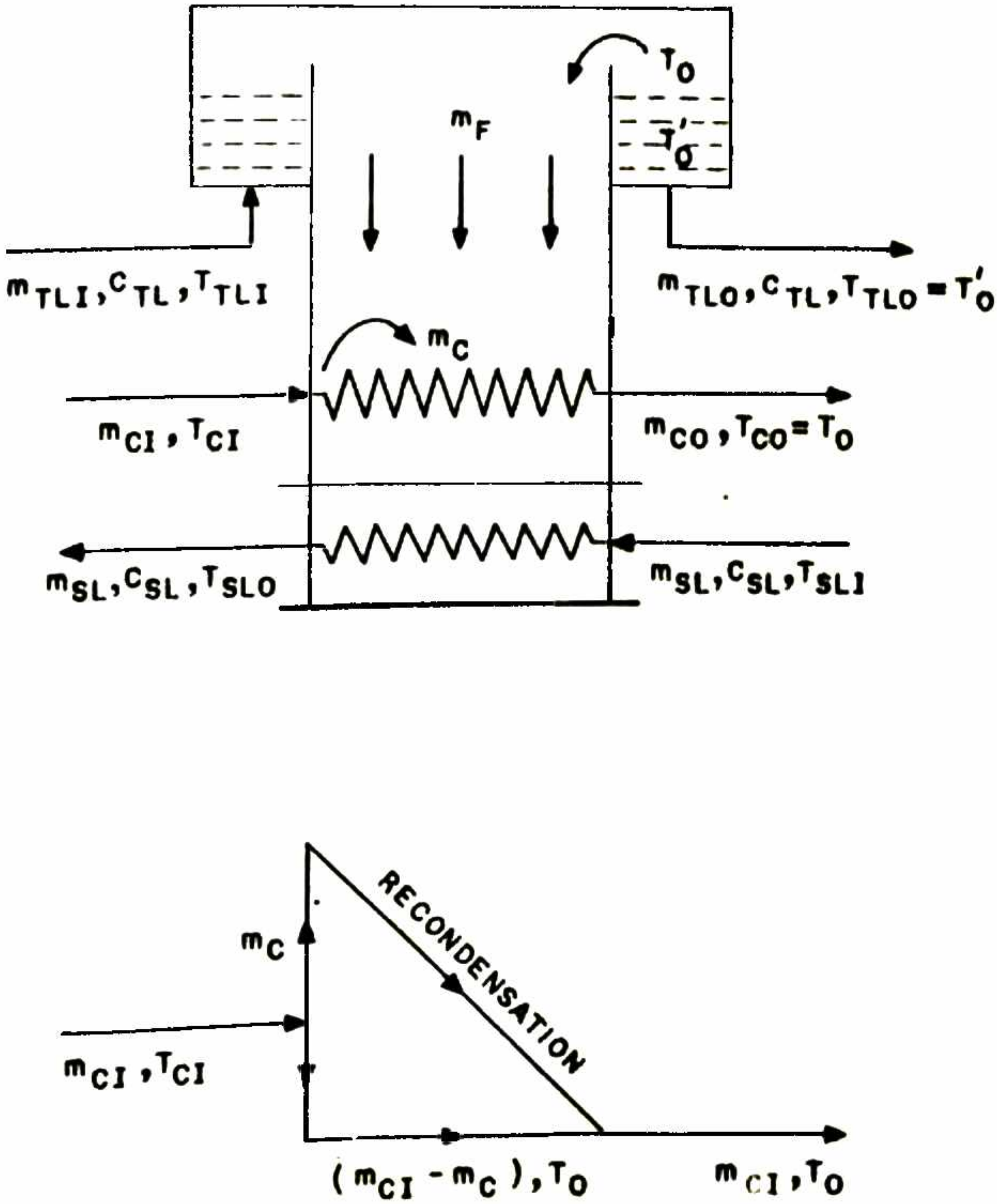

Fig 3.4 SCHEMATIC DIAGRAM FOR A TYPICAL EVAPORATOR EFFECT

T_{TLI} = Inlet temperature of thick liquor, ^oC

T_{TLO} = Outlet temperatatute of thick liquor, ^oC

m_F = Mass rate of vapours flashed from thick liquor, kg/hr

m_C = Mass rate of vapours flashed from the condensate, kg/hr

T_0 = Temperature of vapours flashed, ^oC

T_0' = Temperature of thick liquor in the flash chamber considering boiling-point rise, ^oC

m_S = Total amount of vapours present in the heater, kg/hr

h_F = Enthalpy of vapours at T_0, kcal/kg

The material and heat balance equations around the flash chamber with 0^oC as datum and neglecting heat losses, give the following results

$$m_{TLI} = m_{TLO} + m_F \qquad (3.16)$$

$$m_{TLI}\ C_{TL}\ T_{TLI} = m_{TLO}\ C_{TL}\ T_{TLO} + m_F\ h_F \qquad (3.17)$$

Substitution of Eq 3.16 into Eq 3.17 gives

$$m_{TLI}\ C_{TL}\ T_{TLI} = (m_{TLI} - m_F)\ C_{TL}\ T_{TLO} + m_F\ h_F$$

or $$m_F = \frac{m_{TLI}\ C_{TL}\ (T_{TLI} - T_{TLO})}{h_F - C_{TL}\ T_{TLO}} \qquad (3.18)$$

A part of the condensate entering the evaporator is first evaporated and then recondenses. Heat balance for the condensate at entry to the evaporator gives

$$m_{CI}\ T_{CI} = (m_{CI} - m_C)\ T_0 + m_C\ h_F$$

$$\text{or} \quad m_C = \frac{m_{SI} (T_{CI} - T_O)}{h_F - T_O} \tag{3.19}$$

Total amount of vapours present in the heater is given by

$$m_S = m_C + m_F \tag{3.20}$$

If U is the overall heat transfer coefficient for the effect in kcal/hr m^2 ^oC, A_O is the heat transfer area of the heater tubes based on outside diameter in m^2 and T_m is the log-mean temperature difference,

$$m_{SL} \; C_{SL} \; (T_{SLO} - T_{SLI}) = UA_O \; T_m \tag{3.21}$$

The log-mean temperature difference T_m is given by

$$T_m = \frac{T_{SLO} - T_{SLI}}{\ln \dfrac{T_O - T_{SLI}}{T_O - T_{SLO}}} \tag{3.22}$$

Hence

$$m_{SL} \; C_{SL} \; (T_{SLO} - T_{SLI}) = UA_O \; \frac{T_{SLO} - T_{SLI}}{\ln \dfrac{T_O - T_{SLI}}{T_O - T_{SLO}}}$$

$$\text{or} \quad U = \frac{m_{SL} \; C_{SL}}{A_O} \; \ln \frac{T_O - T_{SLI}}{T_O - T_{SLO}} \tag{3.23}$$

The quantity of steam required in the live-steam heaters can be found by writing the heat balance for each heater. Thus, neglecting losses,

Heat picked up by spent liquor = Heat given by steam or

$$m_{SL}\, C_{SL}\, (T_{SLO} - T_{SLI}) \;=\; SL \qquad (3.24)$$

where S = Mass flow rate of steam supplied to heater, kg/hr

L = Latent heat of steam, kcal/kg

In the above analysis, the shell side vapour is assumed to be saturated. This is the usual practice with shell and tube type heat exchangers. It has been shown by McAdams (58) that even though the mechanism of condensation of superheated vapours differs from that of saturated vapours, little error is caused in computing the rate of heat flow by using latent heat of saturated steam in place of total heat of superheated steam.

3.4.2 Cost of Caustic Cleaning

The cost of caustic cleaning C_0 can be calculated from Eq 3.1 using plant data given in Appendix 1.1 and Fig 3.1. The calculations for the new unit are given below.

1. Cost of lost alumina production

Rate of flow of spent liquor from test tank to new digesters	= 4944lpm
Spent liquor to old ball mills	= 176 lpm
Spent liquor to new ball mills	= 440 lpm
Total spent liquor flow to new heaters	= 5560 lpm
Total spent liquor flow to new digesters	= 5384 lpm

Caustic concentration in test tank = 193 gpl

Caustic utilization factor = 0.93

Test tank alumina-to-caustic ratio = 0.380

Flash effluent alumina-to-caustic ratio = 0.650

Alumina dissolved per day

$$= \frac{5384 \times 193 \times 0.93 \times (.650 - .380) \times 1440}{10^6}$$

$= 375.73$ t

Assuming a plant recovery of 93 per cent

Weight of alumina produced per day $= 375.73 \times .93$

$= 349.43$ t

Spent liquor caustic concentration

during caustic cleaning = 160 gpl

Make up caustic concentration = 800 gpl

Make up caustic flow = 65 lpm

If C is the concentration of caustic in the test tank during caustic cleaning $(5560 - 65) \times 160 + 65 \times 800 = 5560 \times C$

$$\text{or} \quad C = \frac{931200}{5560} = 167.4 \text{ gpl}$$

Therefore, alumina production rate during caustic cleaning

$$= \frac{5384 \times 167.4 \times 0.93 \times 0.27 \times 1440 \times 0.93}{10^6}$$

$= 303.08$ tpd

Loss in alumina production per day $= 349.43 - 303.08$

$= 46.35$ t

Caustic concentration in test tank = 193 gpl

Caustic utilization factor = 0.93

Test tank alumina-to-caustic ratio = 0.380

Flash effluent alumina-to-caustic ratio = 0.650

Alumina dissolved per day

$$= \frac{5384 \times 193 \times 0.93 \times (.650 - .380) \times 1440}{10^6}$$

$$= 375.73 \text{ t}$$

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Weight of alumina produced per day $= 375.73 \times .93$

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Therefore, alumina production rate during caustic cleaning

$$= \frac{5384 \times 167.4 \times 0.93 \times 0.27 \times 1440 \times 0.93}{10^6}$$

$$= 303.08 \text{ tpd}$$

Loss in alumina production per day $= 349.43 - 303.08$

$= 46.35$ t

Since caustic cleaning takes 40 hours, loss in alumina production for each caustic cleaning $= \dfrac{46.35 \times 40}{24}$

$= 77.25$ tonnes

Sale price of alumina = Rs 1625 per tonne

Cost of lost production per caustic cleaning = Rs 77.25 x 1625

= Rs 1,25,531

2. Cost of caustic lost with red mud

Mud load = 40 % of dry bauxite

Solids in mud slurry = 21 %

Density of liquor going with mud slurry = 1.01 gm/cc

Alumina dissolved per day = 375.73 t

Total available alumina in bauxite = 46 %

Extraction efficiency = 94 %

Weight of dry bauxite used per day

$= \dfrac{375.73}{0.46 \times 0.94}$

= 868.94 t

Mud load = 868.94 x 0.4

= 347.6 tpd

Liquor flow with mud-to-lake

$= \dfrac{347.6 \times 0.79 \times 1000}{0.21 \times 1.01 \times 1440}$

= 899.1 lpm

Increase in soda loss due to reduced washing during caustic cleaning = 2.5 gpl

Extra soda loss per day during caustic cleaning

$$= \frac{899.1 \times 2.5 \times 1440}{10^6}$$

$$= 3.23 \text{ tpd}$$

Since caustic to soda ratio in red mud is 0.75, caustic loss per day

$$= 3.23 \times 0.75$$

$$= 2.42 \text{ t}$$

Total loss of caustic in 40 hours

$$= \frac{2.42 \times 40}{24}$$

$$= 4.03 \text{ t}$$

About 40 per cent of this caustic going with red mud is recovered in lake return.

So loss of caustic with red mud	= 4.03 x 0.6
	= 2.42 t
Cost of 100 per cent caustic	= Rs 2500/tonne
Total cost of caustic lost	= 2.42 x 2500
	= Rs 6,050

3. Cost of work done by the maintenance department

Details of work done by the maintenance department have already been given.

Before caustic cleaning on an average 14 men work for 12 hours, during caustic cleaning 8 men work for 16 hours and after caustic cleaning 14 men work for 12 hours.

Maintenance man-hours spent on caustic cleaning

$$= 14 \times 12 + 8 \times 16 + 14 \times 12$$

$$= 464 \text{ man hours}$$

Labour cost at the rate of Rs 20/- per man working for 8 hours $= \frac{464 \times 20}{8}$

$= \text{Rs } 1,160$

The maintenance material cost is given in Table 3.2

Table 3.2 Maintenance material cost per caustic cleaning

	Item	Consumption	Rate	Cost Rs.
1.	Asbestos gasket sheets for blinds 3.2 mm thick	4 sheets	Rs 250/- per sheet	1,000
2.	Welding electrodes	2 packets	Rs 50/- per packet	100
3.	Oxygen	2 cylinders	Rs 75/- per cylinder	150
4.	Acetylene	1 cylinder	Rs 325 per cylinder	325
5.	Bolts and nuts	15 kg	Rs 12 per kg	180
			Total	Rs 1,755

Therefore, total cost incurred on work done by the maintenance department $= \text{Rs } 1,160 + \text{Rs } 1,755$

$= \text{Rs } 2,915$

4. Cost of bauxite saved

Reduction in alumina produced = 77.25 t

Total available alumina in bauxite = 46 %

Extraction efficiency = 94 %

Recovery of dissolved alumina = 93 %

Weight of dry bauxite saved per caustic cleaning

$$= \frac{77.25}{0.93 \times 0.94 \times 0.46}$$

$$= 192.1 \text{ t}$$

Moisture in bauxite = 3 %

Weight of wet bauxite saved $= \frac{192.1}{0.97}$

$= 198.04$ t

Cost of bauxite including transportation

= Rs 95 per tonne

Cost of bauxite saved = 198.04 x 95

= Rs 18,814

The net cost of each caustic cleaning

C_0 = Rs 1,25,531 + 6,050 + 2,915 - 18814

= Rs 1,15,682

say Rs 1,16000

3.4.3 Cost of Steam Per Tonne

Cost of steam per tonne, C_1, can be worked out from the total expenses incurred in the boiler house per month and the average monthly steam generation rate. The total cost incurred in the boiler house consists of cost of fuel, cost of materials supplied from central stores, salaries and fringe benefits of staff, equipment depreciation charges and cost of power consumed. A part of the expenditure incurred in the workshop and the total running expenses of the testing laboratory are also charged to the alumina plant. One-sixth of these expenses are charged to boiler house as per plant practice.

As shown in Appendix 3.1, the current cost of steam generation is Rs 30 per tonne.

3.4.4 Steam Consumption Rate

Steam consumption rate is calculated from Eq 3.24 using design conditions. The increase in steam consumption with scale formation is calculated from observed fall in temperature at the outlet of last evaporator effect.

For the new unit,

Total liquor entering the evaporation sub-system = 7000 lpm

Liquor going to feed flash tank through bypass = 1000 lpm

Density of liquor = 1.24 gm/cc

$$\text{Total liquor entering the sub-system} = \frac{7000 \times 1.24 \times 60}{1000}$$

$$= 520.8 \text{ tph}$$

$$\text{Liquor entering feed flash tank} = \frac{1000 \times 1.24 \times 60}{1000}$$

$$= 74.4 \text{ tph}$$

Liquor to primary evaporators = 446.4 tph

The evaporation in the three primary evaporators can be found by using Eqs 3.16 and 3.18 proceeding backwards from the third effect.

Effect 3

$$m_F = \frac{446.4 \times 0.86\ (122-114)}{642.8 - 0.86 \times 114} = 5.64 \text{ tph}$$

$$m_{TLO} = 446.4 - 5.64 = 440.76 \text{ tph}$$

Effect 2

$$m_F = \frac{440.76 \times 0.86\ (114 - 98)}{635.5 - 0.86 \times 98} = 11 \text{ tph}$$

$$m_{TLO} = 440.76 - 11 = 429.76 \text{ tph}$$

Effect 1

$$m_F = \frac{429.76 \times 0.86 (98-82)}{628.3 - 0.86 \times 82} = 10.60 \text{ tph}$$

$$m_{TLO} = 429.76 - 10.60 = 419.16 \text{ tph}$$

Total evaporation in primary evaporators

$$= 5.64 + 11.0 + 10.60$$

$$= 27.24 \text{ tph}$$

In the feed flash tank 419.16 tph of thick liquor at 82°C mixes with 74.4 tph of spent liquor at 60°C. If t_f is the temperature of the total liquor after mixing

$$419.16 \times 0.86(82 - t_f) = 74.4 \times 0.86\ (t_f - 60)$$

or $$t_f = \frac{419.16 \times 82 + 74.4 \times 60}{74.4 + 419.16}$$

$= 78.7^{o}C$

Outlet temperature from feed flash tank $= 61^{o}C$

Water evaporated in the feed flash tank

$$= \frac{493.56 \times 0.86\ (78.7 - 61)}{624.0 - 0.86 \times 61}$$

$= 13.15$ tph

Flow to secondary evaporators $= 493.56 - 13.15$

$= 480.41$ tph

Proceeding similarly, the total evaporation in the five secondary evaporators, starting with No.5 is found to be 3.85, 6.06, 9.59, 7.20 and 8.44 tph with a total of 35.14 tph.

The steam is supplied to the primary evaporation live-steam heater at 1.06 kgf/cm^2 and to secondary evaporation live steam heaters at 7.03 kgf/cm^2.

From Eq 3.24 amount of steam required for primary evaporation live stem heaters

$$= \frac{446.4 \times 0.86\ (122 - 100)}{525.4}$$

$= 16.08$ tph

Steam required for secondary evaporation live steam heaters

$$= \frac{480.41 \times 0.86(134 - 118)}{489.15}$$

$= 13.51$ tph

The initial steam consumption rate in the evaporation sub-system thus is $(16.08 + 13.51) \times 24$

$$= 710.16 \text{ tph}$$

It has been established by discussion with the plant personnel that the total drop in the temperature pick up over all the primary evaporator effects is $5^{o}C$ in 3 months. The corresponding figure for the secondary evaporators is $6^{o}C$ for the same period. Based on this observation the steam consumption rate at the end of a three month period will be:

Primary evaporation live steam heaters

$$= \frac{446.4 \times 0.86 \times (122 - 95)}{525.4}$$

$$= 19.73 \text{ tph}$$

Secondary evaporation live steam heaters

$$= \frac{420.41 \times 0.86 \times (134 - 112)}{489.15}$$

$$= 18.58 \text{ tph}$$

This gives a steam consumption rate, 90 days after caustic cleaning as $(19.73 + 18.58) \times 24$

$$= 919.44 \text{ tpd}$$

Assuming that each caustic cleaning brings the heater to as new condition, the steam consumption increases from 710.16 tpd to 919.44 tpd in 90 days.

It has been shown by Davidson (21), that increase in cost of boiler fuel due to deterioration of boiler surfaces is a function of steam generated by the boiler. Since evaporators are being continuouslyoperated at almost constant operating conditions, the increase in steam cost can be directly related to number of days the evaporator has been in use. Further, since fall in temperature pick up is only of the order of $\frac{1}{18}$ degrees per day for the primary evaporators and $\frac{1}{15}$ degrees per day for the secondary evaporators, not much error will be introduced if linear increase in steam consumption is assumed instead of the expected exponential one.

The variation in steam consumption rate can thus be expressed as

$$m(t) = 710.16 + \frac{(919.44 - 710.16)t}{90}$$

$$= 710.16 + 2.325\ t \qquad (3.25)$$

This gives values of constants a and b in Eq 3.11 to be

$$a = 710.16 \text{ tpd}$$

$$b = 2.325 \text{ tpd/day}$$

3.5 CALCULATION OF OPTIMAL CLEANING INTERVAL

3.5.1 Optimal Cleaning Interval Neglecting Time Required for Maintenance

From Eq 3.14, the optimal cleaning interval when $t_m << t_c$

is given by

$$t_{c2}^{**} = \sqrt{\left(\frac{2C_o}{bC_1}\right)}$$

Substituting the values of C_o, b and C_1 calculated above

$$t_{c2}^{**} = \sqrt{\left(\frac{2x116000}{2.325x30}\right)}$$

$= 57.67$ days

say 58 days

The total annual cost when operating with a caustic cleaning cycle of t_c days and $t_m << t_c$ is given by Eq 3.12 as

$$C_T = \frac{T}{t_c}\ (C_o + C_1\ a\ t_c + 0.5\ C_1\ bt_c^2)$$

$$= 365\ \left(\frac{116000}{t_c} + 30 \times 710.16 + 0.5 \times 30 \times 2.325\ t_c\right)$$

$$= 365\ \left(\frac{116000}{t_c} + 21304.8 + 34.875\ t_c\right) \qquad (3.26)$$

When $t_c = t_{c2}^{**} = 58$ days

C_T^{**} = Rs 92.45 lakh/year

3.5.2 <u>Optimal Cleaning Interval Taking Maintenance Time into Account</u>

Maintenance time $t_m = 40$ hours

$= 1.67$ days

The optimal cleaning cycle time when t_m is not negligible is given by the relationship (Eq 3.13)

$$t^{*2}_{c2} + 2\, t^{*}_{c2}\, t_m - \frac{2(C_o - aC_1\, t_m)}{bC_1} = 0$$

or
$$t^{*2}_{c2} + 2\, t^{*}_{c2} \times 1.67 - \frac{2(116000-710.16 \times 30 \times 1.67)}{2.325 \times 30} = 0$$

or
$$t^{*2}_{c2} + 3.34\, t^{*}_{c2} - 2306 = 0$$

which gives $t^{*}_{c2} = 46.39$ days

say 47 days

The annual operating cost in this case is given by

$$C_T = \frac{T}{t_c + t_m}\,(C_o + C_1\, a\, t_c + 0.5\, C_1\, bt_c^2)$$

$$= \frac{365}{t_c + 1.67}\,(116000 + 30 \times 710.16\, t_c + 0.5 \times 30 \times 2.325\, t_c^2)$$

$$= \frac{365}{t_c + 1.67}\,(116000 + 21304.8\, t_c + 34.875\, t_c^2) \quad (3.27)$$

When $t_c = t^{*}_{c2} = 47$ days,

C^{*}_{T} = Rs 89.57 lakhs/year.

Table 3.3 gives a comparison of total annual operating costs calculated from Eqs 3.26 and 3.27 for different values of t_{c2}. These values are plotted in Fig.3.5. The following observations can be made from this figure:

1. The optimal interval between caustic cleanings is much less than the presently used interval of 90 days.
2. Neglecting time taken for maintenance, the optimal

Table 3.3 Annual operating cost with different cleaning cycle intervals

Caustic cleaning interval, days	Annual operating cost, Lakhs of Rs	
	Neglecting maintenance time (Eq 3.26)	Including maintenance time (Eq 3.27)
20	101.48	93.66
30	95.69	90.65
40	93.44	89.69
42	93.19	89.63
47	92.75	89.57
50	92.60	89.60
52	92.52	89.65
53	92.50	89.67
58	92.45	89.86
60	92.46	89.95
63	92.50	90.11
70	92.72	90.56
80	93.24	91.33
90	93.92	92.21

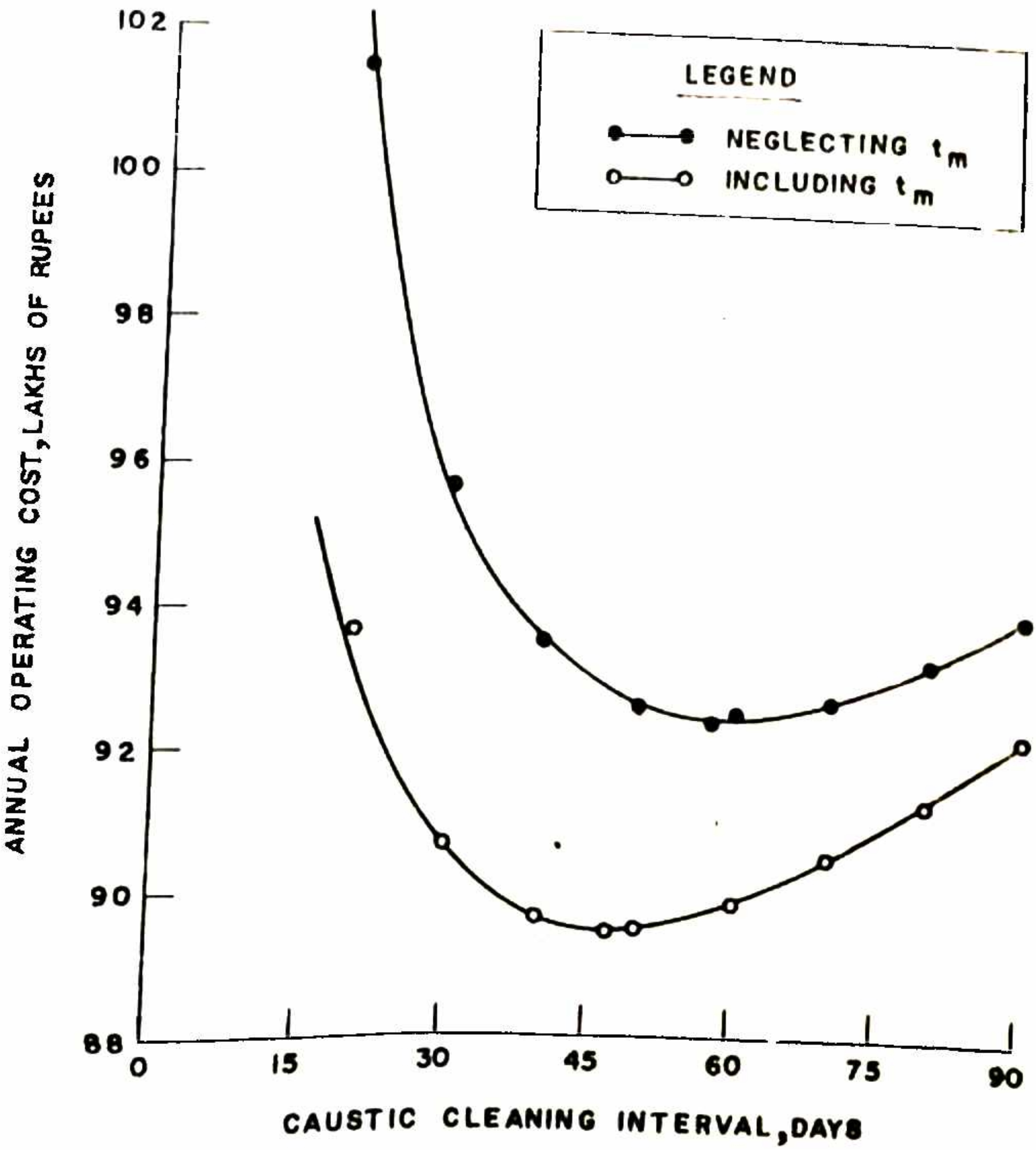

Fig 3.5 EFFECT OF CAUSTIC CLEANING INTERVAL ON ANNUAL OPERATING COST

cleaning cycle interval is 58 days with an annual operating cost of Rs 92.45 lakhs against the current practice of 90 days with an annual cost of Rs 93.92 lakhs. This gives an annual saving of Rs 1.47 lakhs.

3. If cleaning time is taken into account, the optimal caustic cleaning interval reduces to 47 days with an annual cost of Rs 89.57 lakhs against the current cost of Rs 92.21 lakhs for 90 days cleaning interval. The saving in this case is Rs. 2.64 lakhs per year.

4. The variation of total cost with cleaning cycle interval is not verysteep. Scheduling cleaning within $\pm$ 5 days of the optimal value varies the annual cost only by a maximum of Rs.5000 or .054 per cent when t_m is neglected and a maximum of Rs 8000 or .089 per cent when t_m is taken into account.

3.6 SENSITIVITY ANALYSIS OF THE OPTIMAL POLICY

Sensitivity analysis has been carried out to find the variation of optimal cleaning cycle time and annual operating cost with model parameters for the case when $t_m << t_c$. As can be seen from Eqs 3.14 and 3.15 the factors that influence the optimal policy are the steam cost C_1, the maintenance cost C_o and fouling factor b. Any variation in the value of these parameters due to fluctuations in cost or error in their estimate is bound to influence both the optimal cleaning cycle interval and the total annual cost. Sensitivity analysis has therefore been carried out for these three factors.

3.6.1 Sensitivity Analysis of Optimal Maintenance Policy with Respect to Cost of Steam per Tonne

Table 3.4 gives the variation of optimal cleaning cycle time and total annual operating cost at optimal interval for steam cost varying from Rs 24 to Rs 36 per tonne i.e. ± 20 %. of the current rate of Rs 30 per tonne. For comparison, values of annual operating cost with the

Table 3.4 Effect of variation of steam cost on optimal cleaning cycle time and annual operating cost

C_o = Rs 116,000   a = 710.16   b = 2.325

Steam cost C_1 Rupees per tonne	Optimal cycle time t_{c2}^{**}, days (Eq 3.14)	Annual Operating cost C_T^{**} Lakhs of rupees (Eq 3.15)	Annual Operating Cost $C_m(90)$ Lakhs of rupees (Eq 3.12)
24	65	75.34	76.08
26	62	81.06	82.03
28	60	87.76	87.98
30	58	92.45	93.92
32	56	98.11	99.87
34	54	103.76	105.82
36	53	109.40	111.77

present 90 day cycle, $C_T(90)$, are also shown in this table. The latter values have been calculated using Eq 3.12. It can be seen from this table that the optimal cleaning cycle time falls by about 2 days and the annual cost at optimal interval increases by about 6 % for every Rs 2 per tonne increase in steam cost. Also the difference between $C_T(90)$ and C_T^{**} increases with increase in cost of steam underlining the importance of cost optimization studies.

3.6.2 <u>Sensitivity Analysis of Optimal Maintenance Policy with Respect to Caustic Cleaning Cost</u>

The fixed caustic cleaning cost of Rs 1,16,000 has been assumed on the basis of a 40 hour cleaning period as per the existing plant practice. It is possible that this time would be reduced when the cleaning cycle is changed to optimal 58 days in place of the existing 90 days due to reduced scale build up. The cleaning cost will also change if the concentration or quantity of make up caustic supplied in test tanks is changed. Other factors that may influence the cleaning cost are variation in material cost, reduction in loss of caustic with red mud by changing the quantity of lake return or use of higher concentration caustic in test tank.

The effect of variation of C_o on optimal maintenance policy is shown in Table 3.5. From this table it may be observed that the optimal policy cost is not very significantly affected by the variation in caustic cleaning cost. A variation of 50 per cent from a caustic cleaning cost of 0.8 lakhs to 1.2 lakhs increases the cost only by about 3.05 per cent from 89.96 lakhs to 92.70 lakhs. The cleaning interval is, however, changed from 48 days to 59 days with this variation of cleaning cost.

Table 3.5 Effect of variation of caustic cleaning cost on optimal cleaning interval and annual operating cost

C_1 = Rs 30 per tonne a = 710.16 b = 2.325

Fixed cleaning cost C_o Lakhs of Rs	Optimal cycle time t_c^{**} days (Eq 3.14)	Annual operating cost C_T^{**} lakhs of Rs (Eq 3.15)	Annual Operating cost $C_T^{*}(90)$ lakhs of Rs (Eq 3.12)
0.80	48	89.96	92.46
0.90	51	90.70	92.87
1.00	54	91.40	93.27
1.10	56	92.06	93.68
1.16	58	92.45	93.92
1.20	59	92.70	94.09
1.30	61	93.31	94.49
1.40	63	93.89	94.90

3.6.3 Sensitivity Analysis of Optimal Maintenance Policy with Respect to Fouling Factor

It was assumed in the above analysis that the outlet temperature from primary evaporator effects falls by 5 ^oC in 90 days and that from secondary evaporators by 6 ^oC. Any error in this estimate affects the value of b and hence the optimal policy as shown in Table 3.6. It can be observed from Table 3.6 that an error of ± 20 percent in the estimate of fouling factor influences the optimal time by a maximum of 7 days and annual operating cost by 1.84 per cent.

Table 3.6 Effect of error in the estimate of b on optimal maintenance policy

C_o = Rs 1,16,000 C_1 = Rs 30 a = 710.16 b = 2.325

Percentage error in b %	Value of b Rs/day/day	Optimal cycle time t_c^{**} days (Eq 3.14)	Annual Operating cost C_T^{**} Lakhs of Rs (Eq 3.15)	Annual operating cost $C_T(90)$ lakhs of Rs (Eq 3.12)
-30	3.321	48	95.31	98.83
-20	2.906	51	94.18	96.79
-10	2.583	55	93.24	95.19
0	2.325	58	92.45	93.92
+10	2.114	60	91.76	92.88
+20	1.938	63	91.17	92.02
+30	1.788	66	90.64	91.28

4. SLURRY INJECTION PUMPS

4.1 INTRODUCTION

The five slurry injection pumps of the alumina plant operate as two independent, parallel systems with sequential redundancy in each system. Redundancy is a principal method of improving system reliability. Two types of redundancy configurations are commonly used - active parallel redundancy and sequential redundancy. In the active parallel redundancy all the operable units work all the time though the system needs a smaller number of units for its successful operation. In sequential redundancy, the standby units are put into operation only after the operating unit has failed. A standby unit may be 'cold' standby if it is not expected to fail when acting as standby or 'hot' standby if the possibility of such failures also has to be taken into consideration. In the present investigation, the pumps are treated as cold standby units.

Fig 4.1 gives a flow diagram of the slurry-mix area showing position of the slurry injection pumps. As can be seen from this figure there are three pumps in the old unit and two in the new unit. During plant operation only one each of these pumps is working. All pumps use steam at 17.58 kgf/cm^2 pressure taken from the main header. The exhaust steam at 1.06 kgf/cm^2 pressure is used in the clarification area for preheating water required for washing of the red mud.

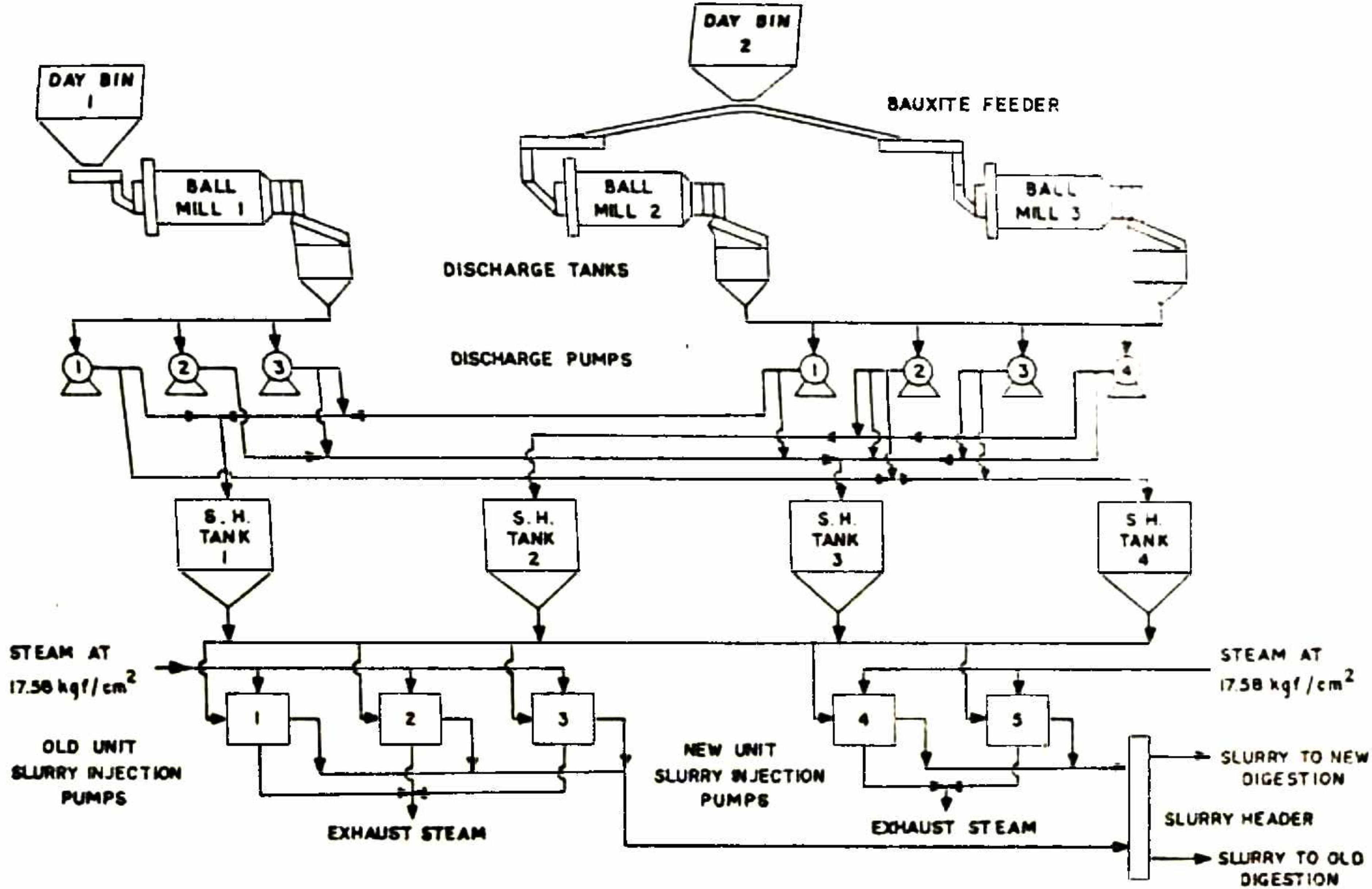

Fig 4.1 FLOW DIAGRAM FOR THE SLURRY - MIX AREA

Steam driven pumps use steam at full pressure throughout the stroke and allow no significant expansion in the cylinder. Duplex arrangement is used in these pumps to ensure that discharge from one cylinder is maximum when the piston in the other cylinder is near the end of its stroke giving no discharge. The resulting discharge is more steady and at a higher average pressure than that for a single cylinder.

4.1.1 <u>Constructional Details of the Pumps</u>

The steam ends of all the pumps are similar. Steam cylinders are cast integral with the piston-valve steam chests. They are closed on the inside end by the centre piece and on the outside end by the cylinder head. The centre piece connects the steam and liquid ends rigidly. It contains a bronze throat bush, cast-iron piston rod glands and the packing through which the steam piston rod enters the steam cylinder. The cylinder is supported on the cylinder foot which is bolted to the cylinder. Cushion valves are installed in the exhaust ports at the ends of the cylinder to permit adjustment of stroke length. These valves control the amount of cushion steam trapped behind the piston at the end of the stroke.

The liquid end design is different for the old and the new unit pumps. The old unit pumps being of the plunger type use two opposed plungers to give delivery corresponding to a single double acting piston. The liquid end in these pumps consists of two cylinder blocks each divided into two compartments one for each plunger. The valve chambers are cast integral with the liquid cylinders. These chambers are divided vertically into two separate compartments so that each liquid cylinder has its own suction and discharge valve. The area under the suction valves and above the discharge valves is common to both plunger compartments. The liquid end of the new unit pumps consists of two liquid cylinders each provided with a double acting piston. The valve chambers are not cast integral with the cylinders. The suction and discharge valves are located outside and below the pump cylinders in a 'surge block'. During operation slurry is not allowed to enter the cylinder. The pump cylinder and the connecting surge pipe is filled with caustic liquor. As the piston is moved back in the cylinder, the pressure above the suction valve reduces allowing slurry to flow into the surge pipe. On the forward stroke, caustic liquor forces the slurry out through the discharge valve into the discharge manifold. The caustic liquor thus acts as a liquid piston to force the slurry through the discharge valve. Additional liquor is added to make up for the amount lost through interface mixing.

The liquid end pistons are made of forged steel and are secured on the tapered end of the piston rod with a cotter pin. They are provided with two rubber packings to reduce the leakage of liquid from the high pressure side to the low pressure side of the piston. The packings are secured to the pistons by means of end plates and snap rings. When the packings become wornout or loose they can be replaced or tightened only by removing the head of the pump. The plunger pumps have a distinct advantage over the piston pumps in this.regard. In the plunger pumps, the single acting plungers work through packings in the head of the cylinder using two outside packings instead of one outside and one inside packing as in the case of piston pumps. With outside packing any leakage is visible to the operator. This and the greater case of repacking result in much better maintenance and less leakage for the plunger pumps. These factors offset the higher initial cost of plunger pumps to some extent. Plunger pumps also have theadvantage that they can give much higher delivery pressures compared to piston pumps of the same size.

4.2 SUBSYSTEM PERFORMANCE ANALYSIS

Appendices 4.1 and 4.2 give the charging time data for the old and new unit pumps respectively for a period of six months. These tables have been prepared from the data collected from the plant operation logbooks and records of the maintenance department for the relevant period. The operation logbooks give the starting and stopping clock time for pumps chronologically along with information like charging loss, reasons for stopping etc. The maintenance records give details of the work done on the pumps by the maintenance department.

Each period from the start of one charging operation to the next has been termed as a charging cycle and given a cycle number for identification. The tables give the number of the pump operating in each charging cycle and length of the uninterrupted charging period. The charging cycle is interrupted when the slurry injection pump is stopped. The stoppage may be necessitated by a fault developing in the slurry injection subsystem itself namely the pumps, slurry holding tanks,suction and discharge manifolds and piping or in the rest of the plant. The faults developing in the subsystem are referred to as 'pump trouble' while all faults occuring outside the subsystem are termed as 'plant trouble'.

When a pump is stopped due to breakdown of the pump itself, the same pump may be put back into operation if the breakdown is minor and can be rectified in a short time, otherwise a standby unit is put into service. This normally requires a very short time and no significant slurry charging loss may result due to pump change-over. But if the breakdown is of a major type and a standby unit is not immediately available for use, pump breakdown may also result in charging loss. Any fault in the subsystem piping network requiring rolling down, cleaning and/or repairing and boxing up of pipe sections, or leakage in valves, gaskets etc. will also result in charging loss.

Typical plant faults which result in suspension of slurry charging include steam shortage, power failure, erosion leakage, low bauxite stock, and planned shutdown. Same pump may be started after an interruption of this type or it may be substituted by a standby unit. When calculating the running time of pumps between failures such interruptions have been disregarded and the running time taken as total of the pump running time before and after interruption. The interruption period is listed as charging loss and associated with the charging cycle which is interrupted by such a loss.

The data given in Appendices 4.1 and 4.2 has been analyzed statistically to find the net time between failures of the pumps, average running time between subsystem failures, average total time between plant failures and the charging loss distributions.

4.2.1 Mean-Time-Between-Pump-Failures

Appendix 4.3 gives the running time in minutes for various pumps in sequential order of their use. Table 4.1 gives the same data rearranged into different classes for statistical analysis. The data suggests negative exponential distribution for the running-time-between-failures for all the pumps. The analysis has been carried out assuming such a distribution to be valid and then testing the goodness-of-fit.

Table 4.1 Running time distribution for the slurry injection pumps

Class No.	Time range minutes	Number of observations				
		Pump No.1	Pump No.2	Pump No.3	Pump No.4	Pump No.5
1	0 - 200	28	25	21	17	5
2	200*- 400	19	18	23	11	7
3	400 - 600	17	12	11	10	6
4	600 - 800	13	7	12	10	8
5	800 - 1000	13	7	5	8	12
6	1000 - 1200	9	3	6	13	6
7	1200 - 1400	1	6	3	8	7
8	1400 - 1600	2	0	1	6	7
9	1600 - 1800	4	1	5	3	7
10	1800 - 2000	3	0	0	1	3
11	2000 - 2200	2	0	0	1	3
12	2200 - 2400	0	0	0	2	3
13	2400 - 2600	1	1	1	1	2
14	2600 - 2800	1	0	0	0	3
15	2800 - 3000	1	0	0	1	3

contd..

Table 4.1 (contd.)

Class No.	Time range minutes	Number of observations				
		Pump No.1	Pump No.2	Pump No.3	Pump No.4	Pump No.5
16	3000 - 3200	1	0	0	0	1
17	3200 - 3400	0	0	0	0	2
18	3400 - 3600	0	0	0	0	0
19	3600 - 3800	0	0	1	0	3
20	3800 - 4000	0	0	0	0	0
21	4000 - 4200	0	0	0	1	2
22	4200 - 4400	0	0	0	0	1
23	4400 - 4600	0	0	0	0	2
24	4600 - 4800	0	0	0	0	0
25	4800 - 5000	0	0	0	0	1
Total	-	115	80	89	93	94

* The end of the class values have been included in the preceding class.

The calculations for this analysis are given in Appendix 4.4. The essential steps in the analysis are as follows:

1. The mean-time-between-failures for each pump is determined using the relationship

$$MTBF = \frac{\sum_{i=1}^{n} f_{oi}\, t_i}{\sum_{i=1}^{n} f_{oi}} \qquad (4.1)$$

where f_{oi} is the observed frequency of failures in interval i, t_i is the mid-point of the class interval and n is the total number of classes as defined in Table 4.1.

2. The observed reliability is calculated by dividing cumulative failures by the total number of failures and subtracting the quotient from 1.

3. The expected reliability is calculated using exponential distribution relationship

$$R(t_i) = e^{-\lambda_i t_i} \qquad (4.2)$$

where $R(t_i)$ is the reliability or the probability of the pump running-time-between-failures exceeding t_i and λ_i is the failure rate of the pump.

4. Goodness-of-fit is tested using Chi-square test. The χ^2 values are calculated by using the relationship

$$X^2 = \sum_{i=1}^{k} \frac{(f_{ei} - f_{oi})^2}{f_{ei}} \quad (4.3)$$

where f_{oi} is the observed frequency in each class, f_{ei} is the expected frequency assuming exponential distribution and k is the number of classes considered.

It has been suggested by Ostle (74) that if the expected number in a class is small, the value of X^2 is inflated misleadingly. In carrying out the reliability analysis for the pumps the classes have been merged with each other wherever the expected number in any class is less than 3 as suggested by Ostle. The number of classes is accordingly reduced and so is the number of degrees of freedom. The last class in each table has been added to take care of expected failures beyond the last recorded failures, as predicted by the assumed negative exponential distribution. Figs.4.2 through 4.6 show the expected negative exponential reliability curves for the pumps with the observed values superimposed in each case. As can be seen from these figures, the agreement between the observed and predicted reliability values is excellent for old unit pumps (Nos.1 to 3) and fairly good for the new unit pumps (Nos. 4 and 5). The MTBF and failure rate values obtained for the various pumps are given in Table 4.2

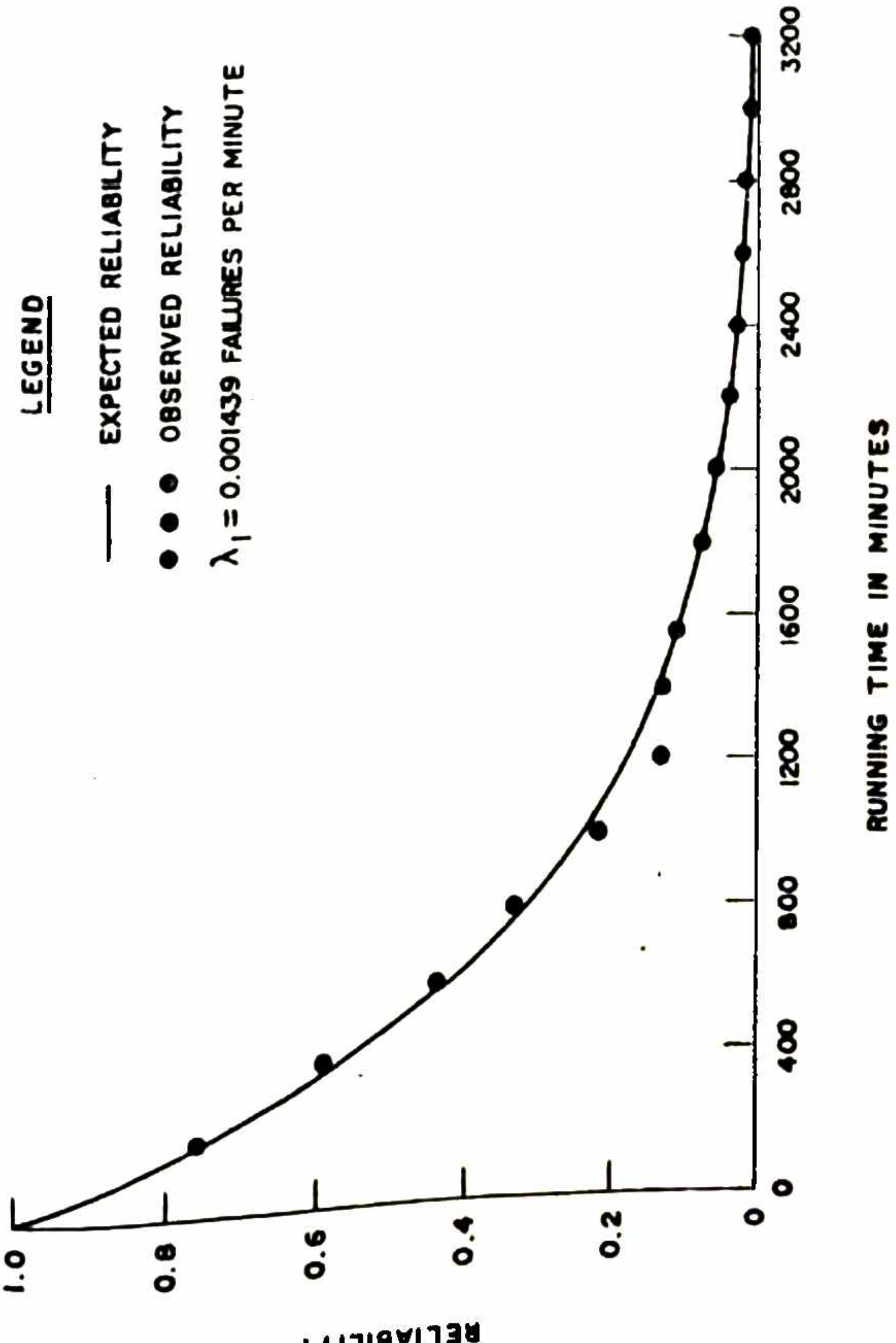

Fig. 4.2 RELIABILITY ANALYSIS FOR PUMP NO. 1

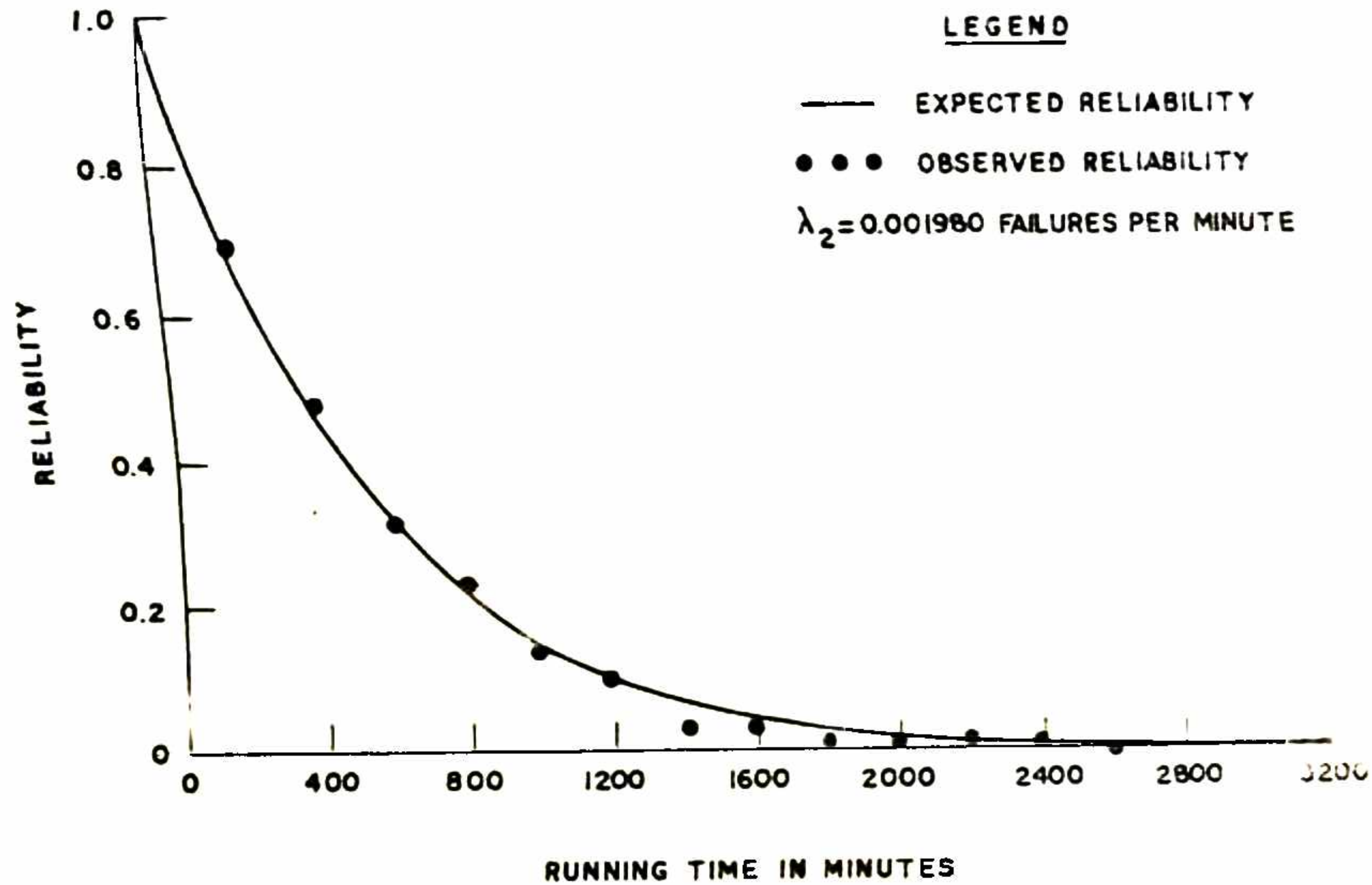

Fig. 4.3 RELIABILITY ANALYSIS FOR PUMP NO. 2

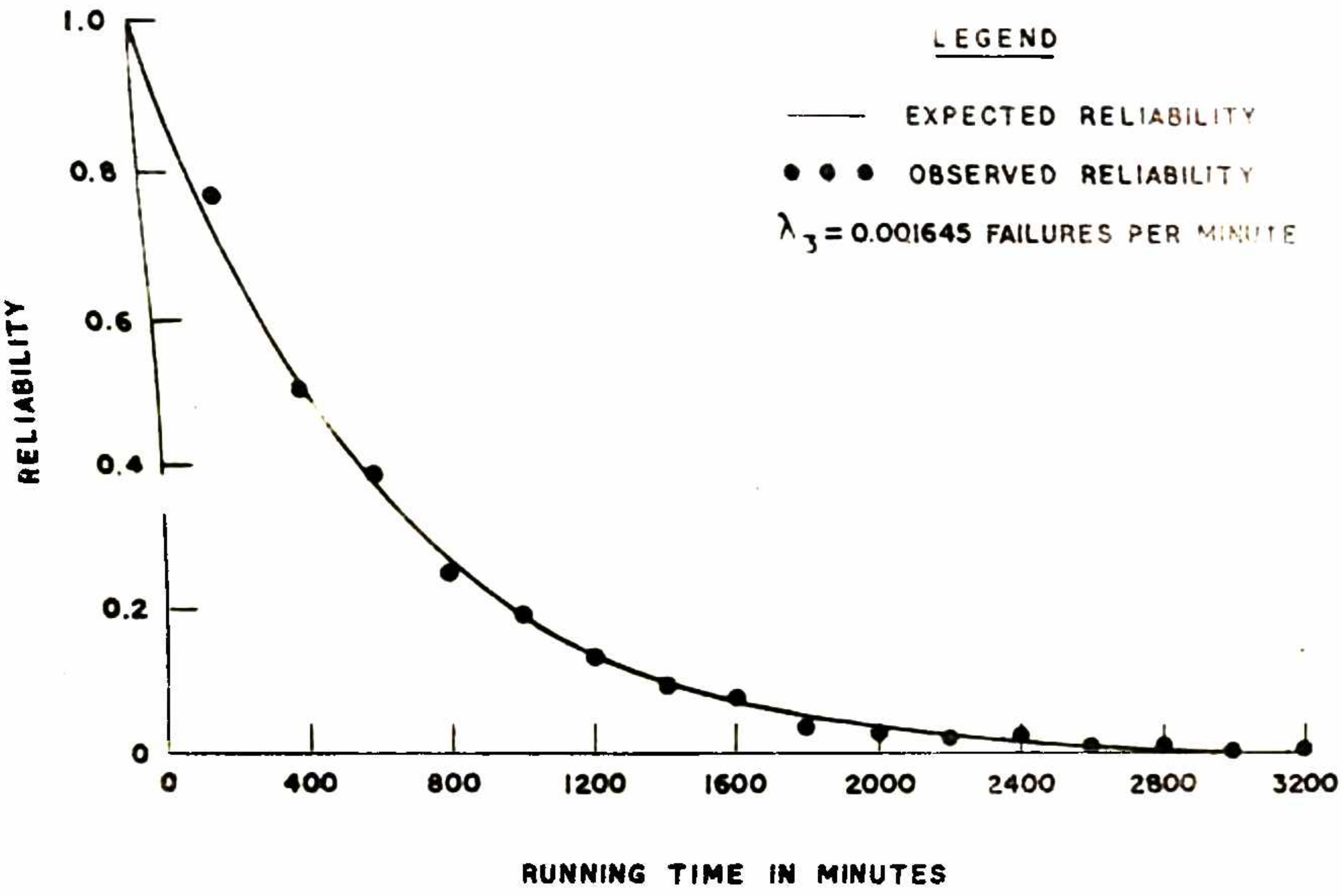

Fig. 4.4 RELIABILITY ANALYSIS FOR PUMP NO. 3

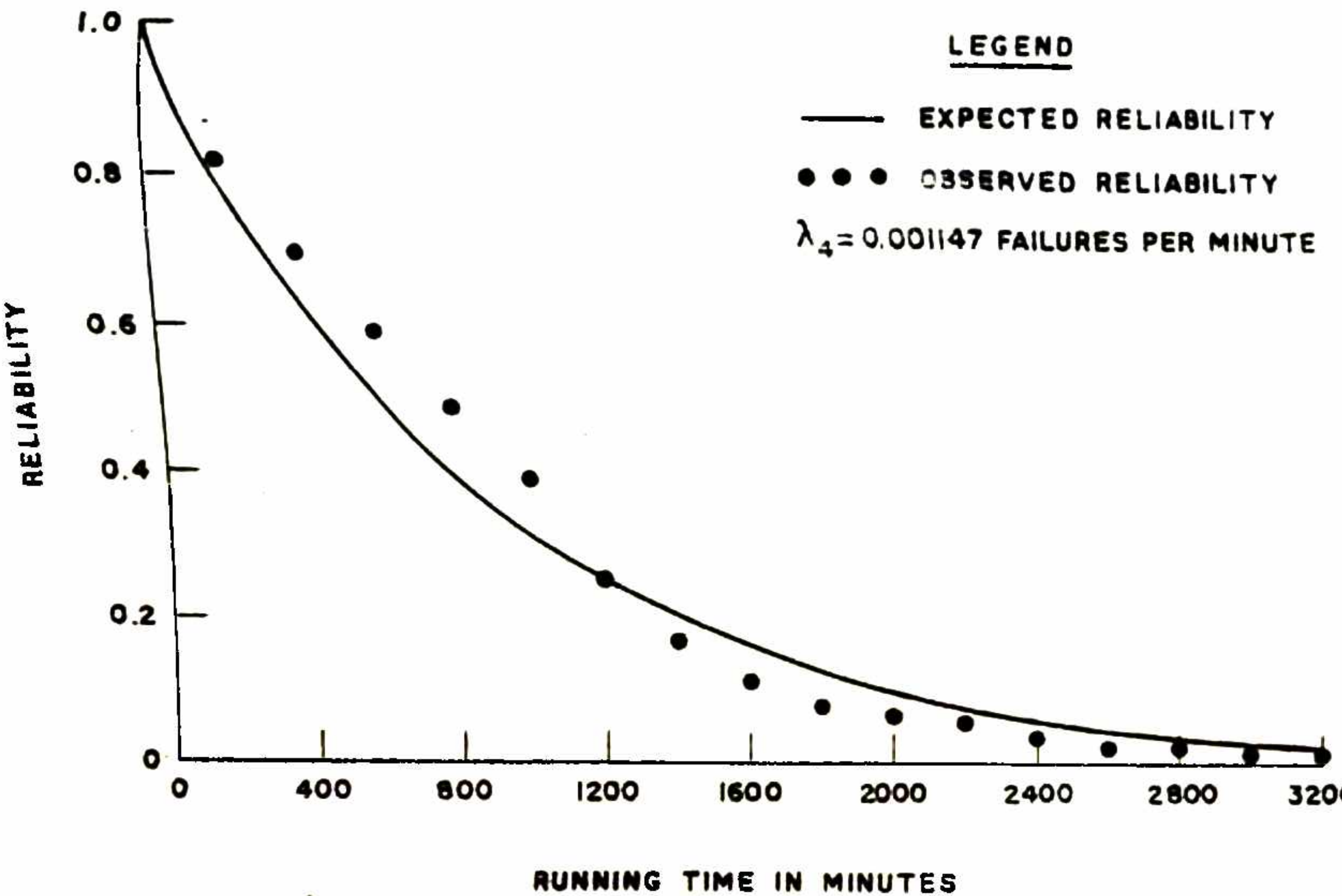

Fig. 4.5 RELIABILITY ANALYSIS FOR PUMP NO. 4

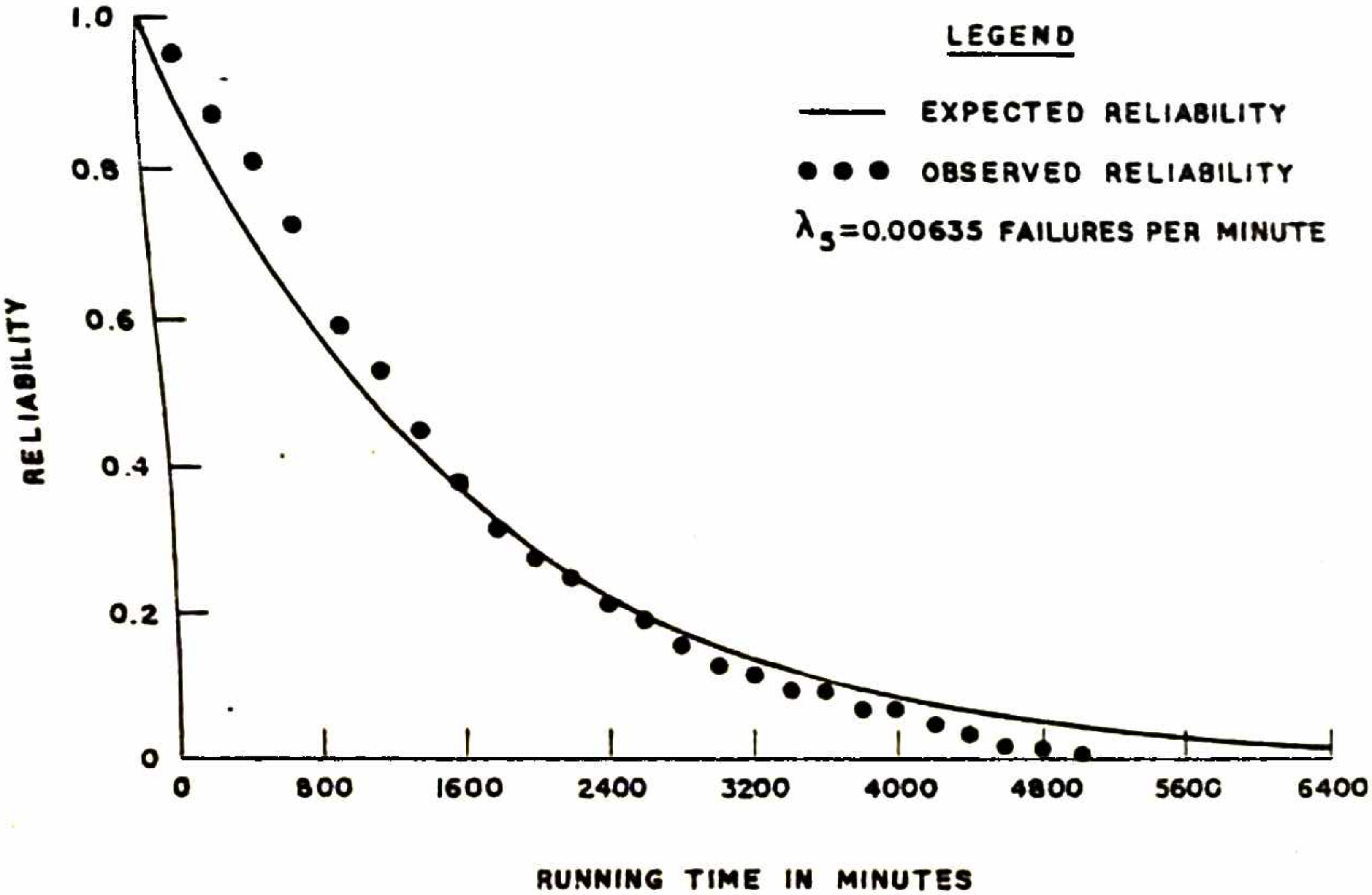

Fig. 4.6 RELIABILITY ANALYSIS FOR PUMP NO. 5

Table 4.2 Failure characteristics of the pumps

Pump No.	MTBF minutes	Failure rate Failures per year
1	695	756.3
2	505	1040.7
3	608	864.6
4	872	602.9
5	1575	333.8

4.2.2 Subsystem and Plant Failure Characteristics

As mentioned earlier, the charging cycle of a pump is interrupted by a failure of the subsystem or a failure in the rest of the plant. These interruptions may or may not lead to charging loss depending upon the nature of the interruption and the state of maintenance of the standby equipment. The data given in Appendices 4.1 and 4.2 was also analyzed to find the nature of distribution of the time-between-subsystem-failures, time between-plant-failures and the duration of charging loss as a result of these failures. It was found that all these distributions also could with reasonable accuracy be taken as exponential distributions. The parameters of these distributions are given in Table 4.3.

Table 4.3 Failure characteristics of the slurry injection subsystem and the plant

	Old Unit	New Unit
Average running time between subsystem-failures, minutes	949.7	3008.3
Average-total time-between plant-failures, minutes	1257.0	2137.3
Average charging loss due to subsystem failure, minutes	22.7	26.4
Average charging loss due to plant-failures, minutes	267.2	54.9

In working out these values, the subsystem running-time-between-failures has been taken as the actual time for which the subsystem worked neglecting stoppages. The plant running-time-between-failures, on the other hand, has been taken as total clock time between two plant stoppages. This has been done considering the fact that unlike subsystem failures plant failures like power shortage, steam trouble, insufficient bauxite stock and erosion leakage are not dependent on working of the slurry injection subsystem. Even when no slurry is being pumped most of the other equipment (except probably a few pumps) is working and hence is subject to wear, erosion etc.

4.2.3 Charging Loss

A date-wise distribution of charging loss occurring in the two units of the alumina plant for the 6 month period under investigation is given in Appendices 4.5 and 4.6. The total charging loss has been attributed to the following six causes:

1. Steam pump trouble (including trouble in slurry holding tanks, subsystem piping etc.)
2. Power failure
3. Steam shortage
4. Erosion leakage
5. Planned plant shutdown
6. Miscellaneous causes like instrument air trouble, precipitation trouble, low condensate level, and shortage of bauxite.

Rewriting the data presented in Appendices 4.5 and 4.6 into Tables 4.4 and 4.5 on monthly basis it is seen that while the total loss amounts to a staggering 26.17 percent of the available time for the old unit it is only 8.58 per-cent for the new unit. This gives a plant availability of 73.83 per cent for the old unit against 91.42 per cent for the new unit. Steam pump trouble is causing a loss of availability of 1.91 per cent in the old unit and 0.79 per-cent in the new unit in spite of the fact that the old unit has two spare pumps against one in the new unit.

Table 4.4 Analysis of the charging loss data for the old unit

Total time span for the data 4046.21 hours

Month	Charging loss in hours due to						Total charging loss hours
	Steam pump trouble	Power failure	Steam Shortage	Erosion leakage	Plant S/D	Misc.	
December	22.64	0.66	46.42	4.66	90.91	56.18	221.47
January	10.00	0.00	103.28	38.08	212.58	1.66	365.60
February	16.43	0.00	5.04	14.32	61.25	7.00	104.04
March	14.72	79.75	49.99	6.33	0.00	13.25	164.04
April	7.87	0.00	7.65	33.90	0.00	1.06	50.48
May	5.54	0.00	127.56	17.50	0.00	2.50	153.10
Total charging loss	77.20	80.41	339.94	114.79	364.74	81.65	1058.73
Percent of total loss	7.29	7.59	32.11	10.84	34.46	7.71	100.00
Percent of total time	1.91	1.99	8.40	2.84	9.01	2.02	26.17

Plant availability = 100 - 26.17

= 73.83 %

Table 4.5 Analysis of the charging loss data for the new unit

Total time span for the data 4232.35 hours

Month	Charging loss in hours due to: Steam pump trouble	Power failure	Steam Shortage	Erosion leakage	Plant S/D	Misc.	Total charging loss hours
December	10.43	0.50	5.47	10.84	0.00	0.25	27.49
January	3.14	0.00	18.34	0.00	144.91	1.83	168.22
February	10.68	0.00	3.32	0.00	0.00	0.25	14.25
March	6.28	85.44	14.70	2.50	0.00	0.00	108.92
April	2.71	0.25	14.61	0.00	0.00	1.16	18.73
May	0.55	0.00	10.69	3.84	0.00	10.66	25.74
Total charging loss	33.79	86.19	67.13	17.18	144.91	14.15	363.35
Percent of total loss	9.30	23.72	18.48	4.73	39.88	3.89	100.00
Percent of total time	0.79	2.04	1.59	0.41	3.42	0.33	8.58

Plant availability = 100 - 8.58

= 91.42 %

4.3 OPTIMAL MAINTENANCE POLICY FOR THE SUBSYSTEM

The fact that the running time-between-failures for the pumps can be fairly accurately represented by a negative exponential distribution implies that the pump failure rate is constant. No useful purpose can therefore be served by performing preventive maintenance of these pumps. The appropriate maintenance procedure is to allow the pumps to break down before performing any restorative action as is being done now in the plant. This follows from the fact that when failures occur according to negative exponential distribution, maintenance before failure does not affect the probability that the equipment will fail in the next instant, given that it is good now. Consequently, money is being wasted if preventive maintenance is applied to such an equipment.

It may be observed from Table 4.2 that the mean-time-between-failures is much higher for the new-unit pumps than the old unit pumps. Furthermore, of the two new unit pumps themselves, pump No.5 has a mean-time-between failures almost twice that of pump No.4. The first of these results can be explained on the basis of the relative ages of the two sets of pumps and the difference in their design. Plant data, however, does not provide any clue to the possible reason for the difference in performance of the two new unit pumps. It is suggested that a close observation of the two pumps be made over a period of a few months to ascertain any difference in maintenance of the two pumps and take advantage of the same for deciding future maintenance policies.

Regarding the nature of losses occuring in the two units, it is found that the old unit is having much higher planned shut down and erosion losses compared to the new unit. That the old plant should need more maintenance is not surprising because of the age of this unit but the higher erosion leakage needs to be looked into. Pipes, valves, tanks etc. being replaceable items, regular inspection and timely replacement of weak parts should be helpful in reducing losses considerably. From a review of Appendix 4.6 it is clear that the maximum erosion leakage is occurring in valves and bends. These units should, therefore, be inspected more frequently and replaced if necessary. Finally, it must be observed that steam and power shortage are causing considerable amount of availability loss in the two units. The higher value of the losses in the old unit is because of the fact that any time there is a steam or power shortage the old unit is shut off. The loss of production time due to steam shortage particularly needs to be investigated because the alumina plant has a captive boiler house with enough installed capacity to meet the steam requirements of the plant.

5. SPENT LIQUOR HEATERS

5.1 SUBSYSTEM DETAILS

Spent liquor heaters are shell and tube type heat exchangers used for preheating test tank liquor before it is fed to the digesters. Steam required for heating is obtained from the flash tanks. This steam is taken on the shell side of the heater while the spent liquor flows inside the tubes.

A flow diagram of the new unit digestion area showing position of the heaters is given in Fig.5.1. This unit has 10 heaters - 2 operating in the high pressure range (18 - 22 kgf/cm^2 abs.) 4 in the medium pressure range (6.5 to 17 kgf/cm^2 abs.) and 4 in the low pressure range (1.5 to 5 kgf/cm^2 abs.). Of these, at any given time, only 7 heaters are in line. The other three heaters - one in each pressure range - act as standby or are under maintenance. All the heaters in this unit are horizontal in construction.

The old unit has 9 heaters in total. Of these 1 in the high pressure range, 2 in the medium pressure range and 3 in the low pressure range are in line at a time. The remaining 3 heaters act as standby. The heaters in the old unit are of vertical design.

Liquor is pumped from test tanks to the low pressure

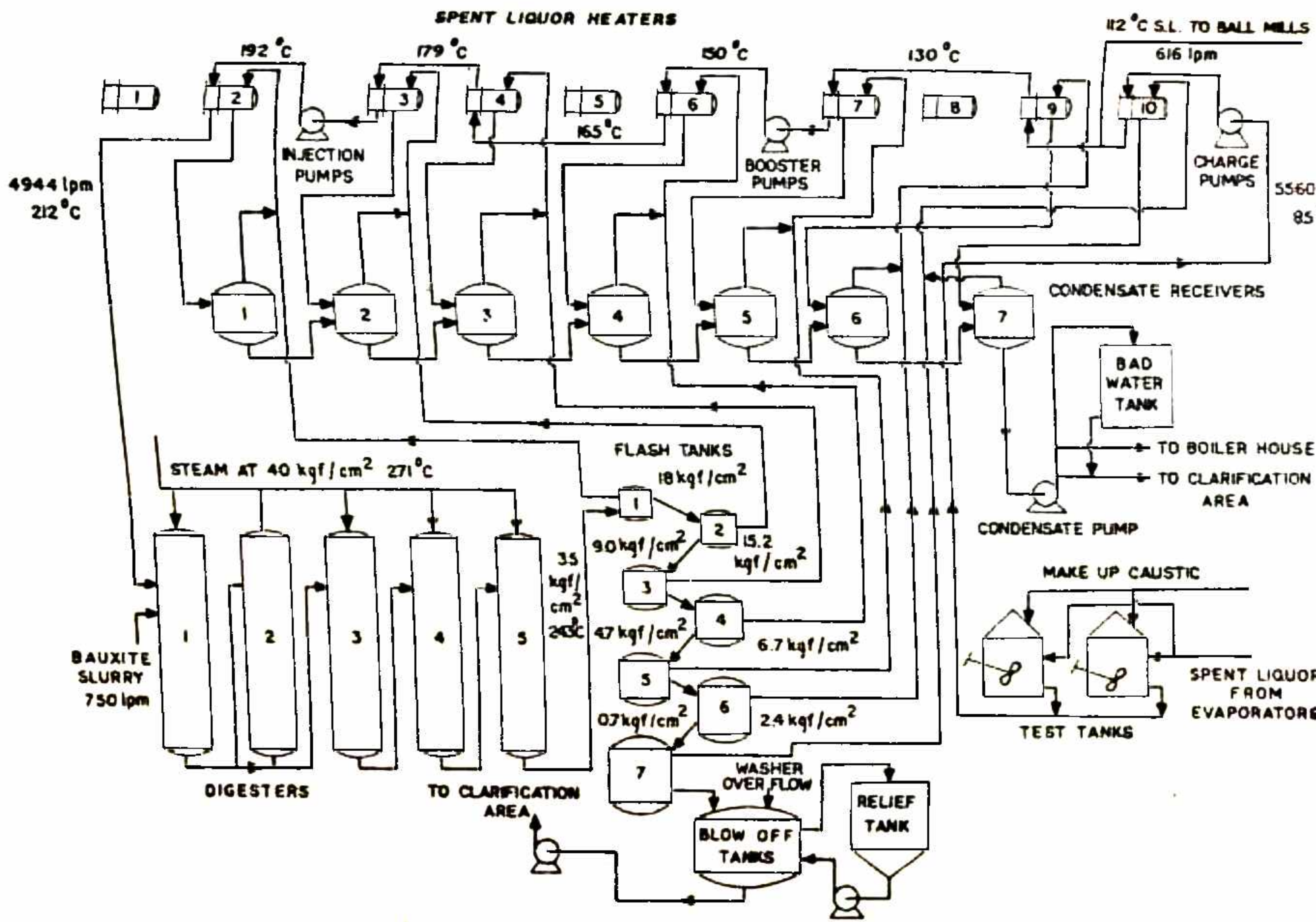

Fig 5.1 FLOW DIAGRAM FOR THE DIGESTION AREA OF THE NEW UNIT

heaters with the help of spent liquor charge pumps. The rate of flow is 2100 lpm in the old unit and 5560 lpm in the new unit. About 10 per cent of the flow in the new unit is bypassed to slurry mix area for wet grinding operation after being heated to 112°C. The temperature of the remaining liquor rises to around 150°C in the low pressure heaters. This liquor is then pumped to medium pressure heaters with the help of booster pumps and comes out from the last heater at about 192°C. It is then forced through the high pressure heater with the help of the injection pump. The discharge from the high pressure heater is at 210 - 212 °C at which temperature the liquor is injected into the digesters. Liquor and steam pipework to the heaters is so arranged that it is possible to isolate any heater for inspection and maintenance while the plant is on stream. The heaters are vented to atmosphere for purging of non-condensable gases. Pipe lines are also provided for acid cleaning of heaters and for supplying steam at 1.06 kgf/cm^2, 7.03 kgf/cm^2 and 17.58 kgf/cm^2 to low pressure, medium pressure and the high pressure heaters respectively at the time of starting.

The condensate from the spent liquor heaters is sent to condensate receivers. These receivers are connected in series. A part of the condensate coming out of a condensate receiver flashes on entry into the next receiver because of the lower pressure in that receiver. This flash steam is mixed with the flash steam coming from the corresponding flash chamber and fed to the heater. At the last condensate receiver, the condensate is tested for its conductivity and either sent to the boiler house as boiler feed water or stored as bad water in the bad water tank for use in the clarification area.

5.2 CLEANING PROCEDURE FOR THE HEATERS

The heaters are taken out of service periodically for removal of scales that are formed on the inner walls of the tubes. The cleaning may be done by 1. acid shooting and 2. mechanical cleaning.

5.2.1 Acid Shooting

Acid shooting is done with 10 percent sulphuric acid solution circulated through the heater at 2 to 2.5 kgf/cm^2 pressure. After isolating the heater with the help of spectacle blinds in the spent liquor and vapour lines, the acid solution is passed through the heaters twice, once along and once against the normal direction of liquor flow through the heater. The dilute acid solution is prepared by pumping concentrated sulphuric acid from the concentrated acid tank into the dilute acid tank filled with water. An inhibitor Agromore Redine S-19 is added to the acid at the rate of 1 per-cent of sulphuric acid by volume, in order to reduce corrosion of the tube material.

Acid shooting continues for about 8 hours. During this time, the shell side of the heater is filled with cold water at 30°C to absorb the heat generated by acid reaction. The scales dissolve in the acid and come out with the flow. Samples of acid are taken and tested every hour. The circulation is continued till the acid strength stops dropping. If it drops to 3 percent or less, the entire tank of dilute acid is dumped to sewer and a new batch is prepared. If, however, the acid strength levels of at 5-7 percent, it is an indication that all scale has been removed. After acid shooting, the acid in the dilute acid tank is pumped out to sewer. About 2 tonnes of acid is used in each heater cleaning.

After the acid solution has been drained off, the system is flushed with fresh water by filling the dilute acid tank with sufficient water and circulating this water with the help of the dilute acid pump. The water returns to the dilute acid tank from where it is finally drained to sewer.

The circulating lines and filling lines for acid cleaning set up are lined for acid resistance. These are arranged as headers in the overhead pipe rack with branches to each liquor heater. The catch basin and exposed sewer lines are also acid resistant to the point where they meet the main sewer line.

5.2.2 Mechanical Cleaning

In mechanical cleaning tubes are cleaned by physical scraping. This is done with the help of pneumatic drills using drill bits of diameter equal to the inner diameter of the tubes. Water is fed into the tubes continuously to remove the chips of the scales.

5.3 OPTIMAL CLEANING FREQUENCY MODEL FOR HIGH PRESSURE HEATERS

5.3.1 Introduction

The optimal frequency of cleaning for the high pressure heaters is found by striking a balance between the cleaning cost and the increase in operating cost that will occur if the heaters are not cleaned. The cleaning cost includes the labour cost and the cost of material used in cleaning. The increase in operating cost occurs due to fall in output temperature from the heater with a consequent increase in amount of steam supplied to the digesters and the cost of production lost due to plugging of heater tubes.

5.3.2 The Optimal Policy Model

Let the maintenance policy be to perform n equally spaced heater cleanings in an interval (0,T) as shown in Fig 5.2. If t_h is the interval between two consecutive cleaning operations, it is proposed to find the optimal

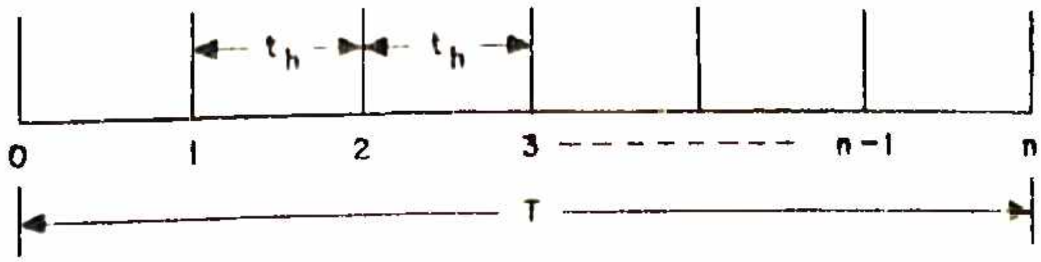

Fig 5.2 MAINTENANCE POLICY FOR SPENT LIQUOR HEATERS

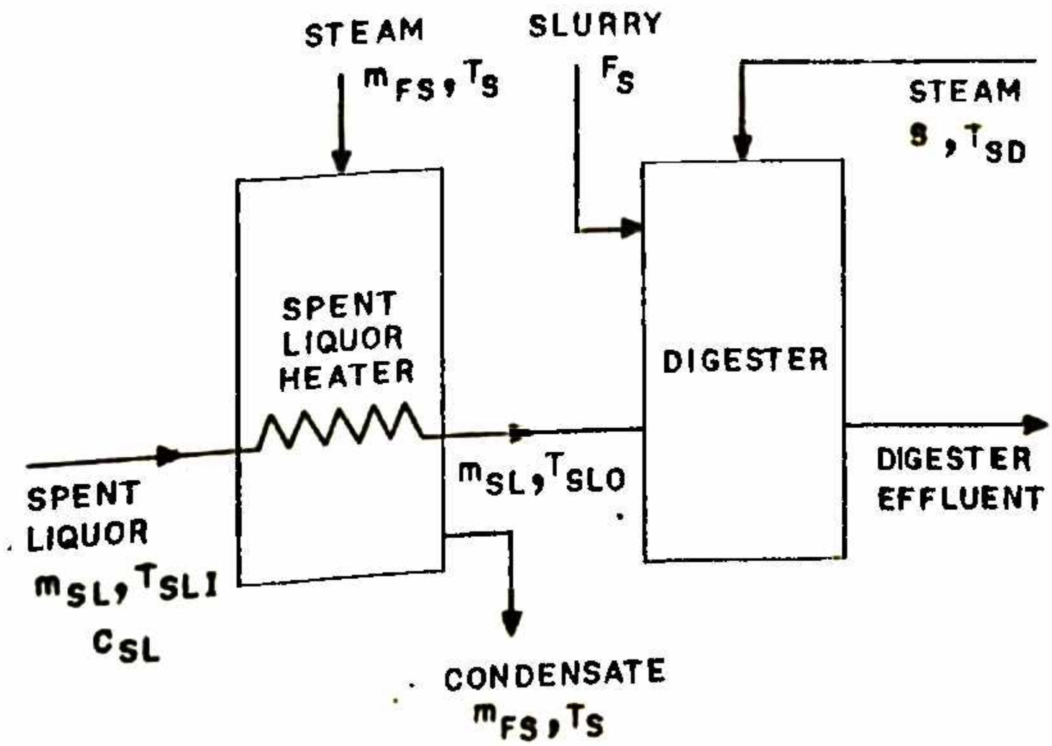

Fig 5.3 SCHEMATIC DIAGRAM FOR THE HIGH PRESSURE SPENT LIQUOR HEATER AND DIGESTER

value $t_{\hat{n}}$ of this interval, which minimizes the total cleaning cost plus the increase in steam cost per year.

Considering the schematic diagram for the heater and digester system shown in Fig 5.3, let

m_{SL} = Mass flow rate of spent liquor to the heater, kg/hr

m_{FS} = Mass flow rate of flash steam into the heater, kg/hr

S = Amount of steam supplied to digesters, kg/hr

T_S = Saturation temperature of shell side steam, ^oC

T_{SLI} = Inlet temperature of spent liquor, ^oC

T_{SLO} = Outlet temperature of spent liquor, ^oC

T_{SD} = Saturation temperature of steam supplied to digester, ^oC

C_{SL} = Specific heat of spent liquor, kcal/kg. ^oC

Applying Eq. 3.23 to this case,

$$U = \frac{m_{SL}\, C_{SL}}{A_o} \quad I_n \quad \frac{T_S - T_{SLI}}{T_S - T_{SLO}} \tag{5.1}$$

where U is the overall heat transfer coefficient for the heater, kcal/hr. m^2. ^oC, A_o is the heat transfer area based on outside diameter, m^2.

If F is the spent liquor flow rate in lpm and ρ is the density of spent liquro, gm/cc

$$m_{SL} = 60\, F \rho \tag{5.2}$$

$$\text{and} \quad U = \frac{60\ F\ \rho\ C_{SL}}{A_o} \quad l_n \quad \frac{T_S - T_{SLI}}{T_S - T_{SLO}}$$

$$= k\ F\ l_n \quad \frac{T_S - T_{SLI}}{T_S - T_{SLO}} \qquad (5.3)$$

$$\text{where } k = \frac{60\ \rho\ C_{SL}}{A_o} \qquad (5.4)$$

For a given heater operating in close temperatufe and pressure range, k may be assumed to be constant.

Rearranging Eq 5.3

$$\frac{U}{kF} = l_n \quad \frac{T_S - T_{SLI}}{T_S - T_{SLO}}$$

$$\text{or} \quad T_{SLO} = T_S - (T_S - T_{SLI})\ e^{-\frac{U}{kF}} \qquad (5.5)$$

If the subscripts 1 and t refer respectively to the first day of heater use and t days later and if inlet temperature from previous heaters is taken as constant, fall in temperature in heater outlet temperature in t days is given by

$$(T_{SLO})_1 - (T_{SLO})_t = (T_S - T_{SLI})\left(e^{-\frac{U_t}{kF_t}} - e^{-\frac{U_1}{kF_1}}\right) \qquad (5.6)$$

It has been discussed already that variations in U in deteriorating heat transfer surfaces can be represented by the relationship

$$\frac{1}{U^2} = a + bt \qquad (5.7)$$

where a and b are constants.

Therefore $U_1 = \frac{1}{\sqrt{a}}$

$$U_t = \frac{1}{\sqrt{a + bt}}$$

Also if the drop in flow due to plugging is linear

$$F_t = F_1 - \beta t \qquad (5.8)$$

where β is the drop in liquor flow rate lpm per day due to plugging.

Substituting these values in Eq 5.6,

$$(T_{SLO})_1 - (T_{SLO})_t = (T_S - T_{SLI})\left(e^{\left(\frac{-(a+bt)}{k(F_1-\beta t)}\right)^{-\frac{1}{2}}} - e^{\left(-\frac{a}{kF_1}\right)^{-\frac{1}{2}}}\right) \qquad (5.9)$$

Let $C_S(t)$ = Increase in cost of steam per day due to reduction in heater outlet temperature, over t days, rupees/day.

α = Increase in steam consumption rate due to reduction in heater outlet temperature per ^oC, tpd/^oC

C_1 = Steam cost, rupees/tonne.

Then

$$C_s(t) = C_1 \alpha (T_S - T_{SLI})\left(e^{\left(\frac{-(a+bt)}{k(F_1-\beta t)}\right)^{-\frac{1}{2}}} - e^{\left(-\frac{a}{kF_1}\right)^{-\frac{1}{2}}}\right) \qquad (5.10)$$

Let $C_p(t)$ = Net cost of production lost per day due to plugging of heater tubes over t days

= Cost of alumina production loss minus cost of bauxite and steam saved , rupees/day

C_2 = Cost of lost production per day due to 1 lpm drop in flow, rupees/day.

$C_d(t)$ = Increase in operating cost per day as a result of scale deposition for t days, rupees/day

Then $$C_p(t) = C_2 \beta t \tag{5.11}$$

$$C_d(t) = C_s(t) + C_p(t)$$
$$= C_1 \alpha (T_S - T_{SLI}) \left(e^{\frac{-(a+bt)}{k(F_1-\beta t)}^{-\frac{1}{2}}} - e^{\frac{-a}{k F_1}^{-\frac{1}{2}}} \right) + C_2 \beta t \tag{5.12}$$

The total cleaning plus excess steam cost over T days for the policy shown in Fig 5.2 is given by the expression

$$Z_T = n \left(C_o + \int_0^{t_h} C_d(t)\, dt \right)$$
$$= \frac{T}{t_h} \left(C_o + \int_0^{t_h} C_d(t)\, dt \right) \tag{5.13}$$

where C_o is the cost of the cleaning operation, assumed to remain constant.

The optimal cleaning interval t_h^* can be obtained from this expression by calculating the value of Z_T for different values of t and plotting them. The value of t for which Z_t is the minimum gives optimal interval.

In the special case when $C_d(t)$ is found to have a straight line variation with slope s, Eq 5.13 may be written as

$$Z_T = \frac{T}{t_h}\left(C_o + \int_o^{t_h} st\,dt\right)$$

$$= \frac{T}{t_h}\left(C_o + 0.5\,st_h^2\right)$$

$$= T\left(\frac{C_o}{t_h} + 0.5\ s\ t_h\right) \tag{5.14}$$

Differentiating with respect to t_h and equating to zero gives the optimal value of time between two acid cleanings as

$$t_h^* = \sqrt{\left(\frac{2C_o}{s}\right)} \tag{5.15}$$

and

$$Z_T^* = T\left(\sqrt{2C_o s}\right) \tag{5.16}$$

Models similar to the above can theoretically be developed for the other heaters to give their optimal cleaning cycle times. A difficulty is, however, expected to arise when predicting the effect of reduction in outlet temperature of say low pressure heater No.8 on increase in steam consumption because of the presence of other heaters in between. In fact the subsystem continuously shifts to new equilibrium position due to deterioration of its heat transfer surfaces. One way of handling the situation is to model the entire slurry mix, digestion, and spent liquor heating system on a computer. The effect of scale deposition can then be easily predicted by writing energy and material balance equations for each effect and solving the resulting equations simultaneously.

5.4 HEATER PERFORMANCE ANALYSIS AND EVALUATION OF MODEL CONSTANTS FOR HIGH PRESSURE HEATERS IN NEW UNIT

The various constants used in the model proposed above can be calculated as follows from the data collected from plant records.

5.4.1 Variation of Overall Heat Transfer Coefficient

According to Eq 5.3

$$U = \frac{60\ F \rho C_{SL}}{A_o} \ l_n \ \frac{T_S - T_{SLI}}{T_S - T_{SLO}}$$

From the data given in Appendixes 1.1 and 1.2

$$\rho = 1.24 \text{ gm/cc} \quad \text{(assumed constant)}$$

$$C_{SL} = 0.86 \text{ kcal/kg } {}^oC \quad \text{(assumed constant)}$$

For heater Nos 1 and 2 in the new unit

$$A_o = 380.9 \text{ m}^2$$

Therefore for these heaters

$$U = \frac{60 \times 1.24 \times 0.86}{380.9} F \ l_n \ \frac{T_S - T_{SLI}}{T_S - T_{SLO}}$$

$$= 0.168F \ l_n \ \frac{T_S - T_{SLI}}{T_S - T_{SLO}} \qquad (5.17)$$

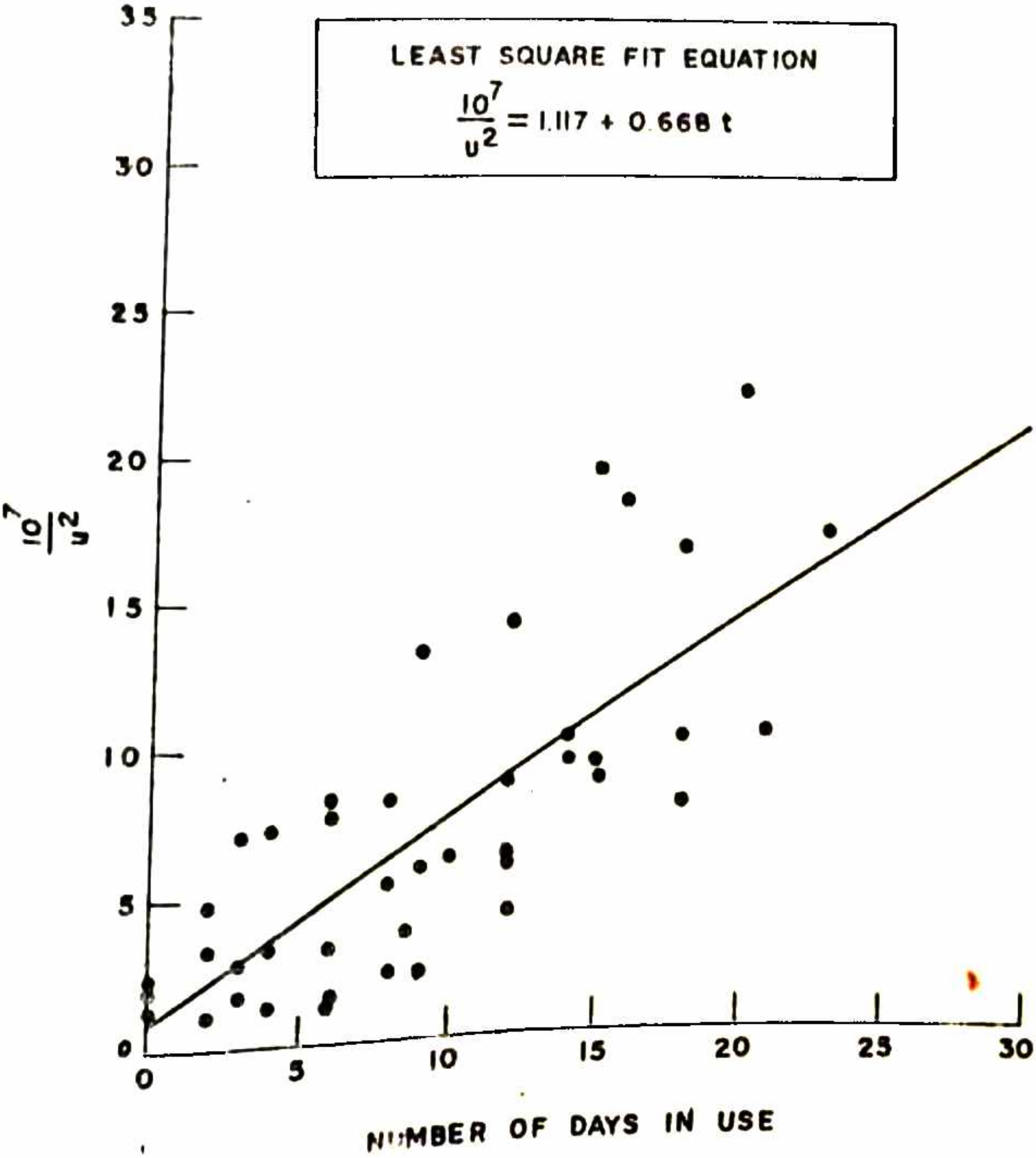

Fig 5.4 VARIATION OF OVERALL HEAT TRANSFER COEFFICIENT WITH TIME FOR HIGH PRESSURE HEATER NOS. 1 AND 2

Appendix 5.1 gives the variation of overall heat transfer coefficient U and $\frac{10^7}{U^2}$ with time calculated from Eq 5.17 for four consecutive cycles of heater number 1 and three cycles of heater number 2. As mentioned earlier only one of the two high pressure heaters is in circuit at any given time and the liquor coming out from the high pressure heater is fed directly to the digesters.

The results of Appendix 5.1 are plotted in Fig.5.4. As can be seen from this plot there is a considerable scatter in the values, yet they can be fairly accurately represented by a straight line. A least square fit to the data yields the following result

$$\frac{10^7}{U^2} = 1.117 + 0.668\ t \qquad (5.18)$$

The values of constants a and b in Eq 5.7 for high pressure heater therefore are

$$a = 1.117 \times 10^{-7}$$

$$b = 0.668 \times 10^{-7}$$

The results of a similar analysis done for medium pressure and low pressure heaters are given in Appendices 5.2, 5.3 and Figs. 5.5, 5.6 respectively. The least square

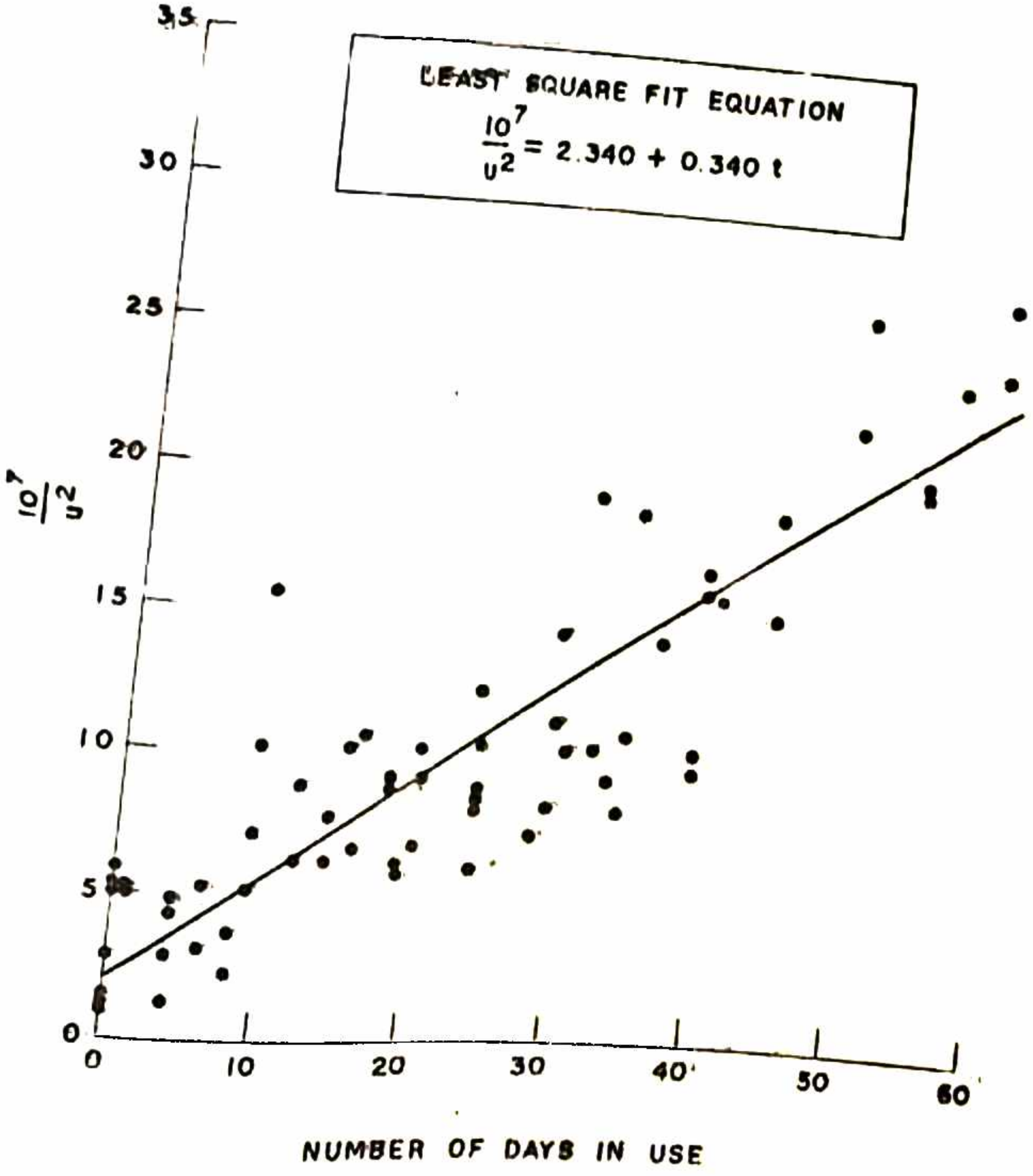

Fig 5.5 VARIATION OF OVERALL HEAT TRANSFER COEFFICIENT WITH TIME FOR MEDIUM PRESSURE HEATER NOS. 3 TO 6

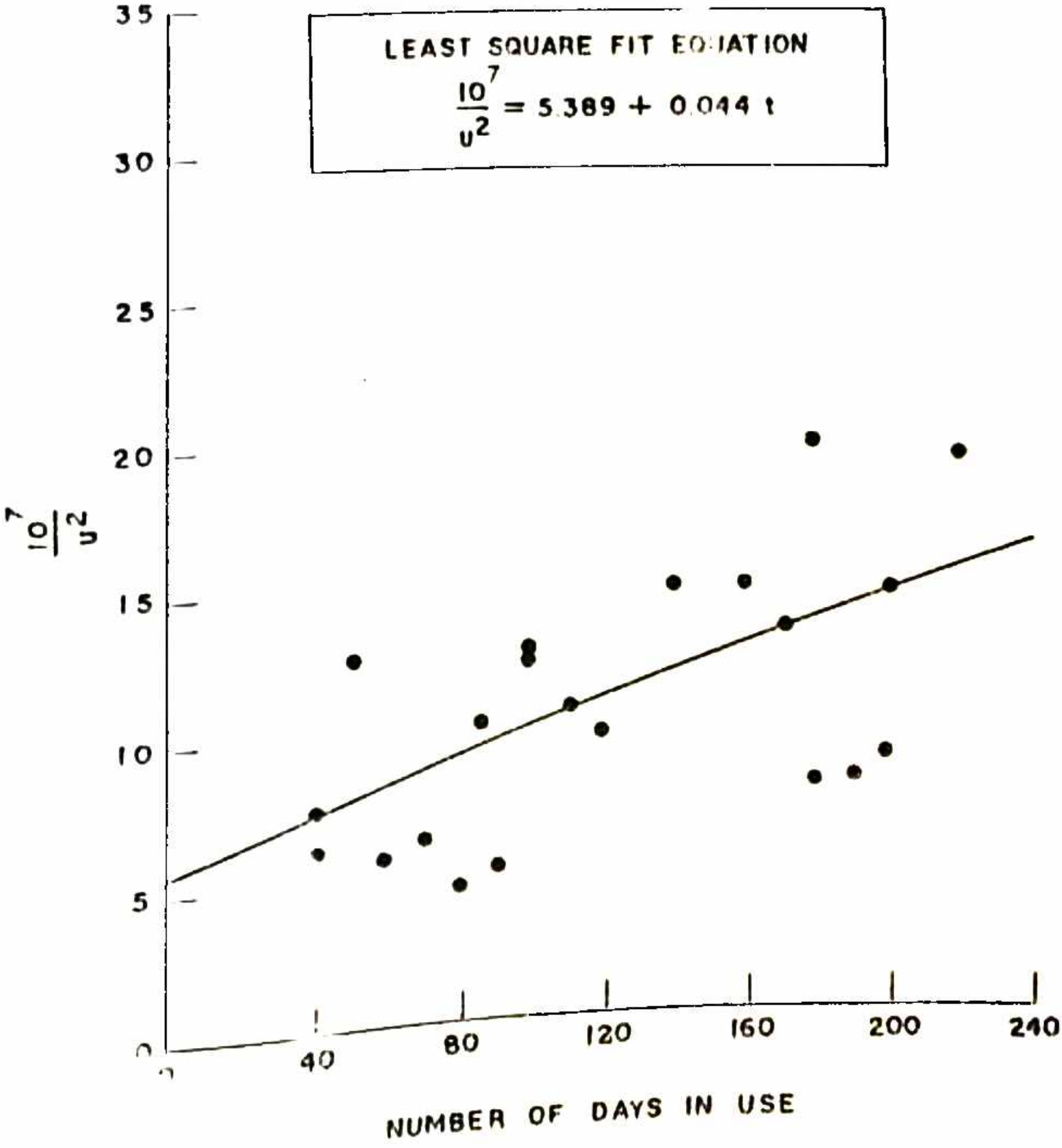

Fig 5.6 VARIATION OF OVERALL HEAT TRANSFER COEFFICIENT WITH TIME FOR LOW PRESSURE HEATER NOS. 7 TO 10

fit lines in these two cases are given by the following equations

For medium pressure heater numbers 3 to 6,

$$\frac{10^7}{U^2} = 2.340 + .340t \tag{5.19}$$

For low pressure heater numbers 7 to 10,

$$\frac{10^7}{U^2} = 5.389 + .044t \tag{5.20}$$

5.4.2 Plugging in the Heaters

The plugging of heater tubes due to deposition of scales manifests itself in terms of reduction in spent liquor flow to the digesters. Plant records show that the effect of plugging is most predominant in high pressure heaters and only occasional in the other heaters. This is to be expected because of the higher scale deposition rates in the former units as a result of higher temperatures.

Table 5.1 and Fig 5.7 give the recorded data from the plant for a period of 6 months. As seen from this table except on two occasions, whenever a heater was bypassed, the flow increased but there is a considerable scatter in the values. In order to establish a correlation between the number of days the heater has been used and the reduction in flow due to plugging, a least square-fit-line for Fig.5.7 has been used. This gives a flow reduction of 13.52 lpm per day of heater use.

Table 5.1 Effect of tube plugging on spent liquor flow rate for high pressure heaters

Date	Heater by passed	No. of days of heater use	Increase in flow on by passing the heater lpm
16th December	2	13	400
19th January	2	24	400
16th February	1	29	355
20th March	1	24	0
2nd April	2	12	400
18th April	1	16	400
8th May	2	20	0
22nd May	1	14	300

5.4.3 Effect of Reduction in Heater Outlet Temperature

Referring again to the plant data for the new unit given in Appendix 1.1 and Fig 1.2,

Rate of flow of spent liquor from high pressure heater to new digester = 4944 lpm

Spent liquor to ball mills = 440 lpm

Total spent liquor to new digesters = 5384 lpm

Caustic concentration in test tank = 193 gpl

Caustic utilization factor = 0.93

Increase in alumina-to-caustic ratio due to digestion. = 0.270

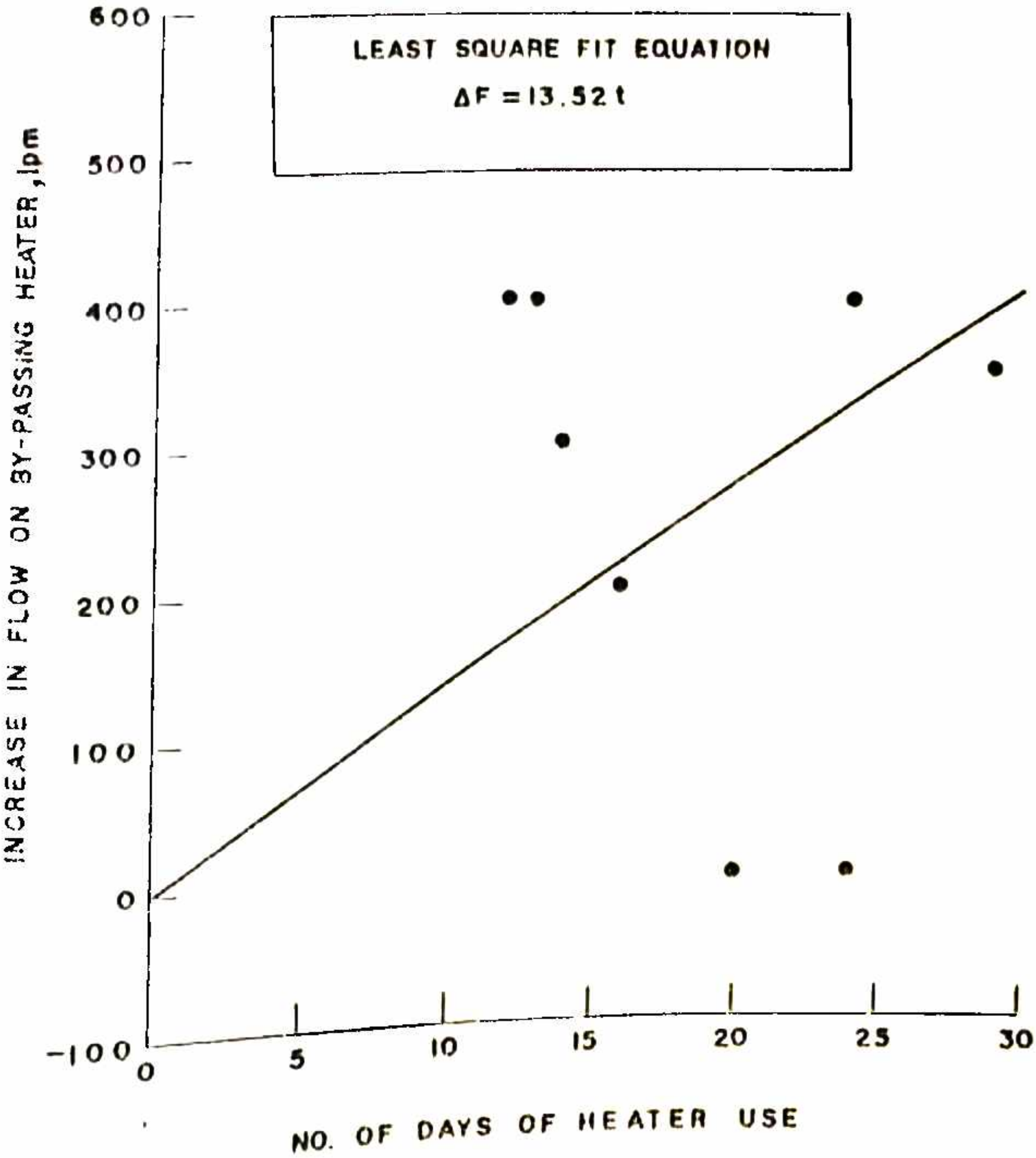

Fig 5.7 EFFECT OF PLUGGING ON SPENT LIQUOR FLOW IN HIGH PRESSURE HEATERS

Pressure of steam supplied = 40 kgf/cm^2 abs

Exit temperature of the digester effluent = 243°C

Temperature of liquor to digesters = 212 °C

Temperature of liquor to ball mills = 112 °C

Density of liquor to ball mills = 1.24 gm/cc

Specific heat of dry bauxite = 0.249 kcal/kg°C

Specific heat of lime = 0.25 kcal/kg°C

Specific heat of liquor = 0.86 kcal/kg°C

Solution heat of trihydrate alumina = 172.2 kcal/kg

Solution heat of monohydrate alumina = 70 kcal/kg

Temperature of dry bauxite = 26.6°C

Radiation losses = 6 % of all other losses

Writing a heat balance for the new unit digesters,

Heat given by steam

= Heat taken by dry bauxite

+ heat taken by water with bauxite

+ heat taken by liquor to slurry mix

+ heat taken by liquor from high pressure heaters

+ heat taken by lime

+ heat taken by water with lime

+ solution heat of trihydrate alumina

+ solution heat of monohydrate alumina

+ radiation losses (5.21)

Heat given by steam per kilogram in condensing and cooling from 271°C to 243 °C

= 427.25 kcal

Heat taken by dry bauxite

$= 868.94 \times .249 \times (243 - 26.6) \times 1000$

$= 46.82 \times 10^6$ kcal/day

Heat taken by bauxite water

$= 26.87 \times (243 - 26.6) \times 1000$

$= 5.815 \times 10^6$ kcal/day

Heat taken by liquor to slurry mix

$= 440 \times 1.24 \times 1440 \times 0.86 \times (243 - 112)$

$= 88.51 \times 10^6$ kcal/day

Heat taken by liquor from heaters

$= 4944 \times 1.24 \times 1440 \times 0.86 \times (243 - 212)$

$= 235.35 \times 10^6$ kcal/day

Heat taken by lime

$= 8.689 \times 0.25 \times (243 - 112) \times 1000$

$= 0.285 \times 10^6$ kcal/day

Heat taken by water with lime

$= 78.2 \times 1 \times (243 - 112) \times 1000$

$= 10.24 \times 10^6$ kcal/day

Solution heat of trihydrate alumina

$= 302.22 \times 172.2 \times 1000$

$= 52.04 \times 10^6$ kcal/day

Solution heat of monohydrate alumina

$$= 73.51 \times 70 \times 1000$$

$$= 5.15 \times 10^6 \text{ kcal/day}$$

If S is the quantity of steam supplied to digesters in kg/hr,

$$S \times 427.25 \times 24 = 1.06\ (46.82 + 5.815 + 88.51 + 235.35 + 0.285 + 10.24 + 52.04 + 5.15) \times 10^6$$

or $\quad S = 0.0459 \times 10^6$ kg/hr

$$= 1101.6 \text{ tpd}$$

Cost of steam per tonne is Rs 30

Therefore,

Steam cost per day=Rs 33048

If outlet temperature from high pressure heaters decreases by $1^{o}C$, heat taken by spent liquor from heaters will increase to

$$4944 \times 1.24 \times 1440 \times 0.86\ (243 - 211)$$

$$= 242.95 \times 10^6 \text{ kcal/day}$$

Increase in steam supplied $\alpha = \dfrac{(242.95 - 235.35) \times 10^6 \times 1.06}{427.25 \times 1000}$

$$= 18.86 \text{ tpd.}$$

The cost of excess steam per day due to each degree drop in heater outlet temperature $=$ Rs 18.86×30

$$= \text{Rs } 565.80$$

5.4.4 Effect of Plugging

If the rate of flow of spent liquor decreases by 1 lpm,

Loss in alumina dissolved per day

$$= \frac{1 \times 193 \times 0.93 \times 0.27 \times 1440}{10^6}$$

$= 0.07$ t

Recovery of dissolved alumina = 93 %

Loss in alumina produced per day = 0.065 t

Saving in wet bauxite, per day $= \dfrac{.07}{0.94 \times 0.46 \times 0.97}$

$= 0.167$ t

Cost of alumina loss per day at the rate of Rs 1625 per tonne $= 0.065 \times 1625$

= Rs 105.63

Saving in bauxite per day at the rate of Rs 95 per tonne $= 0.167 \times 95$

= Rs 15.87

Amount of steam saved per day $= \dfrac{1101.6 \times .07}{375.73}$

$= 0.20$ t

Saving in steam cost per day = Rs 0.20×30

= Rs 6

Increase in operating cost per day due to 1 lpm drop in flow due to plugging, C_2

= Rs 105.63 - 15.87 - 6

= Rs 83.76

5.4.5 Cost of Heater cleaning

The cost of heater cleaning includes three costs namely (i) cost of acid used (ii) cost of maintenance labour and (iii) cost of maintenance material. The following are the estimated values for these costs based on plant records:

Cost of acid used

2 tonnes at the rate of Rs 1000 per tonne

= Rs 2000

Cost of labour

200 man hours at the rate of Rs 20 per man working for 8 hours = Rs. 500

Maintenance material cost

Gaskets, bolts, welding rods, welding gases etc.

= Rs 750

Total cost for each cleaning operation Co = Rs 3250

5.5 CALCULATION OF OPTIMAL CLEANING FREQUENCY FOR THE HIGH PRESSURE HEATERS

According to Eq 5.12

$$C_d(t) = C_1\,\alpha(T_S - T_{SII})\left(e^{\frac{-(a+bt)^{-1/2}}{k(F_1-\beta t)}} - e^{-\frac{a^{-1/2}}{kF_1}}\right) + C_2\,\beta t$$

From plant data,

Average value of T_S = 214.10 ^{o}C

Average value of T_{SII} = 194.75 °C

On substituting the values of the constants obtained in the previous section, the above equation takes the form:

$$C_d(t) = 30x18.86(214.10 - 194.75)\left(e^{-\frac{(1.117x10^{-7}+.668x10^{-7}t)^{-1/2}}{0.168(4944-13.52t)}} - e^{-\frac{(1.117x10^{-7})^{-1/2}}{.168x4944}}\right) + 83.76 \times 13.52xt$$

$$\text{or } C_d(t) = 10948.28\ e^{-\frac{18823.1}{(\sqrt{1.117+.668t})(4944-13.52t)}} - 298.55 + 1132.44\ t \tag{5.22}$$

Table 5.2 gives values of $C_d(t)$ for different values of t calculated from Eq 5.22. These results are plotted in Fig 5.8. As seen from this figure the increase in operating cost with time can be fairly accurately represented by a straight line. The slope s of this line is found to be 1307.63 rupees per day/day.

Table 5.2 Effect of scale formationon operating cost

No. of days of heater use t	Increase in operationg cost per day $C_d(t)$, rupees(Eq 5.22)
2	2916.53
4	5746.54
5	7122.72
10	13720.77
15	20019.92
20	26148.95
25	32170.37
30	38118.33

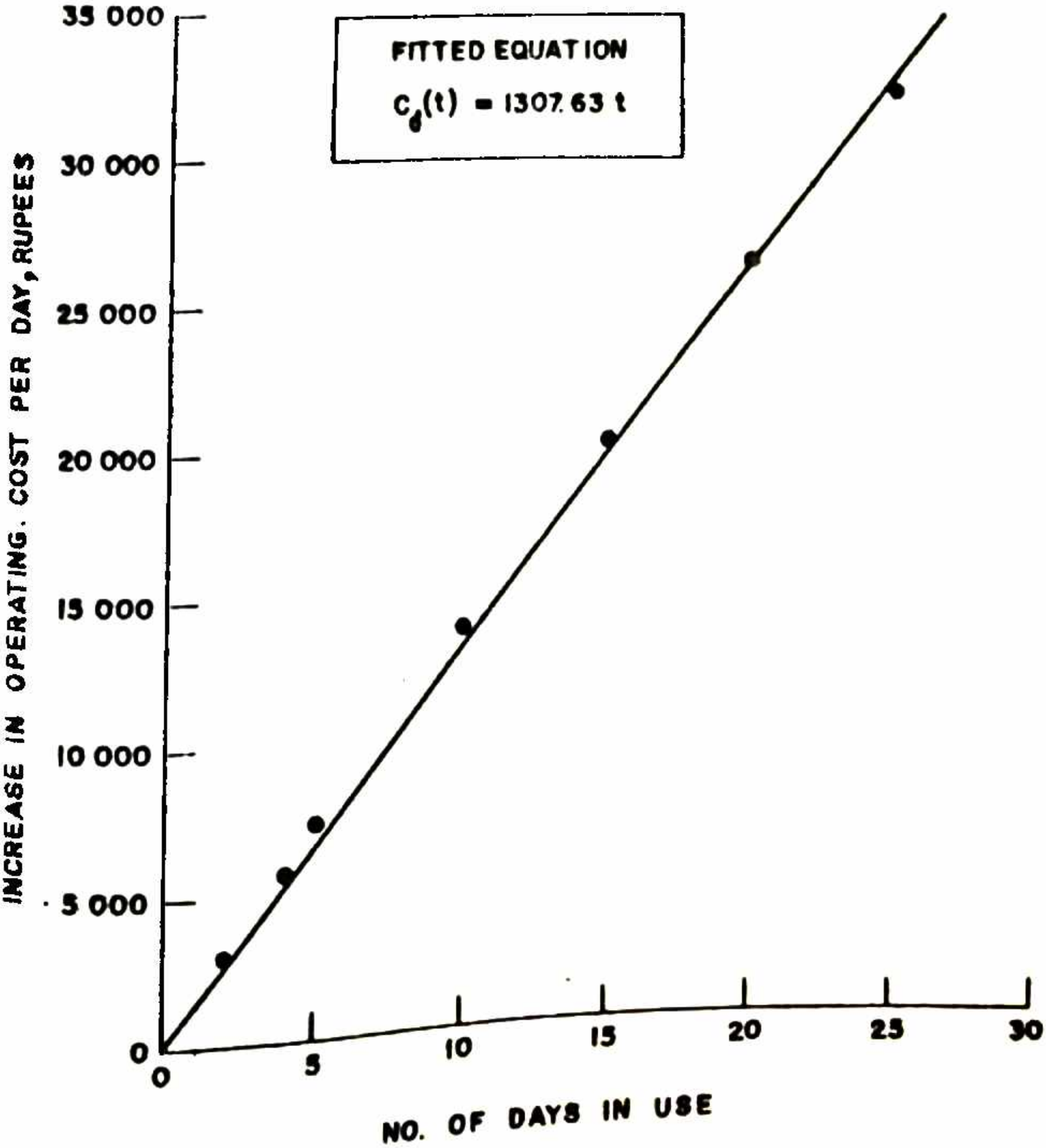

Fig 5.8 INCREASE IN OPERATING COST OF HIGH PRESSURE HEATERS DUE TO SCALE DEPOSITION

Using Eq 5.15 the optimal cleaning interval for the heaters is given by:

$$t_h^* = \sqrt{\frac{2C_o}{(s)}}$$

$$= \sqrt{\frac{2 \times 3250}{1307.63}}$$

$$= 2.29 \text{ days}$$

say 3 days

The annual cleaning plus excess steam cost with this interval of 3 days can be found from Eq 5.14 by putting T = 365 days

Thus

$$Z_T^* = 365 \left(\frac{3250}{3} + 0.5 \times 1307.63 \times 3\right)$$

= Rs 11.11 lakhs/year

The current practice in the plant is to clean these heaters after an interval of 15 days. This gives an annual cleaning plus excess steam cost of Rs 36.59 lakhs. Changing the cleaning interval from present 15 days to the optimal 3 days will therefore result in a saving of Rs 25.48 lakhs or 69.64 percent of the present value.

5.6 SENSITIVITY ANALYSIS OF THE OPTIMAL MAINTENANCE POLICY

Fig 5.9 gives the total annual cleaning plus excess steam cost for different cleaning intervals. As seen from

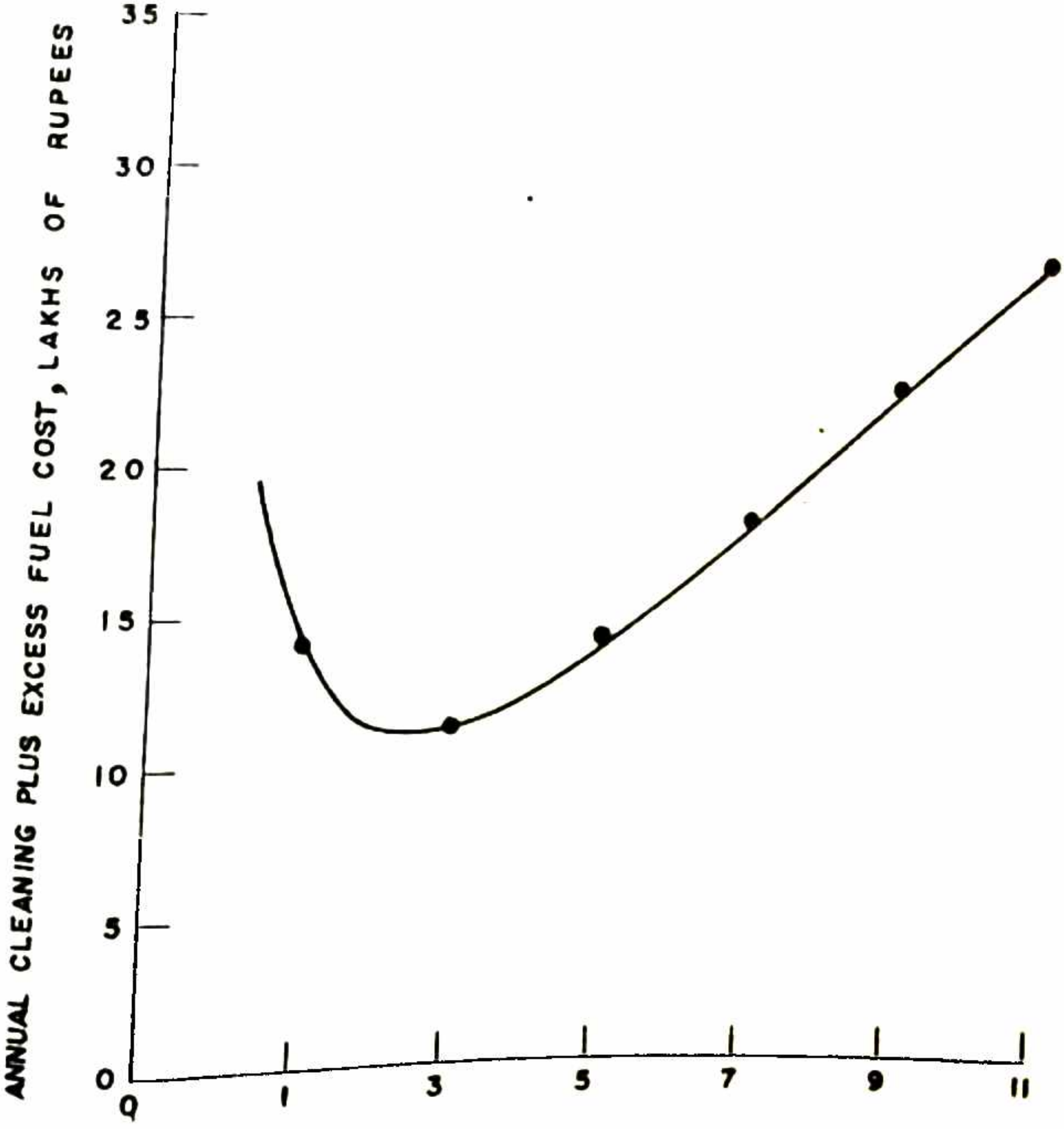

Fig 5.9 VARIATION OF ANNUAL CLEANING PLUS EXCESS STEAM COST WITH CLEANING INTERVAL

this plot the total cost is quite sensitive to the cleaning interval. As such, cleaning of the heaters cannot be much delayed without considerable extra expenditure on steam.

Regarding sensitivity of the cleaning interval to other parameters, it is clear from Eq 5.15 that optimal cleaning interval is directly proportional to the square root of cleaning cost C_o and inversely proportional to the square root of the rate of increase of operating cost with time due to scale deposition.

6. MAINTENANCE ORGANIZATION AND CONTROL

6.1 INTRODUCTION

The preceding chapters have emphasizedthe importance of the maintenance function for production activity and the scope of optimization studies in deciding optimal maintenance policies. No amount of mathematical background can make maintenance effort succesful unless it is backed by a sound maintenance organization which is scientific, alert and up-to-date. This organization must plan maintenance work, decide priorities, allocate staff, procure necessary spare parts and replacements, as well as set and maintain effectiveness standards. The organization must continuouslyreview maintenance procedures and update its data base to be able to take timely corrective actions. The organization is also responsible for providing periodic reports to the plant management showing trends in maintenance effectiveness, liklihood of occurrence of major breakdowns and need for equipment replacement. This is necessary for taking decisions regarding allocation of funds well in advance. This chapter briefly outlines the basic considerations in effective maintenance management and the practices usually followed in industry. The activities of the maintenance group of the alumina plant subsystems of which have been studied in the last three chapters are then reviewed in the light of these observations.

6.2 EFFECTIVE MAINTENANCE MANAGEMENT

6.2.1 Organization and Location of the Maintenance Department

The basic decisions that need to be taken in relation to maintenance organization are whether to use (i) internal or external service personnel, (ii) contract or single-incident negotiation for external service and (iii) centralized or assigned maintenance groups. No simple answers can be given for these questions. The best policy is generally dependent upon factors like nature of the product, size of the plant, availability of alternative maintenance channels, location of the plant, and sophistication of the equipment to be maintained.

In general, use of in plant service personnel lowers the time between breakdown and start of repairs, improves coordination between production and maintenance activities and lowerscosts. Maintenance of sophisticated equipment like computers, numerically controlled machines, automats, control systems and high pressure boilers should, however, be better left to specialized agencies because of the costs involved in maintaining specialists on payroll with very low percentage utilization.

Contract maintenance generally yields better service effectiveness if the incidence of breakdown is high. This is because of the fact that single incidence negotiations normally take more time and consequently lead to longer facility down time periods. Single incidence maintenance on the other hand, is generally cheaper than contract maintenance.

Assigned maintenance groups provide immediate service and better relationship with the production personnel. The effectiveness of the maintenance work also generally improves because of the familiarity of the maintenance staff with the equipment, reduced travel time, lesser paper work and better communications. The productivity of the assigned maintenance staff, however, tends to be lower than that of a centralized organization. The best compromise generally is to provide a small assigned maintenance group backed by centralized units for major jobs. The centralized maintenance staff in such cases has also the responsibility of deciding correct procedures, preparing maintenance schedules, setting time standards, and establishing controls for the entire maintenance staff. Most large plants follow this type of mixed organization.

Creation of a separate department for maintenance relieves the production staff of maintenance work, promotes uniformity of maintenance procedures and improves maintenance effectiveness. Such departments should always be headed by a Maintenance Engineer of the same status as the Production head. This enables the maintenance group to have a say in the selection of equipment with due regard to maintenance aspects, ensures release of machinery by production in time for servicing and prevents excessive use of machines for increasing production.

6.2.2 Maintenance Planning and Scheduling

Proper planning and scheduling is essential for any maintenance system to be optimal and effective. Maintenance planning is carried out with the following objectives:

1. Establishing precise definition of work.
2. Determining the correct method for doing the job.
3. Setting time standards to help in planning, execution and measurement of maintenance effort.
4. Identifying tools and materials required for the job and arranging for their procurement.
5. Deciding man-power requirement and its distribution craft wise.
6. Establishing job priorities.
7. Setting up proper procedures for obtaining regular reports on the progress of work, backlog and expenditure.

Maintenance planning follows broadly the same techniques as production planning but differs fromit in the following respects:

1. Work content of a maintenance job cannot always be estimated. A rusted bolt, a broken screw head, a twisted pipe or a loose key may considerably upset the work schedule.
2. A considerable part of maintenance work is non-repetitive in nature.
3. Maintenance planning must recognise the need and provide for emergency work.

The techniques that are used for obtaining an estimate of the quantity of work involved in a job include the following:

1. Guess estimates
2. Statistical analysis of past performance
3. Time studies
4. Use of elemental time data
5. Predetermined Motion Time Systems (PMTS)
6. Universal Maintenance Standards (UMS)
7. Work Sampling

The choice of technique to be actually used depends upon the desired level of accuracy of results, degree of managementsophistication, availability of required data, and time and resources available for carrying out work measurement.

Using guess estimates by a person who has a knowledge of the job in question may be crude but is probably the only method available when no previous records have been maintained. Statistical analysis of data pertaining to past performance suffers from the disadvantage that time estimates are based on the past performance which may or may not be optimal. This method also does not provide any scope for comparison of alternative methods of maintenance. Time study methods are suitable only for repetitive type of jobs. Use of Standard Time, Predetermined Motion Time Systems and Universal Maintenance Standards all require considerable amount of effort and time for conducting time studies and for calculating job times from elemental times. The Universal Maintenance Standards method is probably the most preferrable because it combines the accuracy and consistency of work measurement standards with the ease and speed of estimating procedures.

In spite of all the difficulties experienced in obtaining an estimate for the time required to complete a maintenance job, obtaining this estimate is economically worthwhile. Installation of a sound work measurement programme is estimated to result in a saving of 20 to 50 per cent in maintenance costs.

Planning, however, should not be carried too far.

The work load for the staff must be planned with enough margin for attending to emergencies which always arise. If the schedule is not made flexible enough to accommodate these emergencies the planned work load tends to be neglected, leading to more emergencies and still more neglect. It has been suggested that planned workload for maintenance staff should be no more than about 65 - 75 per cent of the total available time, leaving the balance for emergencies.

Scheduling of maintenance jobs involves decision making with respect to the time that will be most suitable for undertaking the job. The factors that may influence this decision include production commitments, loss of in-process material, availability of necessary spare parts, tools and man-power required to do the job and so on. It is a repetitive process because of the constant addition of new emergency jobs.

Maintenance schedules should be realistic, balanced over the time-scale and prepared well in advance to allow sufficient time for the procurement and delivery of necessary equipment and materials and for the release of machines. Long term scheduling should be done for routine maintenance, periodic overhauls and component replacements leaving only emergency jobs for short term scheduling. This ensures better man-power utilization, good adherence to schedules, less running about of the maintenance staff and less tension.

Regular meetings between the production, planning and maintenance groups to discuss the progress of maintenance work and decide priorities have often been found to be extremely useful for maintenance scheduling.

6.2.3 Measurement of Maintenance Work

Management has often been described as a combination of measurement and control. Performance measurement in maintenance is expected to indicate the effectiveness of the maintenance activity, provide information for proper planning, indicate trends of behaviour of the plant and yield data for comparisons. A large number of indices have been proposed from time to time to measure the various aspects of the maintenance activity. Three of the most commonly used indices are given below:

1. Man power efficiency $= \dfrac{\text{Total man hours allowed on the job}}{\text{Total man hours worked on the job}}$ (6.1)

2. Work order turnover $= \dfrac{\text{Number of jobs completed}}{\text{Number of jobs handled}}$ (6.2)

3. Down time due to maintenance

$$= \frac{\text{Total down time for service}}{\text{Total shift hours worked}} \qquad (6.3)$$

The cost data for maintenance service may similarly be compiled in terms of total maintenance cost per unit produced, ratio of cost of planned service and total production cost, cost of spares divided by total production cost, cost of overtime etc. The amount and nature of data collected depends upon the size of the plant, management objectives and monitoring desired.

It must be emphasized that occasional calculation of performance indices is not enough. For effective control, these parameters must be continuously observed to recognize trends in plant behaviour. Timely corrections can then be made as soon as plant behaviour begins to show deteriorating trends.

6.2.4 Maintenance Records

It was pointed out in chapter 2 that one of the major hurdles in the way of applying scientific management methods to industrial situations particularly in developing countries is the lack of proper data base. Absence of crucial data severely restricts the scope of maintenance models. It makes it impossible for the maintenance engineer to predict quantitatively the results of any planned maintenance action. Quite often this fact alone stalls implementation of some excellent ideas for equipment maintenance. The establishment of standards, distribution analysis and use of operation research techniques are all facilitated if some prior thought is given to the detail with which data is obtained and cost records maintained. Properly planned maintenance records must reflect the following information:

1. Idle time for machinery waiting for maintenance crew.
2. Idle time of maintenance personnel.
3. Time required for maintenance.
4. Detailed description of work done.
5. Labour (by craft) required for each activity.
6. Spare parts used.
7. Costs incurred due to equipment down time.
8. Reasons for productive unit becoming idle.

It must be stressed here that to be really useful maintenance records must be relevant, accurate and easily retrievable. Asking for too much irrelevant data not only burdens the staff with unnecessary work but also makes its retrieval that much more difficult. The information written on forms is frequently in excess of what is truly required and often it is recorded in such a way as to make it impossible to interpret it at any future date.

6.2.5 Use of Computers in Maintenance Work

The record keeping, scheduling and reporting aspects of the maintenance work lend themselves admirably to the use of the electronic data processing techniques. The capacity of the computer to handle data at high speed, its memory and errorless data processing, its ability to continuously upgrade its data base and to present data in any form desired by the management make it a very useful tool for maintenance work. In complex systems involving a multitude of tasks, events and equipment, the maintenance activity when simulated on a computer enables the maintenance engineer to experiment with and evaluate the effect of alternative plans and parameters. Important applications of computer in maintenance work include the following:

1. Preparation of weekly, fortnightly or monthly schedules for all routine maintenance work along with workorders, indents of supply of parts and instructions for release of equipment.
2. Maintenance of equipment history files.
3. Preparation of cumulative and periodic reports for maintenance control and evaluation.
4. Material control with automatic reordering whenever necessary.
5. PERT/CPM analysis of special projects and shut downs.
6. Statistical analysis of maintenance data to work out preventive maintenance frequencies, crew sizes, new equipment justifications and replacement decisions.
7. Book-keeping jobs like hours worked by each worker or

craft, present level of inventory, bonus and incentive payments.

It must be pointed out here that inspite of all this, maintenance work alone cannot justify the purchase of a computer. Only when such a facility already exists in the organization, can it be used in a big way to help the maintenance staff.

6.3 ALUMINA PLANT MAINTENANCE

6.3.1 Nature of Work

The work done by the maintenance department of the alumina plant can be classified into three categories namely:

1. Break down or repair maintenance
2. Preventive maintenance
3. Planned maintenance

Breakdown or repair maintenance refers to the minor on the spot maintenance work done by the shift maintenance crew. The work is mostly of a routine nature like replacing piston rings, packing pump glands, tightening loose bolts, attending to leaky joints and is carried out with a minimum of paper work and very little preplanning. The only records maintained of this type of work are the reports by the maintenance Foremen in maintenance logbook. This type of maintenance is a necessary component of plant maintenance activities though it generally leads to poor maintenance man-power utilization.

Preventive maintenance refers to maintenance operations which strive to reduce the liklihood of failures. Two types of preventive maintenance activities are being carried out by the department: (i) Periodic inspection and (ii) Lubrication. The aim of the former type of maintenance action is to detect weak points and take corrective action before failure while the latter aims to increase the life of equipment by reducing wear, forces and temperature. Both types of actions involve maintenance work done on a cyclic recurring basis at predetermined frequencies. The instructions for inspection specify parts to be checked, defects to be expected, conditions requiring corrective action, nature of corrective work and action to be taken in case a major repair work is found necessary on inspection. Similarly, instructions for lubrication provide for a daily schedule of lubrication specifying number, name and location of equipment to be lubricated on each day, parts to be lubricated, method of lubrication and the lubricant to be used in each case. This type of maintenance is fully prescheduled and leads to best attainable man-power utilization.

Planned maintenance refers to maintenance work undertaken after proper planning, scheduling and procurement of necessary spare parts, tools and materials. A major portion of this comprises of periodic overhauling of equipment done in accordance with an annual schedule as given in Appendix 6.1. As can be seen from this appendix, the annual schedule specifies the frequency of overhaul for each equipment, the estimated man-power requirement and the week and month in which the work is to be undertaken. Necessary orders for spare part procurement, man-power assignment and release of equipment by operation to maintenance are issued according to this schedule. Planned maintenance also provides for maintenance work arising out of major failures reported by operation or preventive-maintenance groups. These jobs are scheduled keeping in view the overall work load of each crew. This involves regular review of the progress of maintenance work and readjustment of schedules, if necessary.

6.3.2 Organizational Set-up

The plant follows a decentralized type of maintenance organization wherein independent mechanical and electrical maintenance groups are assigned to each area of plant. Fig.6.1 gives the organizational set-up for the Alumina Plant Mechanical Maintenance (Digestion) Group which looks after the maintenance of the three subsystems under investigation. As can be seen from this figure, within itself the group is following a mixed type of organization in that maintenance crews are assigned to individual areas as well as to centralized

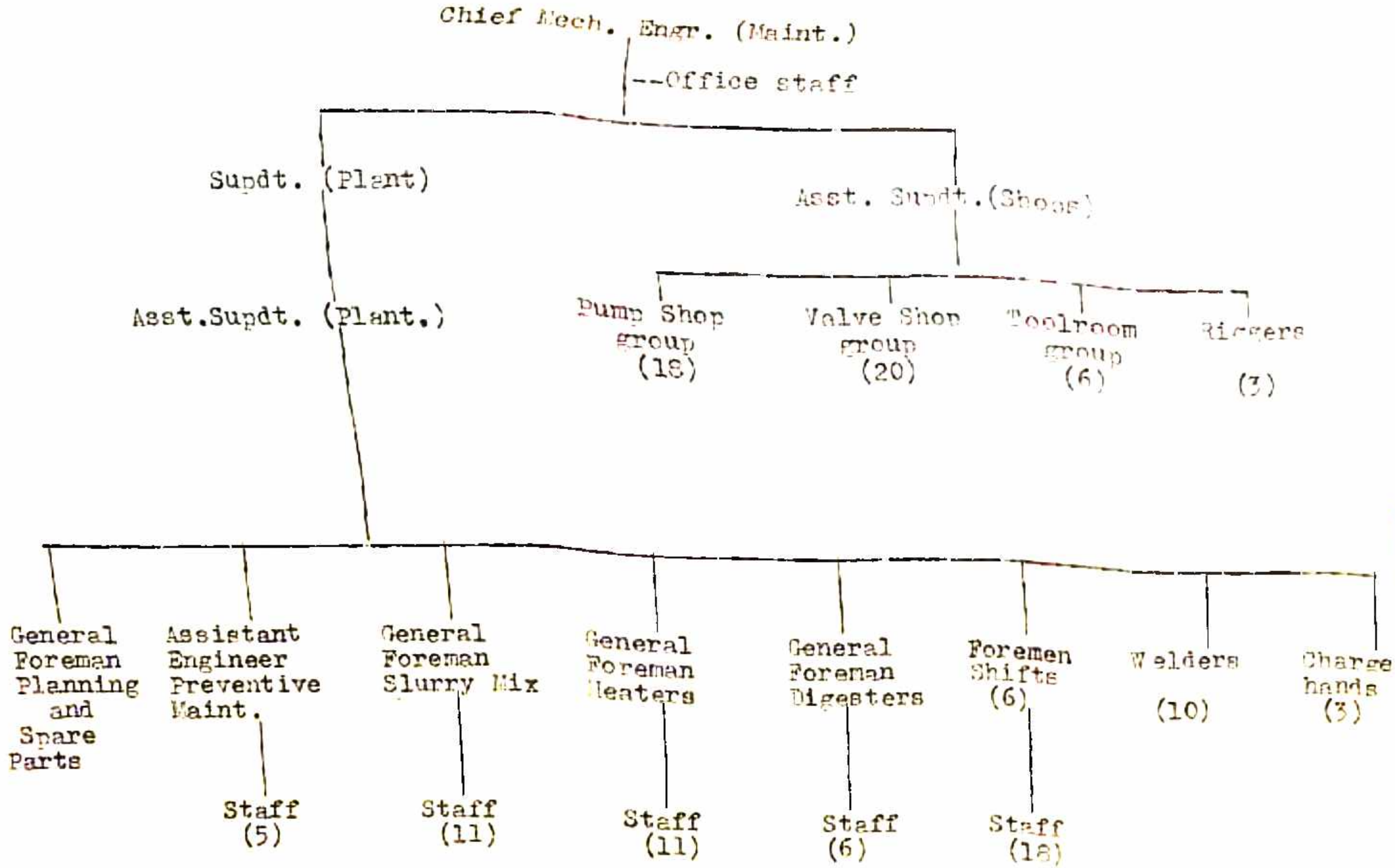

Fig.6.1 ORGANIZATIONAL SETUP FOR ALUMINA PLANT MECHANICAL MAINTENANCE (DIGESTION) GROUP

shops. The pump shop, valve shop and tool room operate as specialized maintenance units attending to equipment brought to them from anywhere in the plant. This has been done to reduce duplication of specialized skills, limit number of test facilities and facilitate use of special tools, jigs etc.

6.3.3 Some Observations on Maintenance Effectiveness

The following observations are based on an on-the-spot study of maintenance operations for a period of $1\frac{1}{2}$ years, difficulties experienced in compiling data from plant records and the restrictions imposed by the insufficiency of the available data on model making for maintenance optimization.

1. Planning

1. It is found that though a sort of an overall planning does exist in the plant for overhauling and preventive actions, by and large, the actual maintenance activity tends to be based more on in-hand job planning rather than on forward planning.

2. An attempt is often made to crowd too much maintenance activity at the time of occasional plant shut downs due to factors like power shortage, erosion leakage or equipment break down. This practice, though apparently useful in reducing plant down time, quite often upsets

maintenance schedules delaying overhauls. Balanced, regular maintenance always results in better overall man-power effectiveness, improved supervision and control, better workmanship and a tension free atmosphere as compared to concentrated bursts of high intensity work.

3. Even at the planning stage there appears to be scope for redistribution of load. An analysis of total man-power requirement for a year as given in Table 6.1 shows that there is considerable variation in work load for different weeks. The planned load for the four weeks of March, for example, is 400, 176, 208 and 272 man-hours against an average work load of 206.7 man-hours per week for the whole year.

Table 6.1 Analysis of the planned overhauling schedu

Month	Estimated manhour load for week No. 1	2	3	4	Total monthly load
January	176	224	160	216	776
February	184	240	216	192	832
March	400	176	208	272	1056
April	240	144	352	240	976
May	192	160	200	176	728
June	168	208	232	160	768
July	312	112	160	200	784
August	232	224	232	192	880
September	216	200	240	224	880
October	120	144	192	240	696
November	336	160	200	120	816
December	232	128	208	160	728
				Total	9920

Average load = 206.7 manhours/week

2. Operation

There is need to standardize the amount of information given by the maintenance personnel in the maintenance logbooks. At present the method and the amount of details given by the staff tend to vary considerably from very sketchy to extremely elaborate depending upon individual preference. Details regarding how much difficulty was experienced in opening a cylinder head or what type of equipment was used in packing pump glands relate at best to routine type of work which can easily be visualized if only the action is mentioned. On the other hand a vital information like what was the strength of acid solution when acid shooting was stopped, if given, can be used advantageously to correlate the effect of operating parameters on scale deposition rates or pin-point trends in maintenance effectiveness. Repetitive and routine type of work in each area should be identified and standardized so that there is no need to repeat same information after each such service.

3. Records

1. At present in many cases very little data is available in maintenance log books regarding the amount of time spent on repairs or the crew size assigned to each job. Absence of such data makes it impossible to carry out any meaningful study to find man-power effectiveness,

optimum size of plant maintenance crews and number of service stations to be set up in each area.

2. There is a similar need for keeping equipment history files up-to-date and complete. History files for major equipment provide invaluable information regarding maintenance behaviour of each equipment and serve to point out unusually high maintenance demands. Only by analyzing the troubles that have occurred, can corrective action be taken to reduce maintenance costs. Such data is also useful in reviewing the frequency of overhaul of equipment.

7. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

7.1 MAINTENANCE OPTIMIZATION MODELS

A detailed state-of-the-art survey of maintenance literature has revealed the following position regarding maintenance investigations and their application to real life industrial situations:

1. During last thirty years or so, industrial management has become increasingly aware of the significant impact of maintenance operations on production costs. Increased automation, higher production rates, complex operations and higher inventory costs are the major reasons for this increasing awareness of the importance of the maintenance function.
2. Use of a variety of mathematical and operations research techniques has considerably increased the scope of maintenance optimization studies. Many new maintenance policies have been evolved with innovative features as a result of different assumptions about the state of the actual system, time-to-failure distribution and objective function to be optimized.
3. The application of theoretically optimal policies to actual maintenance situations is lagging far behind their development. The reasons for this lag

are both technical and psychological. Most theoretical studies are based on one or two homogeneous types of machines with simplifying assumptions regarding their operating characterstics and interdependence. Real life situations are much more complex. There is an inherent hesitancy on the part of maintenance decision makers to venture into new methods. The data required for mathematical analysis is not available in many cases.

4. The management of maintenance in developing countries like India becomes more problematic because of poor or inadequate maintenance organization, limited resources, less than up-to-date repair facilities, poor technological base of maintenance personnel and uncertain supply of spare parts and replacements. Continuous review and updating of maintenance data base and adjustment of maintenance policies necessary for obtaining optimal return from maintenance expenditure is quite often not possible under such situations.

5. The case for establishing sound maintenance management is very strong and pressing because of increasing maintenance costs and an asymptotic saturation in cost reduction from technology development.

Future research in maintenance must try to bridge the gap between theory and practice of maintenance. Optimization models should be applied to more real life situations to demonstrate. their effectiveness inspite of the assumptions involved in developing them.

7.2 EVAPORATORS

The following conclusions can be drawn from the theoretical models proposed for finding the optimal maintenance policy for this subsystem and from the analysis of available plant data:

1. Each caustic cleaning operation of 40 hours costs the plant Rs 1,16,000 in terms of lost alumina production, loss of caustic with redmud and direct material and labour charges.
2. Assuming linear increase in steam consumption rate the annual operating cost of the evaporation sub-system with current practice of 90 days cleaning cycle is Rs 93.92 lakhs when maintenance time is neglected. If the maintenance time per cycle is included, the cost reduces to Rs 92.21 lakhs per year.
3. The optimal cleaning cycle time and annual operating costs for the subsystem can be found from the following relations :-

$$t^{*2}_{c2} + 2\, t^{*}_{c2}\, t_m - \frac{2\,(C_o - aC_1\, t_m)}{bC_1} = 0 \qquad (3.13)$$

and $$C^{*}_{T} = \frac{365}{t^{*}_{c2}+t_m}\left(C_o + C_1\, a\, t^{*}_{c2} + 0.5bC_1\, t^{*2}_{c2}\right) \qquad (3.12)$$

where

t^{*}_{c2} = Optimal interval between caustic cleanings, days

t_m = Time taken for each caustic cleaning, days.

C_o = Cost of each caustic cleaning, rupees.

C_1 = Cost of steam per tonne, rupees.

C^{*}_{T} = Total annual operating cost at optimal interval

a and b are coefficients of linear steam flow rate equation

$$m(t) = a + bt \qquad (3.11)$$

4. When $t_m << t_{c2}$, the above expressions reduce to

$$t^{**2}_{c2} = \frac{2\,C_o}{bC_1} \qquad (3.14)$$

$$C^{**}_{T} = 365\,(\sqrt{2bC_oC_1} + C_1\, a) \qquad (3.15)$$

5. Neglecting time taken for maintenance, the optimal cleaning cycle time is 58 days with an annual operating cost of Rs 92.45 lakhs. This gives an annual saving of Rs 1.47 lakhs against the present policy even though the number of caustic cleanings per year increases from 4 to 6.

6. If the maintenance time is taken into account the optimal cleaning interval reduces to 47 days and the number of cleanings per year increases to 8. But the total operating cost per year reduces by Rs 2.64 lakhs to Rs 89.57 lakhs.

7. Scheduling maintenance within ± 5 days of the optimal value varies the annual cost only by a maximum of .054 percent or Rs 5000 when t_m is neglected and a maximum of .089 percent or Rs 8000 when t_m is taken into account.

8. The optimal cycle time falls by 2-3 days and the total optimal annual operating cost increases by about 6 percent for each Rs 2 per tonne or 6.67 per cent increase in steam cost from the present cost of Rs 30 per tonne.

9. Variations in caustic cleaning cost do not significantly affect the optimal policy. A 50 percent increase in cleaning cost from 0.80 lakhs to 1.2 lakhs increases the annual operating cost by about 2.77 per cent from 89.96 lakhs to 92.70 lakhs provided the cleaning interval is changed from 48 days to 59 days.

10. An error of ± 20 per cent in the estimate of fouling factor b changes the cleaning cycle time by 7 days

and the annual operating cost by 1.84 per cent.

The analysis for the evaporation subsystem needs to be extended in the following directions:

1. The analysis here has assumed that the steam consumption rate increases linearly with time without limit. In many industrial situations flow increases upto a certain limit and then remains constant. This occurs when the rate of flow connot be increased beyond a limit either due to insufficient steam supply or to physical constraint of the amount of steam that can flow through a fully open valve. It is necessary to extend this model to include such flow-constrained variations in steam consumption rate.

2. It is assumed that the caustic cleaning brings the sub-system to 'as new' state so that after each caustic cleaning the steam consumption rate follows the same pattern. As mentioned earlier, this is not strictly true. Some amount of scale does remain even after caustic cleaning and its thickness progressively increases till the unit is mechanically cleaned. The rate at which such permanent scale builds up will vary from effect to effect depending upon the temperature range in each effect. An attempt

should be made to study the growth rate of these permanent scales and their influence on steam consumption rate after caustic cleaning. Davidson has discussed such a model for boilers and shown that increase in cost varies with total steam generated in the boiler to-date.

7. The present investigation has assumed a constant maintenance cost calculated on the basis of current practice in the plant as for as the maintenance procedure is concerned. Two things need to be looked into in this connection. First, it has been assumed that the rate of change of overall heat transfer coefficient will remain the same even when the frequency of cleaning is changed from the present 90 days to the proposed optimal 58 or 47 days. It is not unreasonable to argue that since tube walls will be cleaned more frequently, both the permanent scales and scales removed by caustic cleaning will reduce and hence heat transfer rates may not vary as much as they are varying now. Secondly, it may be possible to reduce the caustic cleaning time from the present 40 hours to a much lesser duration by increasing the caustic concentration or temperature, deploying more man power or reorganizing the work. It is thus necessary to carry out controlled experiments

to evaluate the effect of maintenance work on plant failure characteristics.

4. The scope of the present investigation can be significantly enlarged if a mathematical model can be developed using reaction chemistry to give rate of scale deposition and hence the drop in overall heat transfer coefficient with time. Mass and energy conservation relations can then be used, as done here, to predict changes in output temperature from each effect. Since the subsystem has an inherent cascading nature, a change in any effect produces sequential changes in all effects till the subsystem comes to a new equilibrium. A mathematical model for the entire subsystem will give a theoretical basis for evaluating maintenance effectiveness.

5. Similar mathematical models also need to be developed for finding optimal frequency of mechanical cleaning.

7.3 SLURRY INJECTION PUMPS

The analysis of this subsystem has yielded the following results:

1. The subsystem availability as found from the records of the alumina plant for 6 months is 73.83 percent for the old unit and 91.42 percent for the new unit. Steam pumps are causing a loss of 1.91 percent of availability in the old unit and

0.79 per cent in the new unit in spite of the fact that the old unit has two spare pumps against one in the new unit. The difference in availability is mostly due to higher plant shut-down because of equipment failure, steam and power shortage and leakage due to erosion in the old unit.

2. The charging time between pump and subsystem failures, the total time between plant failures and the charging loss due to subsystem and plant failure can all be represented fairly accurately by negative exponential type of distributions for both the units. The goodness-of-fit has been verified by Chi-square test.

3. The mean-time-between-failures is much less for old unit pumps than that for new unit pumps due to age of the pumps and the difference in design.

4. Of the two new unit pumps, pump No.4 is giving a mean-time-between-failures almost half as much as for pump No.5. The reason for this difference in performance is not clear. It is suggested that this difference in performance be investigated to see if it can be attributed to any difference in maintenance of the two pumps.

5. The optimal maintenance policy for the pumps is to

run the pumps upto failure. Scheduling pump changeover preventively before failure is not expected to yield any increase in plant availability.

6. It is necessary to review the extent and frequency of inspection of the old unit equipment to control erosion leakage. Valves, pipe bends, fittings, spools etc must be regularly inspected and replaced, if necessary, to reduce break down repair.

7. Steam shortage is causing considerable loss of plant uptime particularly in the old unit. Since thealumina plant has a captive boiler house with sufficient installed capacity, there is a need to review the boiler house maintenance position to improve availability of steam.

7.4 Spent Liquor Heaters

The deposition of scales on heater walls affects the plant operation in two ways:

(a) It reduces the temperature of liquor going to digesters thereby increasing the quantity of steam required in the digesters to maintain constant temperature.

(b) It reduces the flow of spent liquor due to plugging resulting in loss of alumina produced.

The following conclusions have been drawn regarding the effect of these factors on plant performance:

1. The steam consumption cost increases at the rate of Rs 565.80 for each degree drop in digester inlet temperature. The loss in flow due to plugging costs Rs 83.76 per day for each lpm drop in flow.

2. The variation in overall heat transfer coefficient, U, for the heaters can be represented by a relationship of the form

$$\frac{10^7}{U^2} = a + bt \qquad (5.7)$$

where a and b are constants and t is the number of days the heater has been in use after acid shooting.

3. Plugging of tubes of the high pressure heaters results in a loss of spent-liquor flow of 13.52 lpm per day of heater use. No appreciable plugging is observed in other heaters.

4. The optimal cleaning frequency for the high pressure heaters assuming a linear increase in operating costs is given by the expression

$$t_h^* = \sqrt{\frac{2Co}{s}} \qquad (5:15)$$

where t_h^* is the optimal interval between heater cleanings, Co is the cost of each cleaning operation and s is rate of increase of operating cost with time due to scale deposition.

5. The optimal cleaning cycle time is 3 days against the

present practice of 15 days. Changing the cleaning interval from present 15 days to optimal 3 days will result in a saving of Rs 25.48 lakhs or 69.64 per cent of present cost per year.

6. The total annual cleaning cost plus excess steam cost is quite sensitive to cleaning interval. Any delay in cleaning beyond the optimal value will cause a considerable increase in cost.

7. Optimal cleaning interval is directly proportional to the square root of cleaning cost and inversely proportional to the square root of the rate of increase of operating cost with scale formation.

The above analysis can be extended in the following directions:

1. The model should be extended to other heaters to find their effect on increase in cost.

2. A comprehensive model including the effect of permanent scales should be developed for the heater subsystem as a whole.

3. A model should be developed for finding optimal mechanical cleaning frequencies.

7.5 MAINTENANCE ORGANIZATION AND CONTROL

The following suggestions emerge as a result of the present investigation, to improve the effectiveness of Alumina

Plant Mechanical Maintenance (Digestion) Group:

1. At present there is considerable variation in the planned overhauling work load from week to week. When the overhauling frequencies are revised in the light of maintenance optimization models, it will be desirable to rework the annual schedule with more balanced distribution of work load.

2. It is suggested that the amount of information given by the maintenance crew in maintenance logbooks be standardized. Routine and repetitive details can be eliminated while factual information like time spent on maintenance, manpower employed, reasons for equipment failure should be included as a rule. This will help in working out optimal maintenance policies.

3. The equipment history files should be maintained upto date and regularly reviewed to discover any unduly high maintenance demand patterns.

4. Unscheduled plant break downs should not be overburdened by diverting too much scheduled overhauling work. Such unscheduled diversions disturb established routine and unnecessarily force the work pace increasing possibilities of unsatisfactory maintenance.

7.6 CONCLUDING REMARKS

The objectives of the present investigation were to carry out an exhaustive state-of-the-art survey of maintenance literature and to discuss case studies for maintenance optimization. The literature survey given in chapter 2 has shown that though there is a considerable scope for use of maintenance optimization studies, the situation obtaining in most industries today can hardly be considered as satisfactory. Considerable efforts are required to be put in order to make the benefits of theoretical investigations available to practical maintenance engineers.

The case studies discussed in chapters 3, 4 and 5 present two types of maintenance models : (1) Descriptive and (2) Prescriptive. The investigation of slurry injection pumps belongs to the descriptive category. Through an analysis of the failure pattern of the subsystem it has been established that no useful purpose will be served by switching over from the present break down maintenance policy to a preventive maintenance policy in which pumps are taken out of service preventively before failure. Any attempt at increasing the plant availability has to be aimed at units outside the charging subsystem. Increasing steam availability and checking erosion leakage in the old unit appear to be the two most promising avenues in this regard.

The models for evaporators and spent liquor heaters fall into the prescriptive category. Both the subsystems are currently being maintained preventively. The study aims at optimizing the frequency of these preventive maintenance activities. The optimal frequency f* obviously depends upon the maintenance policy P, cost of maintenance action Co and the operating cost C i.e.

$$f^* = \phi\,(P,\ C_o,\ C) \tag{7.1}$$

For the evaporation subsystem, C_o is of the order of Rs 1,16,000 and there appears to be a prima facie case for optimization. For spent liquor heaters, the maintenance cost per heater is only Rs 3250 and the need for maintenance optimization study is not so obvious. The analysis of the subsystems has shown that even in those cases where maintenance costs appear to be comparatively insignificant, considerable annual savings may be obtained by a systematic investigation of the maintenance problem.

The distinction between the types of models can be very important methodologically. Generally a descriptive model does not lead to any one single optimal answer. The effects of several possible alternative policies are presented to the decision maker who uses his judgment to select the best answer. In the case of prescriptive models, the maintenance effectiveness is expressed in terms of a single variable and the best solution can directly be calculated from the model. Ideally, all maintenance investigations should lead to prescriptive models but in actual practice it is not always possible to do so. It is then necessary to resort to descriptive models.

Descriptive models which by virtue of description of system behaviour rule out the operational fesibility of all but one type of maintenance action belong to a special class of descriptive models. Such models can be called 'prescriptive models in description'.

It is necessary to point out here that the maintenance optimization process for the Aluminium Corporation has just about begun with the present investigation. The work done here must be extended to other areas of the alumina plant namely digestion, boiler house, precipitation, clarification and the calcination areas and then to other plants. After all the plants have been covered it will be necessary to review the total maintenance problem and take corrective measures wherever called for. These may include revision of maintenance priorities, reassessment and redistribution of work load, changes in planning, recording and evaluating procedures, revision of inventory and reorder policies and a number of other similar decisions. Additional budgetary demands may also have to be reviewed vis-a-vis other commitments and expected return from the investment. The whole process appears to be quite elaborate and very time consuming but the effort is sure to pay rich dividends.

Maintenance investigations of the type carried out here evaluate the effect of operating parameters on plant availability and production cost, give theoretical support to existing policies based on trial and error, suggest desirable policy changes when necessary and effect considerable savings by cost optimization. Properly maintained equipment leads to increased plant availability, higher production rates and extended life of the plant. Needless to say that all these objectives are well worthstriving for in an economy which is capital scarce. The relevance of the effort becomes further evident if in addition to actual cost, the social cost of imported capital equipment is also considered. It is for the first time that a systematic effort of this kind is being made in Indian situation to improve productivity of capital equipment through maintenance optimization.

BIBLIOGRAPHY

1. Abbott, W.R., - 'Repair versus Replacement of Failed Components', Journal of Industrial Engineering, Vol. XIX, No.1, 1968, pp. 21 - 23.
2. Allen, D.S., - 'Equipment Replacement', Operational Research Quarterly, Vol. 17, 1966, pp. 317-318.
3. Arora, S.R. and P.T. Lele, - 'A Note on Optimal Maintenance and Sale Date of a Machine', Management Science, Vol.17, No.3, 1970, pp. 170 - 173.
4. Barlow, R.E. and L.C. Hunter, - 'Optimum Preventive Maintenance Policies', Operations Research, Vol.8, No.1, 1960, pp. 90 - 100.
5. ________, and A.W. Marshall, - 'Bounds on Distributions with Monotone Hazard Rates', Annals of Mathematical Statistics, Vol.35, No.3, 1964, pp. 1234 - 1274.
6. ________, and F. Proschan, - 'Planned Replacement' in 'Studies in Applied Reliability and Management Science', Stanford University Press, 1962.
7. ________, and ________, - 'Comparison of Replacement Policies and Renewal Theory Implications', Annals of Mathematical Statistics, Vol.35, No.2, 1964, pp. 577 - 589.
8. Bartholomew, D.J., - 'Two Stage Replacement Strategies', Operational Research Quarterly, Vol. 14, 1963, pp. 71 - 87.

9. Blanning, R.W., - 'Replacement Strategies', Operational Research Quarterly, Vol.16, No.2, 1965, pp. 253 - 254.

10. Boden, J., - 'Optimum Staffing Model for Machine Maintenance', A.S.M.E. Paper No.70 - PWM - 13, 1970.

11. Brown, D.B. and H.F. Martz, Jr., - 'A Two-Phase Algorithm for the Maintenance of a Deteriorating Component System', A.I.I.E. Transactions, Vol. II, No.2, 1970, pp. 106 - 111.

12. ________ and ________, - 'Simulation Model for the Maintenance of a Deteriorating Component System', I.E.E.E. Transactions on Reliability, Vol. R-20, No. 1, 1971, pp. 28 - 32.

13. Carruthers, J.A., I. MacG Gow and G.C. Hackemer, - 'A Study on the Optimum Size of Plant Maintenance Gangs', in 'Operational Research in Maintenance', Manchester University Press, 1970, pp. 119 - 130.

14. Chandy, K.T., - 'Plant Maintenance Holds Key to Plan's Success', The Hindustan Times, September 17, 1975.

15. Chanin, M.N. and G.P. Sphicals, - 'A Systems Approach to Maintenance Management', in 'Applied Cybernatics and Planning', South Asian, 1980, pp. 93 - 109.

16. Clapham, J.C.R., - 'Economic Life of Equipment', Operational Research Quarterly, Vol.8, 1957, pp. 181-190.

17. Crabill, T.B., - 'Optimal Control of a Maintenance System with Variable Service Rates', Operations Research, Vol.22, No.4, 1974, pp. 736 - 745.

18. Christer, A.H. and W. Goodbody, - 'Equipment Replacement in Unsteady Economy', Journal of Operations Research Society, Vol.31, No.6, 1980, pp. 497-506.

19. Crookes, P.C.I., - 'Replacement Strategies', Operational Research Quarterly, Vol.14, 1963, pp.167-184.

20. Daniel, R.C., - 'Phasing Out Capital Equipment', Operational Research Quarterly, Vol.24, No.1, 1973, pp. 113 - 116.

21. Davidson, D., - 'An Overhaul Policy for Deteriorating Equipment', in 'Operational Research in Maintenance', Manchester University Press, 1970, pp. 72-99.

22. Dê Veroli, J.D., - 'Optimal Continuous Policies for Repair and Replacement', Operational Research Quarterly, Vol.25, No.1, 1974, pp.89 - 98.

23. Dean, B.V., - 'Replacement Theory', in 'Progress in Operations Research', Ed. R.L. Ackoff, Wiley, Vol.1, 1963, pp.328-362.

24. Dreyfus, S.E., - 'A Note on an Industrial Replacement Process', Operational Research Quarterly, Vol.8, 1956, pp. 190 - 193.

25. Drinkwater, R.W. and N.A.J. Hastings, - 'An Economic

Replacement Model', Operational Research Quarterly, Vol.18, No.2, 1967, pp. 121-138.

26. Duncan, J. and L.S. Scholnick, - 'Interrupt and Opportunistic Replacement Strategies for Systems of Deteriorating Components', Operational Research Quarterly, Vol.24, No.2, 1973, pp. 271 - 283.

27. Eilon, S., J.R. King and D.E. Hutchinson, 'A Study in Equipment Replacement', Operational Research Quarterly, Vol.17, No.1, 1966, pp. 59-71.

28. Falkner, C.H., - 'Jointly Optimal Inventory and Maintenance Policies for Stochastically Failing Equipment', Operations Research, Vol.16, No.3, 1968, pp.587 - 601.

29. Fox, B., - 'Age Replacement with Discounting', Operations Research, Vol.14, 1966, pp.533 - 537.

30. Ghare, P.M. and P.E. Torgersen, - 'The Effect of Inflation and Increased Productivity on Machine Replacement', Journal of Industrial Engineering, Vol.XV, No.4, 1964, pp.201 - 207.

31. Goheen, L.C., - 'On the Optimal Operating Policy for the Machine Repair Problem when Failure and Repair Times have Erlang Distribution', Operations Research, Vol.25, No.3, 1977, pp.484 - 492.

32. Gopalan, M.N. and C.A. D'Souza, - 'Probabilistic Analysis of a Two Unit System with Single Service

Facility for Preventive Maintenance and Repair', Operations Research, Vol.23, 1975, pp.173 - 177.

33. ______ and ______, - 'Probabilistic Analysis of a System with Two Dissimilar Units Subject to Preventive Maintenance and a Single Service Facility', Operations Research, Vol.23, No.3, 1975, pp.534-548.

34. Goswami, H., - 'Elimination of Wastage by Means of Standard Maintenance of Machinery', Industrial Engineering and Management, Vol.5, 1970, pp.19 - 23.

35. Graveley, O.W., - 'Breakdown vs Preventive Maintenance', Chemical Engineering, Vol.61, No.8, 1954, pp.193-194.

36. Hackemer, G.C., - 'Equipment Replacement', Operational Research Quarterly, Vol.18, No.1, 1967, p.71.

37. Handlarski, J., - 'Mathematical Analysis of Preventive Maintenance Schemes', Journal of Operations Research Society, Vol.31, No.3, 1980, pp.227 - 237.

38. Hastings, N.A.J., - 'Some Notes on Dynamic Programming and Replacement', Operational Research Quarterly, Vol.19, No.4, 1968, pp. 453-464.

39. ______, - 'The Repair Limit Replacement Method', Operational Research Quarterly, Vol. 20, No.3, 1969, pp. 337 - 350.

40. ______, - 'Equipment Replacement and the Repair Limit Method', in 'Operational Research in Maintenance', Manchester University Press, 1970, pp. 100 - 118.

41. Holland, C.W. and R.A. McLean, - 'Applications of Replacement Theory', A.I.I.E. Transactions, Vol.7, No.1, 1975, pp. 42 - 47.

42. Howard, R.A., - 'Dynamic Programming and Markov Processes', Wiley, 1960.

43. Jain, A. and K.P.K. Nair, - 'Comparison of Replacement Strategies for Items that Fail', I.E.E.E. Transactions on Reliability, Vol.R-23, No.4, 1974, pp.247-251.

44. Jardine, A.K.S., - 'Maintenance Models' in 'Quantitative Techniques in Maintenance Management', University of Strathclyde, 1969.

45. _______, - 'Equipment Replacement Strategies', in 'Operational Research in Maintenance', Manchester University Press, 1970, pp. 20 - 43.

46. Jones, H.G., - 'Equipment Replacement', Operational Research Quarterly, Vol.17, No.3, 1966, p.318.

47. Jorgenson, D.W. and J.J. McCall, - 'Optimal Scheduling of Replacement and Inspection', Operations Research, Vol.11, No.5, 1963, pp.732 - 746.

48. Kay, E., - 'The Effectiveness of Preventive Maintenance', International Journal of Production Research, Vol.14, No.3, 1976, pp. 329 - 344.

49. Kendall, L.A. and A.K. Sheikh, - 'Cost Optimization Models for Planned Replacement', A.S.M.E., Paper No.79 - DET-115, 1979, pp. 1 - 4.

50. Kent, A., - 'The Effect of Discounted Cash Flow on

Replacement Analysis', Operational Research Quarterly, Vol.21, No.1, 1970, pp. 113 - 118.

51. Kirk, E. and D.F. Othmer, - 'Encyclopedia of Chemical Technology', Interscience Publishers, Vol.1, 1963, pp. 937-941.

52. Lambe, T.A., - 'The Decision to Repair or Scrap a Machine', Operational Research Quarterly, Vol.25, No.1, 1974, pp. 99 - 110.

53. Luss, H. and Z. Kander, - 'Inspection Policies when Duration of Checking is Non-Negligible', Operational Research Quarterly, Vol.25, No.2, 1974, pp.299 - 309.

54. Mahon, B.H. and R.J.M. Bailey, - 'A Proposed Improved Replacement Policy for Army Vehicles', Operational Research Quarterly, Vol. 26, No.3, 1975, pp.477-494.

55. Mann, L. Jr., - 'Statistical Methods Facilitate Maintenance Planning and Scheduling', A.S.M.E., Paper No. 66 - PET - 12, 1966, pp. 1 - 4.

56. Marathe, V.P. and K.P.K. Nair, - 'On Multi-Stage Replacement Strategies', Operations Research, Vol.14, No.3, 1966, pp. 537 - 538.

57. ________ and ________, - 'Multi-Stage Planned Replacement Strategies', Operations Research, Vol.14, No.5, 1966, pp. 874 - 887.

58. McAdams, W.H., - 'Heat Transmission', McGraw Hill, 1954, pp. 350 - 354.

59. McCall, J.J., - 'Maintenance Policies for Stochastically

Failing Equipment: A Survey', Management Science, Vol.11, No.5, 1965, pp. 493 - 524.

60. Meisel, W.S., - 'On-Line Optimization of Maintenance and Verification Schedule', I.E.E.E. Transactions on Reliability, Vol.R-18, No.4, 1969, pp. 200 - 201.

61. Mine, H. and H. Kawai, - 'Preventive Replacement of a 1 - Unit System with Wear Out State', I.E.E.E. Transactions on Reliability, Vol.R-23, No.1, pp.24-29.

62. _______ and _______, - 'An Optimal Maintenance Policy for a 2-Unit Parallel System with Degraded States', I.E.E.E. Transactions on Reliability, Vol.R-23, No.2, 1974, pp. 81 - 86.

63. Morse, P.M., - 'Queues, Inventories and Maintenance', Wiley, 1963.

64. Mortimore, R.H., - 'Equipment Replacement', Operational Research Quarterly, Vol.17, No.2, 1966, pp. 193-194.

65. Munford, A.G. and A.K. Shahani, - 'A Nearly Optimal Inspection Policy', Operational Research Quarterly, Vol.23, 1972, p. 373.

66. _______ and _______, - 'An Inspection Policy for the Weibull Case', Operational Research Quarterly, Vol.24, No.3, 1973, pp. 453-458.

67. Naik, M.D. and K.P.K. Nair, - 'Multi-Stage Replacement Strategies', Operations Research, Vol.13, No.2, 1965, pp. 279-290.

68. _______ and _______, - 'Multi-Stage Replacement Strategies with Finite Duration of Transfer', Operations Research, Vol.13, No.5, 1965, pp.828 - 835.

69. Nakagawa, T. and S. Osaki, - 'Optimum Preventive Maintenance Policies for a 2-Unit Redundant System', I.E.E.E. Transactions on Reliability, Vol.R-23, 1974, pp. 86-91.

70. _______ and _______, - 'The Optimum Repair Limit Replacement Policies', Operational Research Quarterly, Vol.25, No.2, 1974, pp. 311 - 317.

71. Newbrough, E.T., - 'Effective Maintenance Management', McGraw Hill, 1967, p.3.

72. Nicholson, T.A.J. and R.D. Pullen, - 'Dynamic Programming Applied to Ship Fleet Management', Operational Research Quarterly, Vol.22, 1971, p.211.

73. Noonan, G.C. and C.G. Fain, - 'Optimum Preventive Maintenance Policies when Immediate Detection of Failures is Uncertain', Operations Research, Vol.10, No.3, 1962, pp. 407-410.

74. Ostle, B., - 'Statistics in Research', Oxford and IBH, 1974, p.127.

75. Pandit, S.M. and A.K. Sheikh, - 'Reliability and Optimal Replacement via Coefficient of Variation', A.S.M.E. Paper No.79 - DET - 108, 1979, pp. 1 - 13.

76. Perry, J.H., - 'Chemical Engineering Handbook', McGraw Hill, 1950, pp. 500 - 522.

77. Pritskar, A.A.B., - 'The Setting of Maintenance Tolerance Limits', Journal of Industrial Engineering, Vol.XIV, No.2, 1963, pp. 80-86.

78. ________, - 'The Monte Carlo Approach to Setting Maintenance Tolerance Limits', Journal of Industrial Engineering, Vol.XIV, No.3, 1963, pp. 115-118.

79. Proctor, C.L. and Y.T. Wang, - 'Optimal Maintenance Policy for Systems that Experience State Degradations', Microelectronics and Reliability, Vol.14, 1975, pp. 199-202.

80. Radnor, R. and D.Jorgenson, - 'Opportunistic Replacement of a Single Part in the Presence of Several Monitored Parts', Management Science, Vol.10, 1963, pp. 70-84.

81. Reed, R. Jr., - 'Plant and Equipment Maintenance', in 'Plant Location, Layout and Maintenance', Richard D. Irwin, 1967, pp. 151 - 180.

82. Roll, Y. and P. Naor, - 'Preventive Maintenance of Equipment Subject to ContinuousDeterioration and Stochastic Failure', Operational Research Quarterly, Vol.19, No.1, 1968, pp. 61 - 71.

83. Sasieni, M.W., - 'A Markov Chain Process in Industrial Replacement', Operational Research Quarterly, Vol.7, No.4, 1956, pp. 148-154.

84. Sathe, P.T. and W.M. Hancock, - 'A Bayesian Approach to the Scheduling of Preventive Maintenance',Transactions A.I.I.E., Vol.5, No.2, 1973, pp.172 - 179.

85. Schweitzer, P.J., - 'Optimal Replacement Policies for Hyper - Exponentially and Uniformly Distributed Life Times', Operations Research, Vol.15, No.2, 1967, pp.360 - 363.

86. Signorini, G., - 'Find Optimum Frequency of Inspection', Chemical Engineering, Vol.68, No.5, 1961, pp.138-142.

87. Srinivasan, S.K. and M.N. Gopalan, - 'Probabilistic Analysis of a Two Unit System with a Warm Standby and a Single Repair Facility', Operations Research, Vol.21, No.3, 1973, pp. 748-754.

88. ________ and ________, - 'Probabilistic Analysis of a Two Unit Cold Standby System with a Single Repair Facility', I.E.E.E. Transactions on Reliability, Vol.R-22, No.5, 1973, pp. 250 - 254.

89. Srinivasan, V.S., - 'The Effect of Standby Redundancy on Systems Failure with Repair Maintenance', Operations Research, Vol.14, No.6, 1966, pp.1024 - 1036.

90. Stuart, S.W., - 'Managing Maintenance; the State of Art', Plant Engineering, July 1974, pp. 27 - 29.

91. Terborgh, G., - 'Dynamic Equipment Policy', McGraw Hill, 1949.

92. Thompson, G.L. - 'Optimal Maintenance Policy and Sale Date of a Machine', Management Science, Vol.14, 1968, pp. 543 - 550.

93. Watson, C., - 'Is Preventive Maintenance Worthwhile', in 'Operational Research in Maintenance', Manchester University Press, 1970, pp. 142 - 173.

94. White, D.J. - 'Setting Maintenance Inspection Intervals using Dynamic Programming', Journal of Industrial Engineering, Vol. 18, No.6, 1967, pp. 376 - 381.

95. ________, W.A. Donaldson and N.L. Lawrie, - 'Operational Research Techniques', Business Books, Vol.1, 1969.

96. Winstor, W., - 'Optimal Control of Discrete and ContinuousTime Maintenance Systems with Variable Service Rates', Operations Research, Vol.25, No.2, 1977, pp.259 - 268.

97. Woodman, R.C., - 'Replacement Strategies', Operational Research Quarterly, Vol.18, No.2, 1967, pp. 193 - 195.

98. ________, - 'Replacement Policies for Components that Deteriorate', Operational Research Quarterly, Vol.18, No.3, 1967, pp. 267 - 280.

99. ________, - An Economic Replacement Model', Operational Research Quarterly, Vol.18, No.4, 1967, p. 468.

100. Yakkundi, S.V. and S.K. Barat, - 'An Approach Towards Estimation of Man Power Requirement for Maintenance Department of a Mechanised Foundary', Industrial Engineering and Management, Vol.6, No.3-4, 1971, pp. 57 - 77.

Appendix 1.1

PLANT OPERATING CONDITIONS

The numerical figures related to plant operation given in the thesis are based on the following assumptions:

1. GENERAL

Alumina produced per year		170,000 t
Number of working days per year		343
Recovery of dissolved alumina		93 %
Alumina dissolved per day :	Old unit	160 t
	New unit	375 t
	Total	535 t
Extraction efficiency		94 %

2. SLURRY-MIX AREA

Total available alumina in bauxite		46 %
Trihydrate alumina		37 %
Monohydrate alumina		9 %
Weight of dry bauxite used per day		1237.3 t
Moisture in bauxite		3 %
Specific heat of dry bauxite		0.249 kcal/kg °C
Temperature of dry bauxite		26.6 °C
Lime to slurry-mix area		1 % of dry bauxite
Water with lime		9 t/t of lime
Specific heat of lime		0.25 k cal/kg °C
Spent liquor to slurry-mix area:	Old unit	176 lpm
	New unit	440 lpm
	Total	616 lpm

Density of spent liquor	1.24 gm/cc
Temperature of spent liquor to ball mills	112 °C
Slurry pumping rate to digesters: Old unit	320 lpm
New unit	750 lpm
Total	1070 lpm
Density of slurry to digesters	1.62 gm/cc
Solids in slurry to digesters	50 %
Pressure of steam supplied to slurry injection pumps	17.58 kgf/cm^2 (gauge)
Pressure of exhaust steam from the pumps	1.06 kgf/cm^2 (gauge)

3. SPENT LIQUOR HEATERS

Caustic concentration in test tank	193 gpl
Test tank alumina-to-caustic ratio	0.380
Spent liquor flow to heaters: Old unit	2100 lpm
New unit	5560 lpm
Total	7660 lpm
Spent liquor flow through new unit heaters after taking ball mill flow	4944 lpm
Specific heat of liquor	0.86 k cal/kg °C
Temperature of spent liquor to digesters	212 °C
Temperature of liquor input to heaters	85 °C
Temperature of liquor output from heaters	212 °C

4. DIGESTERS

Pressure of steam supplied to digesters	40 kgf/cm^2 abs.
Temperature of steam supplied to digesters	271 ^oC
Exit temperature from the digesters	243 ^oC
Solution heat of trihydrate alumina	172.2 k cal/kg
Solution heat of monohydrate alumina	70 k cal/kg
Radiation losses in digesters	6 % of all other losses
Total flash effluent flow	7212 lpm
Flash effluent alumina-to-caustic ratio	0.650
Caustic in flash effluent	205 gpl
Caustic utilization factor	0.93

5. CLARIFICATION

Settler feed flow	10112 lpm
Settler feed caustic concentration	162 gpl
Dilution liquor	2900 lpm
Dilution caustic concentration	55 gpl
Mud load	494.92 tpd
Solids in settler underflow slurry	25 %
Density of settler underflow slurry	1.44 gm/cc
Settler underflow	955 lpm

Solids in mud-to-lake slurry	21 %
Density of mud-to-lake slurry	1.20 gm/cc
Mud-to-lake flow	1364 lpm
Lake return	40 %
Caustic-to-soda ratio in red mud	0.75
Soda loss with red mud during normal operation	2.5 gpl
Density of liquor going with red mud slurry	1.01 gm/cc

6. <u>EVAPORATION</u>

Spent liquor to evaporation :	Old unit	2340 lpm
	New Unit	7000 lpm
	Total	9340 lpm
New unit primary evaporation by pass flow		1000 lpm
Liquor-to-evaporation caustic concentration		160 gpl
Temperature of liquor to evaporation		60 ^oC
Caustic concentration at evaporation outlet		195 gpl
Total evaporation expected		100.8 tph
Evaporation in Old unit :	Primary evaporators	10.4 tph
	Feed flash tank	8.4 tph
	Secondary evaporators	6.5 tph
	Total	25.3 tph
Evaporation in new unit :	Primary evaporators	27.2 tph
	Feed flash tank	13.2 tph

	Secondary evaporators	35.1 tph
	Total	75.5 tph
Temperature at the outlet of primary evaporation live-steam heater	122 °C	
Temperature at the outlet of the secondary evaporation live - steam heater	134 °C	
Pressure of steam supplied to primary evaporation live-steam heater :	Old unit	7.03 kgf/cm^2 (gauge)
	New unit	1.06 kgf/cm^2 (gauge)
Pressure of steam supplied to secondary evaporation live - steam heater :	Old unit	7.03 kgf/cm^2 (gauge)
	New unit	7.03 kgf/cm^2 (gauge)

EQUIPMENT SPECIFICATIONS

1. PRIMARY EVAPORATORS

Fluid handled on tube side	Spent liquor
Fluid handled on shell side	Condensate from previous effect and vapours flashed in flash chamber of the same effect.
Tube size	32 mm O.D., 7.32 m long, 12 BWG
Total number of tubes	1296
Number of passes	4 tube side, 1 shell side
Total heating surface, m^2	789.7 based on inner diameter 956.9 based on outer diameter

Diameter of liquor inlet and outlet pipe, mm	254
Diameter of condensate inlet and outlet pipe, mm	101.6
Diameter of non-condensable vapour vent, mm	50.8
Diameter of caustic header for cleaning, mm	101.6

2. PRIMARY EVAPORATION LIVE STEAM HEATER

Number of heaters	1
Fluid handled on tube side	Spent liquor
Fluid handled on shell side	Steam at 1.06 kgf/cm^2 gauge
Tube size	32 mm O.D., 7.32 m long, 12BWG
Total number of tubes	380
Number of passes	2 tube side, 1 shell side
Total heat transfer area, m^2	281 based on outer diameter.

3. FEED FLASH TANK

Diameter of the tank, m	3.66
Height of the tank, m	3.05
Diameter of the liquor inlet and outlet pipe, mm	254
Diameter of the vapour outlet pipe, mm	812.8

4. SECONDARY EVAPORATORS

Fluid handled on the tube side	Spent liquor
Fluid handled on the shell side	Condensate from previous effect and vapours flashed in flash chamber of the same effect.
Tube size	32 mm O.D., 7.32 m long, 12 BWG
Total number of tubes	760
Number of passes	4 tube side, 1 shell side
Total heating area, m^2	464.5 based on inner diameter 562 based on outer diameter
Diameter of liquor inlet and outlet pipe, mm	254
Diameter of condensate inlet and outlet pipe, mm	101.6
Diameter of non-condensable vapour vent, mm	50.8
Diameter of caustic header for cleaning, mm	101.6

5. SECONDARY EVAPORATION LIVE STEAM HEATERS

Number of heaters	2
Fluid handled on the tube side	Spent liquor
Fluid handled on the shell side	Steam at 7.03 kgf/cm^2 gauge
Tube size	32 mm O.D., 7.32 m long, 12 BWG

Total number of tubes	380
Number of passes	2 tube side, 1 shell side
Total heat transfer area, m^2	232.2 based on inner diameter 281 based on outer diameter

6. SLURRY INJECTION PUMPS

Pump numbers	1,2,3	4,5
Unit	Old	New
Fluid pumped	Bauxite slurry	Bauxite slurry
Specific gravity of fluid	1.61	1.61
Temperature, °C	88	88
Solid content, percent	50-60	50-60
Caustic concentration, percent	11.5	11.5
Discharge, lpm	272-340	775
Discharge pressure, kgf/cm^2	44.2	38.0
Pump type	Reciprocating, duplex, plunger type	Reciprocating, duplex, piston type with surgeblock
Type of suction	Single, double acting	Single, double acting
Speed, strokes/mt	18-19	14-15
Steam inlet pressure, kgf/cm^2(gauge)	17.58	17.58
Casing material	Steel	Cast steel lined
Seal	Stuffing box	Stuffing box
Manufacturer	Warren Pumps Inc.	Warren Pumps Inc.

7. SPENT LIQUOR HEATERS

Unit	Old	New
Position	Vertical	Horizontal
Number of heaters	9	10
Type of heaters	Shell and tube type	Shell and tube type
Fluid circulating on the shell side	Flash steam (Saturated)	Flash Steam (Saturated)
Fluid circulating on the tube side	Spent liquor	Spent liquor
Specific gravity of liquor	1.148-1.24	1.148-1.24
Caustic concentration of liquor, gpl	185-225	185-225
Number of passes on shell side	1	1
Number of passes on tube side	6	6
Total number of tubes	192	522
Tube size	32mm O.D.,7.32m long,12BWG	32 mm O.D. 7.32m long,12 BWG
Tube pitch, mm	44.5 (triangular)	44.5 (triangular)
Heat transfer area based on outside diameter, m^2	140.1	380.9
Shell material	Cast steel	Cast steel
Shell side pressure, kgf/cm^2 (gauge)	0.9-24.0	0.9-24.0

Appendix 3.1

COST OF STEAM PER TONNE

Following average monthly values have been obtained from records of boiler house, central stores and Accounts department.

Cost of 12000 tonnes of coal consumed per month at the rate of Rs 130 per tonne	Rs 15,60,000
Cost of material supplied from the stores	Rs 1,51,000
Depreciation charges	Rs 2,01,000
Salary of workers and supervisory staff	Rs 1,42,000
Fringe benefits	Rs 60,900
Cost of power	Rs 1,87,000
Workshop Cost (1/3 rd of the total cost incurred in the workshop is charged to alumina plant and 1/6th of the amount charged to alumina plant is charged to boiler house)	Rs 2,900
Laboratory cost (Cost incurred in laboratory is fully charged to alumina plant and 1/6th of this amount is charged to boiler house)	Rs 3,150
Total monthly cost incurred in the boiler house	Rs 23,07,950

Average monthly steam generation rate = 78, 000 t

Cost of steam per tonne $= \frac{2307950}{78000}$

= Rs 29.59

Say Rs 30 per tonne.

Appendix 4.1

CHARGING TIME DATA FOR OLD UNIT PUMPS FROM DECEMBER 1974 TO MAY 1975

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
1	3	480	40	Plant trouble (Power failure)
2	3	395	20	Pump trouble
3	3	85	15	Plant trouble (Steam shortage)
4	3	215	0	Pump trouble
5	1	485	12	Plant trouble (Steam shortage)
6	1	308	45	Plant trouble (Steam shortage)
7	1	75	10	Plant trouble (Steam shortage)
8	1	135	10	Pump trouble
9	1	10	10	Pump trouble
10	3	1245	20	Pump trouble
11	1	655	15	Pump trouble
12	3	85	15	Pump trouble
13	2	55	35	Plant trouble (Trouble in flash tank)
14	2	100	40	Pump trouble
15	2	40	75	Pump trouble
16	1	225	32	Pump trouble
17	2	1503	20	Pump trouble
18	2	160	20	Pump trouble
19	1	230	20	Plant trouble (Steam shortage)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
20	1	610	5455	Plant trouble (Plant S/D)
21	1	105	30	Pump trouble
22	3	160	10	Pump trouble
23	3	70	0	Pump trouble
24	1	75	20	Plant trouble (Steam shortage)
25	1	245	20	Pump trouble
26	2	270	30	Plant trouble (Steam shortage)
27	2	10	10	Pump trouble
28	3	370	30	Pump trouble
29	1	395	0	Pump trouble
30	3	350	0	Pump trouble
31	2	195	30	Pump trouble
32	1	770	10	Pump trouble
33	2	230	15	Pump trouble
34	3	120	70	Pump trouble
35	1	355	12	Pump trouble
36	3	598	0	Pump trouble
37	2	770	15	Pump trouble
38	1	285	75	Planttrouble (Erosion leakage)
39	1	635	0	Pump trouble
40	3	225	220	Pump trouble
41	2	725	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
42	1	35	50	Plant trouble (Precipitation trouble)
43	1	615	10	Pump trouble
44	1	597	1668	Plant trouble (Steam shortage)
45	1	85	137	Plant trouble (Flash tank trouble)
46	1	268	13	Plant trouble (Steam trouble)
47	1	107	5	Pump trouble
48	1	490	0	Pump trouble
49	3	280	5	Pump trouble
50	1	5	15	Pump trouble
51	1	80	0	Pump trouble
52	2	100	30	Pump trouble
53	2	45	35	Pump trouble
54	2	105	1280	Plant trouble (Plugging in digester area)
55	2	490	25	Pump trouble
56	1	1545	0	Pump trouble
57	3	5	10	Pump trouble
58	2	355	20	Pump trouble
59	1	485	10	Pump trouble
60	2	1040	10	Pump trouble
61	3	15	1080	Plant trouble (Plugging in flash tank)
62	1	60	10	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
63	1	30	0	Pump trouble
64	2	210	15	Pump trouble
65	2	405	790	Plant trouble (Low condensate level)
66	2	650	0	Pump trouble
67	3	145	10	Pump trouble
68	1	705	8	Pump trouble
69	2	152	33	Pump trouble
70	3	2	35	Pump trouble
71	1	570	10	Pump trouble
72	1	300	0	Pump trouble
73	2	585	10	Pump trouble
74	3	30	10	Pump trouble
75	3	130	0	Pump trouble
76	1	665	10	Pump trouble
77	3	190	35	Pump trouble
78	2	35	70	Pump trouble
79	1	60	105	Pump trouble
80	2	785	0	Pump trouble
81	1	950	15	Plant trouble (Steam shortage)
82	1	15	0	Pump trouble
83	2	20	10	Pump trouble
84	2	80	205	Plant trouble (Erosion leakage)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
85	2	220	20	Pump trouble
86	1	50	10	Pump trouble
87	1	95	7	Pump trouble
88	3	183	20	Pump trouble
89	2	600	230	Plant trouble (Steam shortage)
90	2	105	10	Pump trouble
91	2	180	695	Plant trouble (Steam shortage)
92	1	1715	10	Pump trouble
93	2	40	145	Pump trouble
94.	1	770	0	Pump trouble
95.	2	540	0	Pump trouble
96	1	45	15	Pump trouble
97	1	200	50	Plant trouble (Steam shortage)
98	1	20	12	Plant trouble (Steam shortage)
99	1	73	11315	Plant trouble (Shut down)
100	1	210	135	Plant trouble (Erosion leakage)
101	1	255	1440	Plant trouble (Steam line maintenance)
102	1	190	105	Plant trouble (Erosion leakage)
103	1	157	18	Pump trouble
104	2	85	10	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
105	2	620	15	Plant trouble (No slurry)
106	2	20	85	Plant trouble (No slurry)
107	1	45	0	Pump trouble
108	5	205	0	Pump trouble
109	1	785	0	Pump trouble
110	5	45	130	Plant trouble (Steam shortage)
111	5	25	20	Plant trouble (Steam shortage)
112	5	35	40	Plant trouble (Steam shortage)
113	5	15	0	Pump trouble
114	2	275	1395	Plant trouble (Erosion leakage)
			600	Plant trouble (Steam shortage)
115	2	120	30	Plant trouble (Steam shortage)
116	2	90	25	Plant trouble (Steam shortage)
117	2	155	105	Plant trouble (Steam shortage)
118	2	175	25	Pump trouble
119	1	130	10	Pump trouble
120	1	530	1940	Plant trouble (Steam shortage)
121	2	780	375	Plant trouble (Erosion leakage)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
122	2	340	90	Plant trouble (Steam shortage)
123	2	55	15	Plant trouble (Steam shortage)
124	2	205	0	Pump trouble
125	1	2	8	Pump trouble
126	1	200	10	Pump trouble
127	1	185	0	Pump trouble
128	2	535	0	Pump trouble
129	1	545	75	Plant trouble (Steam shortage)
130	1	220	1155	Plant trouble (Steam shortage)
131	1	160	20	Pump trouble
132	2	185	0	Pump trouble
133	1	95	15	Pump trouble
134	2	255	0	Pump trouble
135	1	165	45	Pump trouble
136	1	120	10	Pump trouble
137	1	1770	0	Pump trouble
138	2	30	175	Plant trouble (Erosion Leakage)
139	1	950	35	Plant trouble (Steam shortage)
140	1	60	0	Pump trouble
141	2	305	35	Pump trouble
142	1	1675	1540	Plant trouble (Steam shortage)

Charging Cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
143	1	30	215	Plant trouble (Steam shortage)
144	1	1240	10	Plant trouble (Steam shortage)
145	1	90	45	Pump trouble
146	2	935	5	Pump trouble
147	1	335	10	Plant trouble (Steam shortage)
148	1	10	20	Plant trouble (Steam shortage)
149	1	720	0	Pump trouble
150	2	585	12	Pump trouble
151	1	88	10	Plant trouble (Steam shortage)
152	1	495	0	Pump trouble
153	2	410	20	Pump trouble
154	1	45	18	Pump trouble
155	1	2	75	Pump trouble
156	2	228	12	Plant trouble (Steam shortage)
157	2	645	10	Pump trouble
158	2	140	100	Plant trouble (Erosion leakage)
159	2	5	25	Pump trouble
160	1	330	15	Pump trouble
161	2	315	60	Plant trouble (Steam shortage)
162	2	1025	215	Plant trouble (Precipitation trouble)
163	1	600	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
164	2	280	125	Plant trouble (Erosion leakage)
165	2	485	20	Pump trouble
166	1	1460	10	Pump trouble
167	2	35	23	Plant trouble (Steam shortage)
168	2	2392	0	Pump trouble
169	1	955	20	Pump trouble
170	2	157	15	Pump trouble
171	1	100	15	Plant trouble (Steam shortage)
172	1	405	0	Pump trouble
173	2	1215	0	Pump trouble
174	1	510	25	Pump trouble
175	2	250	15	Pump trouble
176	1	25	60	Pump trouble
			15	Plant trouble (Steam shortage)
177	1	255	0	Pump trouble
178	2	160	10	Pump trouble
179	2	1085	15	Pump trouble
180	1	970	100	Plant trouble (Erosion Leakage)
181	1	20	10	Pump trouble
182	2	480	0	Pump trouble
183	1	480	0	Pump trouble
184	2	565	32	Pump trouble
			18	Plant trouble (Bauxite shortage)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
185	1	165	15	Pump trouble
186	2	180	0	Pump trouble
187	1	30	125	Plant trouble (Flash tank leakage)
188	1	885	10	Pump trouble
189	2	35	45	Pump trouble
190	2	145	15	Pump trouble
191	2	30	25	Pump trouble
192	1	65	60	Pump trouble
193	2	845	20	Pump trouble
194	1	290	15	Pump trouble
195	2	5	115	Plant trouble (Erosion leakage)
196	2	70	120	Pump trouble
197	1	185	0	Pump trouble
198	2	175	100	Pump trouble
199	1	400	18	Pump trouble
200	2	302	15	Pump trouble
201	1	340	155	Plant trouble (Erosion leakage)
202	1	490	7	Pump trouble
203	2	373	240	Plant trouble (Erosion leakage)
204	1	655	0	Pump trouble
205	2	205	5	Pump trouble
206	2	5	5	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
207	2	230	5	Pump trouble
208	1	400	10	Pump trouble
209	2	195	5	Pump trouble
210	1	540	0	Pump trouble
211	2	225	0	Pump trouble
212	1	50	110	Pump trouble
213	2	50	15	Pump trouble
214	1	320	8	Pump trouble
215	2	17	20	Pump trouble
216	2	140	10	Pump trouble
217	1	15	30	Pump trouble
218	1	125	20	Plant trouble (Low slurry level)
219	1	270	3675	Plant trouble (Ball mill No.2 down)
220	1	320	30	Pump trouble
221	1	35	30	Pump trouble
222	2	200	10	Pump trouble
223	1	545	0	Pump trouble
224	2	255	0	Pump trouble
225	3	615	10	Plant trouble (Steam shortage)
226	3	25	230	Plant trouble (Steam shortage)
227	3	185	0	Pump trouble
228	1	430	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
229	3	110	10	Plant trouble (Charge pump trouble)
230	3	1175	10	Plant trouble (Steam shortage)
231	3	1332	3	Plant trouble (Charge pump trouble)
232	3	30	155	Plant trouble (Injection pump trouble)
233	3	1080	0	Pump trouble
234	1	375	0	Pump trouble
235	2	40	80	Pump trouble
236	1	410	0	Pump trouble
237	3	120	165	Plant trouble (Steam shortage)
238	3	290	0	Pump trouble
239	1	330	1425	Plant trouble (Steam shortage)
240	1	870	30	Pump trouble
241	3	315	315	Plant trouble (Steam shortage)
242	3	50	10	Pump trouble
243	1	120	0	Pump trouble
244	2	180	25	Pump trouble
245	1	85	20	Pump trouble
246	3	300	10	Pump trouble
247	1	360	140	Plant trouble (Erosion leakage)
248	3	500	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging Loss mts.	Remarks
249	2	315	10	Pump trouble
250	3	15	0	Pump trouble
251	2	105	10	Pump trouble
252	3	60	0	Pump trouble
253	2	342	8	Pump trouble
254	3	175	0	Pump trouble
255	1	90	0	Pump trouble
256	3	240	0	Pump trouble
257	1	180	0	Pump trouble
258	2	225	15	Pump trouble
259	3	105	120	Plant trouble (Erosion leakage)
260	3	600	0	Pump trouble
261	1	870	15	Plant trouble (Charge pump tripped)
262	1	1020	10	Pump trouble
263	3	365	10	Plant trouble (Steam shortage)
264	3	95	0	Pump trouble
265	1	760	0	Pump trouble
266	3	95	0	Pump trouble
267	1	675	1000	Plant trouble (Steam shortage)
268	3	1760	10	Pump trouble
269	2	105	0	Pump trouble
270	3	430	7	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
			5	Plant trouble (Steam shortage)
271	1	388		
			10	Pump trouble
272	1	755		
			4785	Plant trouble (Power failure)
273	1	35		
			780	Plant trouble (Low condensate level)
			110	Plant trouble (Steam shortage)
274	1	320		
			20	Pumptrouble
275	1	245		
			5	Pump trouble
276	3	200		
			0	Pump trouble
277	3	435		
			5	Pump trouble
278	2	425		
			8	Pump trouble
279	2	442		
			0	Pump trouble
280	2	5		
			0	Pump trouble
281	1	200		
			110	Plant trouble (Steam shortage)
282	3	320		
			40	Plant trouble (Steam shortage)
283	3	30		
			10	Pump trouble
284	3	2195		
			10	Pump trouble
285	2	585		
			40	Pump trouble
286	3	175		
			95	Pump trouble
287	2	35		
			0	Pump trouble
288	3	1090		
			0	Pump trouble
289	2	180		
			0	Pump trouble
290	3	720		

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
291	2	65	10	Pump trouble
292	2	165	35	Pump trouble
293	2	70	0	Pump trouble
294	3	770	20	Pump trouble
295	2	260	0	Pump trouble
296	3	780	15	Pump trouble
2 97	2	10	35	Pump trouble
298	2	65	50	Pump trouble
299	3	260	0	Pump trouble
300	2	847	3	Pump trouble
301	2	80	0	Pump trouble
302	3	165	75	Pump trouble
303	2	250	165	Pump trouble
304	2	95	15	Pump trouble
305	3	940	15	Pump trouble
306	2	1040	15	Pump trouble
307	3	690	0	Pump trouble
308	2	570	10	Pump trouble
309	3	1275	0	Pump trouble
310	2	175	0	Pump trouble
311	3	295	0	Pump trouble
312	2	810	0	Pump trouble
313	3	1095	0	Pump trouble
314	2	745		

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
315	3	230	90	Pump trouble
316	2	115	10	Pump trouble
317	2	340	10	Plant trouble (Booster pump tripped)
318	2	125	0	Pump trouble
319	1	1130	0	Pump trouble
320	2	130	0	Pump trouble
321	3	220	10	Plant trouble (Booster pump tripped)
322	3	1250	0	Pump trouble
323	1	230	105	Pump trouble
324	1	1920	40	Plant trouble (Low test tank level)
325	1	745	10	Pump trouble
326	2	1300	20	Pump trouble
327	3	215	15	Pump trouble
328	3	400	0	Pump trouble
329	1	155	0	Pump trouble
330	3	455	10	Pump trouble
331	2	535	0	Pump trouble
332	1	20	0	Pump trouble
333	2	10	0	Pump trouble
334	1	35	0	Pump trouble
335	3	730	15	Pump trouble
336	1	995	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
337	3	1615	0	Pump trouble
338	1	1995	0	Pump trouble
339	3	80	10	Pump trouble
340	1	1025	0	Pump trouble
341	3	215	35	Pump trouble
342	3	110	10	Plant trouble (Steam shortage)
343	3	265	0	Pump trouble
344	1	570	220	Plant trouble (Erosion leakage)
345	1	545	155	Plant trouble (Erosion leakage)
346	1	710	0	Pump trouble
347	3	120	25	Pump trouble
348	3	320	5	Plant trouble (Steam shortage)
349	3	740	0	Pump trouble
350	1	555	5	Pump trouble
351	3	785	5	Pump trouble
352	3	90	45	Plant trouble (Steam shortage)
353	3	280	0	Pump trouble
354	1	15	10	Pump trouble
355	1	460	720	Plant trouble (Erosion leakage)
356	1	295	100	Plant trouble (Erosion leakage)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
357	1	272	18	Plant trouble (Steam shortage)
358	1	185	0	Pump trouble
359	3	905	0	Pump trouble
360	1	115	0	Pump trouble
361	3	233	47	Plant trouble (Steam shortage)
362	3	5	255	Plant trouble (Steam shortage)
363	3	135	45	Plant trouble (Steam shortage)
364	3	255	0	Pump trouble
365	1	280	55	Pump trouble
366	3	325	35	Plant trouble (Steam shortage)
367	3	145	0	Pump trouble
368	1	2485	0	Pump trouble
369	3	695	0	Pump trouble
370	1	565	20	Pump trouble
371	3	70	0	Pump trouble
372	1	447	5	Plant trouble (Booster pump tripped)
373	1	143	0	Pump trouble
374	3	835	840	Plant trouble (Erosion leakage)
375	1	615	0	Pump trouble
376	3	65	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
377	1	1029	11	Pump trouble
378	3	670	15	Pump trouble
379	1	445	0	Pump trouble
380	3	375	0	Pump trouble
381	1	95	0	Pump trouble
382	3	5	0	Pump trouble
383	1	95	0	Pump trouble
384	3	750	0	Pump trouble
385	1	95	20	Plant trouble (Steam shortage)
386	1	765	0	Pump trouble
387	3	320	45	Plant trouble (Steam shortage)
388	3	45	335	Plant trouble (Erosion leakage)
389	3	1430	0	Pump trouble
390	1	1300	595	Plant trouble (Erosion leakage)
391	1	1380	1620	Plant trouble (Steam shortage)
392	3	390	0	Pump trouble
393	3	915	75	Pump trouble
394	3	400	275	Plant trouble (Steam shortage)
395	1	825	0	Pump trouble
396	1	855	75	Plant trouble (Booster pump trouble)
			50	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
397	3	70	5	Pump trouble
398	3	280	0	Pump trouble
399	1	165	0	Pump trouble
400	3	70	20	Plant trouble (Steam shortage)
401	3	55	0	Pump trouble
402	1	230	45	Plant trouble (Steam shortage)
403	1	45	20	Plant trouble
404	1	265	0	Pump trouble
405	3	340	5	Pump trouble
406	1	295	0	Pump trouble
407	3	380	30	Plant trouble (Steam shortage)
408	3	25	35	Plant trouble (Steam shortage)
409	3	10	15	Plant trouble (Steam shortage)
410	3	830	0	Pump trouble
411	1	825	60	Plant trouble (Steam shortage)
412	1	850	0	Pump trouble
413	3	295	15	Pump trouble
414	3	70	0	Pump trouble
415	1	1035	5235	Plant trouble (Steam shortage)
416	3	800	55	Plant trouble (Low air pressure)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
417	3	240	0	Pump trouble
418	1	55	20	Pump trouble
419	1	240	10	Pump trouble
420	3	160	12	Pump trouble
421	1	673	0	Pump trouble
422	3	225	0	Pump trouble
423	1	260	17	Pump trouble
424	3	378	35	Pump trouble
425	1	85	20	Plant trouble (Steam shortage)
426	1	435	0	Pump trouble
427	3	525	10	Pump trouble
428	1	200	7	Pump trouble
429	3	283	25	Plant trouble (Steam shortage)
430	3	165	0	Pump trouble
431	1	565	0	Pump trouble
432	3	80	15	Pump trouble
433	3	215	0	Pump trouble
434	1	280	0	Pump trouble
435	3	370	0	Pump trouble
436	1	320	0	Pump trouble
437	3	375	0	Pump trouble
438	1	255	0	Pump trouble
439	3	210	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
440	1	280	0	Pump trouble
441	3	215	85	Plant trouble (Steam shortage)
442	3	280	10	Pump trouble
443	1	720	0	Pump trouble
444	3	70	120	Plant trouble (Erosion leakage)
445	3	245	0	Pump trouble
446	1	195	10	Pump trouble
447	3	290	0	Pump trouble
448	1	60	110	Plant trouble (Steam shortage)
449	1	860	0	Pump trouble
450	3	192	8	Pump trouble
451	3	735	0	Pump trouble
452	1	220	0	Pump trouble
453	3	565	15	Plant trouble (Steam shortage)
454	3	1185	15	Pump trouble
455	1	805	0	Pump trouble

Appendix 4.2

CHARGING TIME DATA FOR NEW UNIT PUMPS

FROM DECEMBER 1974 TO MAY 1975

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
1	5	720	5	Pump trouble
2	5	35	55	Pump trouble
3	5	160	20	Plant trouble (Steam shortage)
4	4	405	30	Plant trouble (Power failure)
5	4	170	35	Pump trouble (Slurry line under maintenance)
6	5	980	20	Pump trouble
7	4	0	30	Plant trouble (Steam shortage)
8	4	185	7	Pump trouble
9	4	143	10	Pump trouble
10	4	570	5	Pump trouble
11	4	0	5	Plant trouble (Steam shortage)
12	4	180	20	Pump trouble (Leakage)
13	5	1090	0	Pump trouble
14	4	30	0	Pump trouble
15	5	640	10	Pump trouble
16	5	135	85	Pump trouble
17	5	5	25	Plant trouble (Steam shortage)
18	5	975	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
19	4	425	10	Pump trouble
20	4	200	15	Plant trouble (cleaning slurry line of S.H. tank)
21	4	430	0	Pump trouble
22	5	705	0	Pump trouble
23	4	1055	0	Pump trouble
24	5	30	20	Pump trouble
25	4	785	10	Pump trouble
26	5	1220	20	Pump trouble
27	5	182	8	Plant trouble (steam shortage)
28	5	350	0	Pump trouble
29	4	50	0	Pump trouble
30	5	90	90	Pump trouble
31	5	505	20	Plant trouble (Steam shortage)
32	5	345	0	Pump trouble
33	4	155	0	Pump trouble
34	5	9	4	Pump trouble (Leakage)
35	5	837	650	Plant trouble (Flash tank No.4 outlet spool leakage)
36	5	630	0	Pump trouble
37	4	1725	0	Pump trouble
38	5	1620	10	Pump trouble
39	5	1170	0	Pump trouble
40	4	1220	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
63	5	130	100	Plant trouble (Steam shortage)
64	5	300	0	Pump trouble
65	4	1105	10	Pump trouble
66	4	235	70	Pump trouble
67	4	145	45	Pump trouble
68	4	60	0	Pump trouble
69	5	60	8	Plant trouble (Steam shortage)
70	5	2	12	Pump trouble
71	5	113	10	Plant trouble (Steam shortage)
72	5	340	5	Pump trouble
73	5	1040	0	Pump trouble
74	4	175	30	Plant trouble (Steam shortage)
75	4	205	0	Pump trouble
76	5	115	55	Plant trouble (Steam shortage)
77	5	65	30	Plant trouble (Steam shortage)
78	5	1330	0	Pump trouble
79	4	1435	15	Plant trouble (Air trouble)
80	4	1135	0	Pump trouble
81	5	920	5	Plant trouble (Mech. Maintenance)
82	5	65	55	Plant trouble (Steam shortage)
83	5	10	50	Plant trouble (Steam shortage)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
84	5	535	100	Plant trouble (Steam shortage)
85	5	915	0	Pump trouble
86	4	625	0	Pump trouble
87	5	695	90	Plant trouble(High F.E. A/C)
88	5	535	5	Plant trouble (Steam shortage)
89	5	1065	0	Pump trouble
90	4	1410	25	Plant trouble (Steam shortage)
91	4	200	8695	Plant trouble (Planned shut down)
92	4	285	0	Pump trouble
93	5	795	0	Pump trouble
94	4	90	7	Pump trouble
95	4	993	35	Pump trouble
96	4	582	0	Pump trouble
97	5	393	110	Plant trouble(Steam shortage)
98	5	40	20	Plant trouble (Steam shortage)
99	5	1595	20	Plant trouble (Steam shortage)
100	5	35	85	Plant trouble (Steam shortage)
101	5	155	0	Pump trouble
102	4	125	240	Plant trouble (Steam shortage)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
103	4	1895	10	Plant trouble(Steam shortage)
104	4	2020	0	Pump trouble
105	5	960	10	Plant trouble (Steam shortage)
106	5	390	10	Plant trouble(Steam shortage)
107	5	325	25	Plant trouble(Steam shortage)
108	5	5	25	Plant trouble(Steam shortage)
109	5	1385	10	Plant trouble(Steam shortage)
110	5	1035	0	Pump trouble
111	4	1550	0	Pump trouble
112	5	1790	30	Plant trouble(Steam shortage)
113	5	250	0	Pump trouble
114	4	1160	20	Plant trouble(Steam shortage)
115	4	940	35	Pump trouble
116	5	310	15	Plant trouble (Steam shortage)
117	5	1235	30	Pump trouble
118	4	315	95	Plant trouble(Steam shortage)
119	5	15	0	Pump trouble
120	4	15	10	Plant trouble (Steam shortage)
121	4	140	20	Pump trouble
122	5	1645	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
123	4	385	15	Pump trouble
124	5	1780	0	Pump trouble
125	4	175	35	Plant trouble (Steam shortage)
126	4	540	0	Pump trouble
127	5	2950	0	Pump trouble
128	4	55	0	Pump trouble
129	5	20	5	Pump trouble
130	4	415	0	Pump trouble
131	5	75	15	Plant trouble (Steam shortage)
132	5	70	20	Plant trouble (Steam shortage)
133	5	1425	0	Pump trouble
134	4	1315	0	Pump trouble
135	5	200	10	Pump trouble
136	5	10	25	Pump trouble
137	4	365	5	Pump trouble
138	4	55	15	Pump trouble
139	5	935	20	Plant trouble (Steam shortage)
140	5	1685	115	Pump trouble
141	5	1170	0	Pump trouble
142	4	60	0	Pump trouble
143	5	740	0	Pump trouble
144	4	35	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
145	5	110	0	Pump trouble
146	4	180	15	Pump trouble
147	5	1315	0	Pump trouble
148	4	290	0	Pump trouble
149	5	1170	0	Pump trouble
150	4	820	0	Pump trouble
151	5	657	10	Pump trouble (Tightening the gland)
152	5	3358	0	Pump trouble
153	4	965	77	Pump trouble (Erosion leakage in slurry discharge line of the pump)
154	5	818	0	Pump trouble
155	4	2290	10	Pump trouble
156	5	940	0	Pump trouble
157	4	270	0	Pump trouble
158	5	40	0	Pump trouble
159	4	240	15	Plant trouble (Air failure)
160	4	725	40	Pump trouble (Erosion leakage in slurry discharge line of the pump)
161	5	1555	0	Pump trouble
162	4	190	30	Pump trouble
163	4	590	50	Pump trouble
164	5	1165	0	Pump trouble
165	4	280	135	Pump trouble
166	5	45	80	Plant trouble (Steam shortage)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
167	5	1960	0	Pump trouble
168	4	765	0	Pump trouble
169	5	580	0	Pump trouble
170	4	380	55	Pump trouble
171	4	880	15	Pump trouble (Leakage)
172	5	590	20	Plant trouble (Steam shortage)
173	5	320	0	Pump trouble
174	4	45	15	Pump trouble
175	4	15	10	Plant trouble (Steam shortage)
176	4	490	5	Pump trouble
177	4	275	0	Pump trouble
178	5	590	20	Plant trouble (Steam shortage)
179	5	75	10	Plant trouble (Steam shortage)
180	5	20	75	Plant trouble (Steam shortage)
181	5	1005	0	Pump trouble
182	4	1150	0	Pump trouble
183	5	790	150	Plant trouble (Erosion leakage in F.TK.No.2 down block valve)
184	5	7	163	Plant trouble (Steam shortage)
185	5	130	0	Pump trouble
186	4	35	25	Plant trouble (Steam shortage)
187	4	240	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
188	5	325	5	Pump trouble
189	5	60	0	Pump trouble
190	4	305	0	Pump trouble
191	5	630	15	Pump trouble
192	4	105	15	Pump trouble
193	4	375	20	Pump trouble
194	5	150	5	Pump trouble
195	5	70	15	Plant trouble(Steam shortage)
196	5	5	190	Pump trouble
197	4	377	83	Pump trouble(Leakage)
198	4	300	25	Plant trouble (Steam shortage)
199	4	230	0	Pump trouble
200	5	1845	0	Pump trouble
201	4	695	0	Pump trouble
202	5	985	15	Plant trouble(Steam shortage)
203	5	100	5	Plant trouble(Steam shortage)
204	5	95	5	Plant trouble(Steam shortage)
205	5	25	10	Plant trouble(Steam shortage)
206	5	50	40	Plant trouble(Steam Shortage)
207	5	1885	15	Plant trouble(Steam shortage)
208	5	165	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
209	4	1605	0	Pump trouble
210	5	575	160	Plant trouble (Steam shortage)
211	5	20	40	Plant trouble (Steam shortage)
212	5	550	65	Plant trouble (Steam shortage)
213	5	15	10	Plant trouble (Steam shortage)
214	5	125	25	Plant trouble (Steam shortage)
215	5	175	15	Pump trouble
216	5	1500	0	Pump trouble
217	4	1350	0	Pump trouble
218	5	80	20	Plant trouble (Steam shortage)
219	5	528	5127	Plant trouble (Power failure at Renu Sagar)
220	4	660	25	Pump trouble
221	4	185	0	Pump trouble
222	5	2600	100	Plant trouble (Steam shortage)
223	5	35	40	Plant trouble (Steam shortage)
224	5	2240	0	Pump trouble
225	4	502	0	Pump trouble
226	5	2308	0	Pump trouble
227	4	30	0	Pump trouble
228	5	767	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
229	4	653	0	Pump trouble
230	5	1280	0	Pump trouble
231	4	15	0	Pump trouble
232	5	1225	0	Pump trouble
233	4	25	0	Pump trouble
234	5	850	0	Pump trouble
235	4	525	20	Pump trouble
236	5	45	40	Plant trouble (Booster pump trouble)
237	5	470	0	Pump trouble
238	4	80	0	Pump trouble
239	5	475	0	Pump trouble
240	4	665	25	Plant trouble (Steam shortage)
241	4	610	10	Plant trouble (Steam shortage)
242	4	305	0	Pump trouble
243	5	635	0	Pump trouble
244	4	500	35	Pump trouble
245	5	2800	0	Pump trouble
246	4	350	0	Pump trouble
247	5	375	15	Plant trouble (Steam shortage)
248	5	570	0	Pump trouble
249	4	600	0	Pump trouble
250	5	1800	0	Pump trouble
251	4	265	0	Pump trouble
252	5	1175	0	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
253	4	155	0	Pump trouble
254	5	385	0	Pump trouble
255	4	1180	0	Pump trouble
256	5	3060	0	Pump trouble
257	4	980	0	Pump trouble
258	5	795	0	Pump trouble
259	4	100	0	Pump trouble
260	5	1035	0	Pump trouble
261	4	1085	45	Pump trouble
262	5	270	15	Pump trouble
263	4	1222	15	Pump trouble
264	5	128	5	Plant trouble (Steam shortage)
265	5	2940	10	Plant trouble (Steam shortage)
266	5	255	0	Pump trouble
267	4	548	0	Pump trouble
268	5	1372	70	Plant trouble (Steam shortage)
269	5	240	30	Plant trouble (S/D by mistake)
270	5	387	0	Pump trouble
271	4	383	0	Pump trouble
272	5	220	10	Plant trouble (Steam shortage)
273	5	850	15	Plant trouble (Steam shortage)
274	5	55	0	Plant trouble (Steam shortage)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
275	4	640	0	Pump trouble
276	5	125	10	Plant trouble (Steam shortage)
277	5	60	545	Plant trouble (Steam shortage)
278	5	15	35	Plant trouble (Steam shortage)
279	5	15	75	Plant trouble (Steam shortage)
280	5	370	35	Plant trouble (Steam shortage)
281	5	685	0	Pump trouble
282	4	180	25	Plant trouble (Steam shortage)
283	4	205	15	Plant trouble (Steam shortage)
284	4	985	10	Plant trouble (Steam shortage)
285	4	1380	15	Pump trouble
286	4	95	10	Pump trouble
287	4	10	8	Pump trouble
288	5	4207	0	Pump trouble
289	4	832	0	Pump trouble
290	5	2108	0	Pump trouble
291	4	625	35	Plant trouble (Steam shortage)
292	4	165	0	Pump trouble
293	5	470	640	Plant trouble (Bearing trouble in Charge pump)

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
294	4	1507	0	Pump trouble
295	5	863	0	Pump trouble
296	4	1080	0	Pump trouble
297	5	530	0	Pump trouble
298	4	1300	0	Pump trouble
299	5	1927	0	Pump trouble
300	4	143	0	Pump trouble
301	5	615	52	Plant trouble (Steam shortage)
302	5	223	5	Plant trouble (Steam shortage)
303	5	560	0	Pump trouble
304	4	1275	0	Pump trouble
305	5	940	15	Plant trouble (Steam shortage)
306	5	1740	80	Plant trouble (Steam shortage)
307	5	325	95	Plant trouble (Steam shortage)
308	5	30	55	Plant trouble (Steam shortage)
309	5	730	0	Pump trouble
310	4	55	230	Plant trouble (Erosion leakage)
311	4	115	10	Plant trouble (Steam shortage)
312	4	1030	0	Pump trouble
313	5	2635	0	Pump trouble
314	4	210	10	Pump trouble

Charging cycle No.	Pump No.	Charging time mts.	Charging loss mts.	Remarks
315	4	835	0	Pump trouble
316	5	950	40	Plant trouble (Steam shortage)
317	5	1470	0	Pump trouble
318	4	2297	13	Pump trouble
319	5	260	20	Pump trouble
320	4	1015	0	Pump trouble
321	5	1365	0	Pump trouble
322	4	445	110	Plant trouble (Steam shortage)
323	4	755	0	Pump trouble
324	5	3735	0	Pump trouble
325	4	200	90	Plant trouble (Steam shortage)
326	4	1035	0	Pump trouble
327	5	195	45	Plant trouble (Steam shortage)
328	5	4225	0	Pump trouble

Appendix 4.3

RUNNING TIME FOR SLURRY INJECTION PUMPS

1. PUMP No.1

Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts
1	1013	21	1715	41	510	61	410
2	655	22	770	42	280	62	1200
3	225	23	1150	43	990	63	120
4	945	24	45	44	480	64	85
5	320	25	785	45	165	65	360
6	395	26	660	46	915	66	90
7	770	27	387	47	65	67	180
8	355	28	925	48	290	68	1890
9	920	29	95	49	185	69	760
10	2197	30	2055	50	400	70	675
11	85	31	1010	51	830	71	1743
12	1545	32	3035	52	655	72	200
13	485	33	1065	53	400	73	1130
14	90	34	583	54	540	74	2895
15	705	35	47	55	50	75	155
16	870	36	330	56	320	76	20
17	665	37	600	57	765	77	35
18	60	38	1460	58	545	78	995
19	965	39	955	59	430	79	1995
20	145	40	505	60	375	80	1025

Appendix 4.3 (contd.)

Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts
81	1825	90	1029	99	1675	108	320
82	555	91	445	100	1035	109	255
83	1227	92	45	101	295	110	280
84	115	93	860	102	673	111	720
85	280	94	2680	103	260	112	195
86	2485	95	1680	104	520	113	920
87	565	96	165	105	200	114	220
88	590	97	540	106	565	115	805
89	615	98	295	107	280		

2. PUMP NO.2

Pump cycle No.	Running time mts	Pump Cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts
1	195	11	1265	21	815	31	1018
2	1663	12	152	22	1380	32	1340
3	280	13	585	23	535	33	765
4	195	14	35	24	185	34	2427
5	230	15	785	25	255	35	157
6	770	16	320	26	30	36	1215
7	725	17	885	27	305	37	250
8	740	18	40	28	935	38	1245
9	355	19	540	29	585	39	480
10	1040	20	725	30	410	40	565

Appendix 4.3 (contd.)

Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts
41	180	51	50	61	105	71	1040
42	210	52	157	62	872	72	570
43	845	53	200	63	585	73	175
44	75	54	255	64	35	74	810
45	175	55	40	65	180	75	745
46	302	56	180	66	300	76	580
47	373	57	315	67	260	77	130
48	440	58	105	68	75	78	1300
49	195	59	342	69	927	79	535
50	225	60	225	70	345	80	10

3. PUMP No.3

Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts
1	1175	11	5	21	365	31	1760
2	1245	12	15	22	300	32	430
3	85	13	145	23	500	33	635
4	230	14	2	24	15	34	2545
5	370	15	160	25	60	35	175
6	350	16	190	26	175	36	1090
7	120	17	183	27	240	37	720
8	598	18	825	28	705	38	770
9	225	19	3727	29	460	39	780
10	280	20	410	30	95	40	260

Appendix 4.3 (contd.)

Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts
29	155	46	280	63	25	80	2855
30	385	47	765	64	525	81	832
31	715	48	1260	65	80	82	790
32	55	49	825	66	1580	83	1507
33	415	50	1150	67	500	84	1080
34	1315	51	275	68	350	85	1300
35	420	52	305	69	600	86	143
36	60	53	480	70	265	87	1275
37	35	54	907	71	155	88	1200
38	180	55	695	72	1180	89	1045
39	290	56	1605	73	980	90	2297
40	820	57	1350	74	100	91	1015
41	965	58	845	75	1085	92	1200
42	2290	59	502	76	1222	93	1235
43	270	60	30	77	548		
44	965	61	653	78	383		
45	780	62	15	79	640		

5. PUMP No.5

Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts
1	915	5	785	9	1476	13	1510
2	980	6	30	10	2790	14	1350
3	1090	7	1752	11	1697	15	4415
4	1755	8	940	12	930	16	400

Appendix 4.3 (contd.)

Pump cycle No.	Running time mts	Pump cycle No.	Running time No.	Pump cycle No.	Running time mts	Pump cycle No.	Running time mts
17	970	37	740	57	2960	77	3323
18	2858	38	110	58	608	78	1999
19	430	39	1315	59	4875	79	1125
20	1555	40	1170	60	2309	80	1270
21	1510	41	4015	61	767	81	4207
22	2445	42	818	62	1280	82	2108
23	2295	43	940	63	1225	83	470
24	795	44	40	64	850	84	863
25	2218	45	1555	65	515	85	530
26	4100	46	1165	66	475	86	1927
27	2040	47	2005	67	635	87	1398
28	1545	48	580	68	2800	88	3765
29	15	49	910	69	945	89	2635
30	1645	50	1690	70	1800	90	2420
31	1780	51	927	71	1175	91	260
32	2950	52	385	72	385	92	1365
33	20	53	630	73	3060	93	3735
34	1570	54	225	74	795	94	4420
35	210	55	1845	75	1035		
36	3790	56	3305	76	270		

Appendix 4.4

RALIABILITY ANALYSIS FOR PUMPS

1. PUMP No.1

Class No.	Class interval mts.	t_i mts	Observed failures f_{oi}	Cumulative failures Σf_{oi}	Observed reliability R_{to}	Expected reliability $e^{-\lambda_i t_i}$	Expected failures f_{ei}	$\frac{(f_{ei}-f_{oi})^2}{f_{ei}}$
1	0-200	100	28	28	.7565	.7498	28.77	0.021
2	200-400	300	19	47	.5913	.5621	21.56	0.304
3	400-600	500	17	64	.4435	.4215	16.17	0.043
4	600-800	700	13	77	.3304	.3160	12.13	0.062
5	800-1000	900	13	90	.2174	.2369	9.10	1.671
6	1000-1200	1100	9	99	.1391	.1776	6.82	0.697
7	1200-1400	1300	1	100	.1304	.1332	5.11	
8	1400-1600	1500	2	102	.1130	.0998	3.34	
9	1600-1800	1700	4	106	.0782	.0749	2.86	0.823
10	1800-2000	1900	3	109	.0522	.0561	2.16	
11	2000-2200	2100	2	111	.0348	0421	1.61	
12	2200-2400	2300	0	111	.0348	.0316	1.21	
13	2400-2600	2500	1	112	.0261	.0237	0.91	
14	2600-2800	2700	1	113	.0174	.0177	0.69	0.149
15	2800-3000	2900	1	114	.0087	.0133	0.51	
16	3000-3200	3100	1	115	0	.0099	0.39	
17	>3200	-	0	115	0	0	1.14	

$X^2 = 3.770$

MTBF = 694.8 Minutes

say 695 minutes

Degrees of freedom 6

Probability of fit about 71 %.

λ_1 = .001439 failures per minute

= 756.3 failures per year

Appendix 4.4 (contd.)

2. PUMP No.2

Class No.	Class interval mts.	t_i mts.	Observed failures f_{oi}	Cumulative failures Σf_{oi}	Observed reliability R_{to}	Expected reliability $e^{-\lambda_i t_i}$	Expected failures f_{ei}	$(f_{ei}-f_{oi})^2$
1	0-200	100	25	25	.6875	.6730	26.16	0.051
2	200-400	300	18	43	.4625	.4529	17.61	0.009
3	400-600	500	12	55	.3125	.3048	11.85	0.002
4	600-800	700	7	62	.2250	.2051	7.98	0.120
5	800-1000	900	7	69	.1375	.1380	5.37	0.495
6	1000-1200	1100	3	72	.1000	.0929	3.61	1.475
7	1200-1400	1300	6	78	.0250	.0625	2.41	
8	1400-1600	1500	0	78	.0250	.0421	1.63	
9	1600-1800	1700	1	79	.0125	.0283	1.10	
10	1800-2000	1900	0	79	.0125	.0191	0.74	1.792
11	2000-2200	2100	0	79	.0125	.0128	0.50	
12	2200-2400	2300	0	79	.0125	.0066	0.34	
13	2400-2600	2500	1	80	0	.0058	0.22	
14	>2600	-	0	80	0	0	0.46	

MTBF = 505 minute ; X^2 = 3.944

Degrees of freedom 5

λ_2 = 0.001980 failures per minute

Probability of fit about 60 %.

= 1040.7 failures per year

Appendix 4.4 (contd.)

3. PUMP NO.3

Class No.	Class interval mts.	t_i mts.	Observed failures f_{oi}	Cumulative failures Σf_{oi}	Observed reliability R_{to}	Expected reliability $e^{-\lambda_i t_i}$	Expected failures f_{ei}	$\frac{(f_{ei}-f_{oi})^2}{f_{ei}}$
1	0-200	100	21	21	.7640	.7189	25.02	0.646
2	200-400	300	23	44	.5056	.5168	17.99	1.395
3	400-600	500	11	55	.3820	.3716	12.92	0.285
4	600-800	700	12	67	.2472	.2671	9.30	0.784
5	800-1000	900	5	72	.1910	.1920	6.68	0.423
6	1000-1200	1100	6	78	.1236	.1381	4.80	0.300
7	1200-1400	1300	3	81	.0899	.0993	3.45	0.059
8	1400-1600	1500	1	82	.0787	.0714	2.48	0.701
9	1600-1800	1700	5	87	.0225	.0513	1.79	
10	1800-2000	1900	0	87	.0225	.0369	1.28	
11	2000-2200	2100	0	87	.0225	.0265	0.93	
12	2200-2400	2300	0	87	.0225	.0191	0.66	
13	2400-2600	2500	1	88	.0112	.0137	0.48	
14	2600-2800	2700	0	88	.0112	.0099	0.34	1.442
15	2800-3000	2900	0	88	.0112	.0071	0.25	
16	3000-3200	3100	0	88	.0112	.0051	0.18	
17	3200-3400	3300	0	88	.0112	.0037	0.12	
18	3400-3600	3500	0	88	.0112	.0026	0.10	
19	3600-3800	3700	1	89	0	.0019	0.06	
20	>3800	-	0	89	0	0	0.17	

$\chi^2 = 6.035$

Degrees of freedom 7

Probability of fit about 60 %

MTBF = 607.87 minutes
say 608 minutes

λ_3 = .001645 failures per minute
= 864.6 failures per year

Appendix 4.4 (contd.)

4. PUMP NO.4

Class No.	Class Interval mts.	t_i mts.	Observed failures f_{oi}	Cumulative failures Σf_{oi}	Observed reliability R_{to}	Expected reliability $e^{-\lambda_i t_i}$	Expected failures f_{ei}	$\frac{(f_{ei}-f_{oi})^2}{f_{ei}}$
1	0-200	100	17	17	.8172	.7950	19.07	0.225
2	200-400	300	11	28	.6989	.6321	15.15	1.137
3	400-600	500	10	38	.5914	.5025	12.05	0.349
4	600-800	700	10	48	.4839	.3995	9.56	0.020
5	800-1000	900	8	56	.3978	.3177	7.61	0.020
6	1000-1200	1100	13	69	.2581	.2525	6.06	7.948
7	1200-1400	1300	8	77	.1720	.2008	4.81	2.116
8	1400-1600	1500	6	83	.1075	.1596	3.83	1.229
9	1600-1800	1700	3	86	.0753	.1269	3.04	0.000
10	1800-2000	1900	1	87	.0645	.1009	2.42	1.270
11	2000-2200	2100	1	88	.0538	.0802	1.93	
12	2200-2400	2300	2	90	.0323	.638	1.53	0.139
13	2400-2600	2500	1	91	.0215	.0507	1.22	
14	2600-2800	2700	0	91	.0215	.0403	0.97	
15	2800-3000	2900	1	92	.0108	.0321	0.76	0.815
16	3000-3200	3100	0	92	.0108	.0255	0.61	
17	3200-3400	3300	0	92	.0108	.0203	0.48	
18	3400-3600	3500	0	92	.0108	.0161	0.39	
19	3600-3800	3700	0	92	.0108	.0128	0.31	
20	3800-4000	3900	0	92	.0108	.0102	0.24	
21	4000-4200	4100	1	93	0	.0081	0.19	
22	>4200	-	0	93	0	0	0.75	

MTBF = 8.72 minutes

λ_4 = .001147 failures per minute

= 602.9 failures per year

χ^2 = 7.32

Degrees of freedom 9

Probability of fit about 65 %.

(Neglecting S.No.6)

Appendix 4.4 (contd.)

5. PUMP No.5

Class No.	Class interval mts	t_i mts.	Observed failures f_{oi}	Cumulative failures Σf_{oi}	Observed reliability R_{to}	Expected reliability $e^{-\lambda_i t_i}$	Expected failures f_{ei}	$\frac{(f_{ei}-f_{oi})^2}{f_{ei}}$
1	0-200	100	5	5	.9468	.8807	11.21	3.440
2	200-400	300	7	12	.8723	.7757	9.87	0.834
3	400-600	500	6	18	.8085	.6832	8.70	0.838
4	600-800	700	8	26	.7234	.6017	7.66	0.015
5	800-1000	900	12	38	.5957	.5300	6.74	4.105
6	1000-1200	1100	6	44	.5319	.4668	5.94	0.000
7	1200-1400	1300	7	51	.4574	.4111	5.24	0.591
8	1400-1600	1500	7	58	.3830	.3621	4.61	1.239
9	1600-1800	1700	7	65	.3085	.3189	4.06	2.129
10	1800-2000	1900	3	68	.2766	.2809	3.57	0.091
11	2000-2200	2100	3	71	.2447	.2474	3.15	0.007
12	2200-2400	2300	3	74	.2128	.2179	2.77	0.008
13	2400-2600	2500	2	76	.1915	.1919	2.44	
14	2600-2800	2700	3	79	.1596	.1690	2.15	0.951
15	2800-3000	2900	3	82	.1277	.1489	1.89	
16	3000-3200	3100	1	83	.1170	.1311	1.67	0.007
17	3200-3400	3300	2	85	.0957	.1155	1.48	
18	3400-3600	3500	0	85	.0957	.1017	1.30	0.097
19	3600-3800	3700	3	88	.0638	.0898	1.12	
20	3800-4000	3900	0	88	.0638	.0789	1.02	
21	4000-4200	4100	2	90	.0426	.0692	0.91	

Appendix 4.4 (contd.)

Class No.	Class interval mts	t_i mts.	Observed failures f_{oi}	Cumulative failures Σf_{oi}	Observed reliability R_{to}	Expected reliability $e^{-\lambda_i t_i}$	Expected failures f_{ei}	$\frac{(f_{ei}-f_{oi})^2}{f_{ei}}$
22	4200–4400	4300	1	91	.0319	.0614	0.73	
23	4400–4600	4500	2	93	.0106	.0539	0.71	
24	4600–4800	4700	0	93	.0106	.0476	0.59	0.968
25	4800–5000	4900	1	94	0	.0418	0.55	
26	>5000	-	0	94	0	0	3.93	

MTBF = 1574.46 minutes

say 1575 minutes

λ_5 = 0.000635 failures per minute

= 333.8 failures per year

χ^2 = 15.320

Degrees of freedom 14

Probability of fit about 45 %.

Appendix 4.5

CHARGING LOSS FOR OLD UNIT PUMPS

1. DECEMBER

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
							Charging started after S/D at 03 - 00 hrs
	0.33	0.66	0.25				
	0.33		1.11				
	0.84					0.58*	*F.Tk. No1 trouble
	2.45						
	0.67		0.33		22.16*		*S/D at 08-50 hrs
					24.00		
					24.00		
					20.75*		*Charging restarted at 03-45 hrs
	0.50						
	1.16		0.84				
	0.50						
	1.78			1.25*			*T.V.(E) discharge bend leakage
	0.25						
	3.66					0.84*	*Precipitation trouble
	0.16						
			23.55			2.28	
	0.08		4.47			13.66*	*Plugging in T.V.(E) and F.Tk No.1 outlet
	1.41						

Appendix 4.5 (contd.)

1. DECEMBER (contd.)

Date	Charging loss in hours due to: Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
20	0.41					7.66*	*Plugging T.V.(E) and F.Tk No.1 outlet
21	0.16						
22	0.50					18.00*	*F.Tk.No.1 outlet plugging
23	0.33					13.16*	*Low condensate level
24	0.25						
25	0.30						
26	1.30						
27	2.25						
28	1.75						
29	1.11		0.25	3.41*			*Leakage in T.V.
30	0.16		10.58				
31			4.84				
Total	22.64	0.66	46.42	4.66	90.91	56.18	221.47

NOTE: As per plant practice 1st December is counted from 07.00 hrs on 1st December to 07.00 hrs on 2nd December and so on.

Appendix 4.5 (contd)

2. JANUARY

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
1	2.58				6.58*		*S/D at 00-25 hours
2	0.25		1.03				
3					24.00		
4					24.00		
5					24.00		
6					24.00		
7					24.00		
8					24.00		
9					24.00		
10				2.25*	14.00		*Leakage in heater No.4 bypass valve
11					24.00		
12	0.47			1.75*		1.66**	*Leakage in F.Tk. No.3 inlet **slurry shortage
13			3.16				
14				23.25*			*F.Tk No.2 outlet spool leakage
15	0.41		12.66				
16	0.16		14.75				
17			17.58				
18			1.75	6.25*			*Tail valve leakage
19	0.30						
20			19.00				
21	1.50		1.50				
22							

Appendix 4.5 (contd.)

2. JANUARY (contd.)

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
23			0.58	2.92*			*F.Tk.No.4 outlet leakage
24	0.58						
25			16.75				
26			12.50				
27	0.75		0.16				
28	0.08		0.50				
29	0.20		0.16				
30	2.47		0.20	1.66*			*Leakage in F.Tk. No.2 spool
31	0.25		1.00				
Total	10.00	0.00	103.28	38.08	212.58	1.66	365.60

Appendix 4.5 (contd.)

3. FEBRUARY

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
1				2.00*		3.58**	*F.Tk No.3 North down block valve leakage **Precipitation trouble
2	0.33						
3	0.16		0.38				
4						NA*	*Data not available from 01-05 hours on 5th Feb. to 10-28 hours on 9th Feb. Total 81.38 hours
5	0.33					NA	
6						NA	
7						NA	
8							
9	0.25		0.25				
10	0.41						
11	1.41		0.25	1.66			
12	0.41					0.30*	*Bauxite shortage
13	0.28			2.08*			*Leakage in F.Tk No.2 outlet
14	0.66						
15	2.75			1.92*			*Leakage in F.Tk No.3 North down block valve
16	4.21			2.58*			*Leakage in F.Tk No.4 outlet
17	0.36			4.00*			*Leakage in F.Tk No.4 outlet
18	0.16						

Appendix 4.5 (contd.)

3. FEBRUARY (contd.)

Date	Charging loss in hours due to Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
19	0.33				4.50*	0.33**	*S/D due to Ball mill No.2 motor failure **Slurry level low
20	3.22						
					24.00		
21					24.00		
22					8.75		
23	1.16						
24			4.00			0.16*	*Charge pump trouble
25							
26			0.16			2.63*	*Injection pump trouble
27						N.A.	
28							
Total	16.43	0.00	5.04	14.32	61.25	7.00	104.04

Appendix 4.5 (contd.)

4. MARCH

Date	Charging loss in hours due to: Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
1						N.A.*	*Data not available from 15-45 hrs. on 28th Feb. to 15-20 hrs. on 2nd March Total time 47.58 hrs.
2	1.33		2.75	2.00			
3			15.75				
4	0.50		8.00				
5	1.08		2.25				
6	0.33			2.33*			*Leakage in F.Tk No.2 reducer
7	0.13			2.00*			*Leakage in F.Tk. reducer
8	0.25					0.25*	*Charge pump tripped
9	0.16						
10			0.16			N.A.*	*Data not available from 01-55 hours on 10th March to 07-00 hours on 13th March Total time 53.08 hrs.
11							
12							
13			11.16				
14			5.50				
15	0.28						*Power failure at Renusagar
16	0.16	7.75*	0.08				
17		24.00					
18		24.00					
19		24.00				13.00*	*Low condensate level
20			1.84				

Appendix 4.5 (contd.)

4. MARCH (contd.)

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
21	0.50						
22	0.13		2.50				
23							
24	2.58						
25							
26	1.08					N.A.	Data not available from 09-30 hours on 27th March to 13-45 hours on 29th March Total time 52.25 hrs.
27						N.A.	
28							
29	1.66						
30	1.30						
31	3.25						
Total	14.72	79.75	49.99	6.33	0.00	13.25	164.04

Appendix 4.5 (contd.)

5. APRIL

Date	Charging loss in hours due to: Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
1	0.25						
2	0.16						
3							
4							
5							
6	1.66					0.16*	*Booster pump trouble
7						0.16*	*Booster pump trouble
8							
9	1.75					0.66*	*Low test tank level
10							
11	0.16						
12	0.58						
13	0.16						
14	0.25						
15							
16							
17	0.16		0.16	3.66*			*Leakage in F.Tk No.3 inlet
18	0.58			2.58*			*Leakage in F.Tk No.2 discharge line
19							

Appendix 4.5 (contd.)

5. APRIL (contd.)

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
20	0.41		0.08				
21	0.16		0.75				
22	0.16			12.00*			*Leakage in F.Tk No.3 pipe
23			0.30	1.66*			*Leakage in heater No.5
24			5.78				
25	0.92		0.58				
26							
27							
28	0.33					0.08*	*Booster pump trouble
29				14.00*			*Leakage in relief by pass of Digester No.1
30	0.18						
Total	7.87	0.00	7.55	33.90	0.00	1.06	50.48

Appendix 4.5 (contd.)

6. MAY

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
1	0.25						
2			0.33				
3			0.75	5.58*			*F.Tk No.4 outlet spool leakage
4							
5				9.92*			*F.Tk No.2 control valve leakage
6			24.00				
7			3.00				
8	1.25						
9			4.58			1.25*	*Booster pump trouble
10	0.92					0.33*	*Plant trouble
11	0.08		1.08				
12			1.33				
13			1.00				
14	0.25						
15			19.25				
16			24.00				
17			24.00				
18			20.00			0.92*	*Instrument air pressure low
19	0.70						

Appendix 4.5 (contd.)

6. MAY (contd.)

Date	Charging loss in hours due to Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
20	0.28						
21	0.86		0.33				
22	0.25		0.41				
23							
24	0.16		1.41	2.00*			*F Tk No.4 slurry line, north spool lekage
25	0.16		1.84				
26	0.13						
27			0.25				
28	0.25						*Data considered upto 11 - 30 hours on 29.5.75
29*							
30							
31							
Total	5.54	0.00	127.56	17.50	0.00	2.50	153.10

Appendix 4.6

CHARGING LOSS FOR NEW UNIT PUMPS

1. DECEMBER

Date	Charging loss in hours due to: Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
1	1.00		0.33				Restarted after valve change at 11.40 a.m.
2	0.58	0.50					
3	1.03		0.58				
4							
5	1.59		0.41			0.25*	*Cleaning slurry line of SH Tk No.3
6	0.16						
7	0.33						
8	0.16						
9	1.83		0.13				
10	0.07		0.33	10.84			Fl Tk No.4 outlet spool leakage
11							
12							
13							
14	0.16						
15							
16							
17			1.58				
18			0.45				

Appendix 4.6 (contd.)

1. DECEMBER (contd.)

Date	Charging loss in hours due to: Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
19	1.33						
20							
21							
22							
23							
24							
25							
26							
27							
28	0.16						
29	0.62						
30	0.08		1.66				
31	1.33						
Total	10.43	0.50	5.47	10.84	0.00	0.25	27.49

Appendix 4.6 (contd.)

2. JANUARY

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
1	1.03		0.30				
2			1.92				
3							
4						0.25	Instrument air pressure low
5							
6			3.42			0.08*	*Mechanical maintenance
7							
8			0.08			1.50*	*High F.E. A/C
9							
10			0.41		11.75		Stopped at 19 hr 15 mt
11					24.00		
12					24.00		
13					24.00		
14					24.00		
15					24.00		
16					13.16		Restarted at 20 hr 10 mt
17	0.11						
18	0.58		2.16				
19			0.33				

Appendix 4.6 (contd.)

2. JANUARY (contd.)

Date	Charging loss in hours due to Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
20			5.41				
21			0.16				
22							
23			0.16				
24			1.00				
25			0.16				
26							
27							
28			0.50				
29			0.33				
30	0.58		0.25				
31	0.84		1.75				
Total	3.14	0.00	18.34	0.00	144.91	1.83	168.22

Appendix 4.6 (contd.)

3. FEBRUARY

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
1							
2	0.25						
3			0.58				
4							
5	0.08						
6			0.58				
7							
8	0.92						
9			0.33				
10	1.92						
11							
12	0.25						
13							
14							
15	0.16						
16							Leakage in slurry discharge line of steam pump No.4
17							
18	1.28						
19							
20	0.16						

Appendix 4.6 (contd.)

3. FEBRUARY (contd.)

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
21	0.66					0.25*	*Instrument air pressure low
22							
23	1.33						
24	2.25		1.33				
25							
26							
27	0.92						
28	0.50		0.50				
Total	10.68	0.00	3.32	0.00	0.00	0.25	14.25

Appendix 4.6 (contd.)

4. MARCH

Date	Charging loss in hours due to: Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
1	0.08						
2			1.75				
3							
4			0.55	2.50*			*Leakage in F.Tk No.2 west down block valve
5	0.08		2.58				
6	4.08		0.25				
7	1.38		0.41				
8							
9							
10			1.25				
11			0.25				
12							
13			5.00				
14	0.25						
15							
16		12.53*	0.33				*SD from 18 - 28 hrs due to power failure in Renusagar
17		24.00					
18		24.00					
19		24.00					Started again at 7.55 after S/D
20	0.41	0.92					

Appendix 4.6 (contd.)

4. MARCH (contd.)

Date	Charging loss in hours due to: Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
21							Boiler feed pump failure
22			2.33				
23							
24							
25							
26						NA	Data not available from 06 - 35 hours on 27th March to 15 - 10 hours on 31st March Total time 80.58 hrs.
27							
						NA	
28						NA	
29						NA	
30							
31							
Total	6.28	85.44	14.70	2.50	0.00	0.00	108.92

Appendix 4.6 (contd.)

5. APRIL

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam Shortage	Erosion leakage	Plant S/D	Misc.	
1							
2	0.33					0.66*	*Booster pump trouble
3			0.41				
4			0.16				
5	0.58						
6							
7		0.25					
8							
9							
10							
11							
12							
13							
14							
15							
16							
17	1.00						
18	0.25		0.08				
19							
20			0.16				

Appendix 4.6 (contd.)

5. APRIL (contd.)

Date	Charging loss in hours due to: Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
21			1.16				Feed water pump tripped
22			0.16			0.50*	*Shut down by mistake
23			1.58				
24			10.08				
25			0.66				
26			0.16				
27	0.55						
28							
29							
30							
Total	2.71	0.25	14.61	0.00	0.00	1.16	18.73

Appendix 4.6 (contd.)

6. MAY

Date	Charging loss in hours due to						Remarks
	Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	
1							
2			0.58			10.66	Bearing trouble in charge pump(E)
3							
4							
5							
6							
7							
8			0.95				Boiler feed water pump tripped
9							
10			0.25				
11			3.84				*Leakage in slurry charging line
12			0.16	3.84*			
13							
14						NA	Data not available from 03-50 hours on 16th May to 09-10 hours on 20th May Total 77.33 hrs
15			0.16				
16						NA	
17						NA	
18							

Appendix 4.6 (contd.)

6. MAY (contd.)

Date	Charging loss in hours due to Steam pump trouble	Power failure	Steam shortage	Erosion leakage	Plant S/D	Misc.	Remarks
19						NA	
20						NA	
21			0.66				
22							
23	0.55						
24							
25			1.84				
26							
27							
28							
29			1.50				
30			0.75				
31							
Total	0.55	0.00	10.69	3.84	0.00	10.66	25.74

Appendix 5.1

PERFORMANCE ANALYSIS FOR HIGH PRESSURE HEATERS (1 and 2)

$$U = 0.168\ F \ln\left(\frac{T_S - T_{SLI}}{T_S - T_{SLO}}\right)$$

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S °C	T_{SLI} °C	T_{SLO} °C	$T_S - T_{SLI}$ °C	$T_S - T_{SLO}$ °C	F 1pm	U kcal/hr m^2 °C	$\frac{10^7}{U}$
Heater No.1 Cycle 1									
0	17.0	203.4	183	202	20.4	1.4	4500	2025	2.44
3	20.90	213.6	187	208	26.6	5.6	4500	1178	7.21
6	22.5	217.4	196	212	21.4	5.4	4950	1145	7.62
9	23	218.5	194	210	24.5	8.5	4975	867	13.30
12	23.3	219.2	195	210	24.2	9.2	5115	831	14.48
15	21.9	216	195	207	21	9	5030	716	19.50
Heater No.1 Cycle 2									
3	21.4	214.9	195	214	19.9	0.9	4920	2559	1.53
6	22.5	217.4	197	215	20.4	2.4	4840	1740	3.30
9	21.6	215.4	192.5	211	22.9	4.4	4700	1302	5.89
12	22	216.2	191	211	25.2	5.2	4790	1270	6.20
15	22.7	217.9	194	211	23.9	6.9	4970	1037	9.29
18	20.6	212.9	192.8	207.5	20.1	5.4	4520	998	10.03
21	20.2	212	190	205.3	22	6.7	4910	981	10.40
23	20.8	213.4	190	205	23.4	8.4	4420	761	17.28

Appendix 5.1 (contd.)

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S °C	T_{SLI} °C	T_{SLO} °C	T_S
Heater No.1 Cycle 3					
2	21.7	215.6	191	215	
4	21.4	214.9	192	214	
6	23.8	220.4	202.3	217.8	
8	22.7	217.9	200.1	215	
10	21.9	216.0	198.8	212.8	
12	22.7	217.9	198.3	212.8	
14	23.2	219	200	213.8	
Heater No.1 Cycle 4					
0	20.8	213.4	193.8	212.7	
2	20.6	212.9	191.8	210.8	
4	20.5	212.6	193.3	210.5	
6	19.6	210.4	193	210	
8	20.3	212.3	196.3	211	

$- T_{SLI}$ °C	$T_S - T_{SLO}$ °C	F lpm	U kcal/kg m^2 °C	$\frac{10^7}{U^2}$
24.6	0.6	4900	3057	1.07
22.9	0.9	5100	2773	1.30
18.1	2.6	5100	1663	3.61
17.8	2.9	4520	1378	5.27
17.2	3.2	4475	1264	6.25
19.6	5.1	4750	1074	8.66
19	5.2	4770	1038	9.28
19.6	0.7	4950	2771	1.30
21.1	2.1	4560	1768	3.20
19.3	2.1	4715	1757	3.24
17.4	0.4	4740	3004	1.11
16	1.3	4800	2024	2.44

Appendix 5.1 (contd.)

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S °C	T_{SLI} °C	T_{SLO} °C	$T_S - T_{SLI}$ °C	T
Heater No.2 Cycle 1						
12	18.8	208.3	192	205.5	16.3	
14	19	208.8	192.3	204	16.5	
16	19.9	211.2	193	204	18.2	
18	19.4	209.9	192	203.3	17.9	
20	20.1	211.7	196.5	205.5	15.2	
Heater No.2 Cycle 2						
0	21.1	214.1	189.3	212.3	24.8	
2	21.2	214.3	190.3	211	24	
4	21	213.9	186.3	209	27.6	
6	21.5	215.1	189.5	209.5	25.6	
8	22.1	216.5	190	210	26.5	
Heater No.2 Cycle 3						
3	21.4	214.9	198.5	213.5	16.4	
6	21.4	214.9	197.5	214.5	17.4	
9	21	213.9	197	211.3	16.9	
12	21.4	214.9	200	212.5	14.9	
15	21.2	214.4	200.7	210.7	13.7	
18	20.3	212.3	197.3	208.5	15	

S - T_{SIO} °C	F lpm	U kcal/kg m^2 °C	$\frac{10^7}{U^2}$
2.8	4445	1315.5	5.78
4.8	4790	993.6	10.13
7.2	4740	738.5	18.34
6.6	4630	776	16.6
6.2	4460	671.9	22.15
1.8	4560	2009	2.48
3.3	4260	1420	4.96
4.9	4020	1167.4	7.34
5.6	4270	1090.3	8.41
6.5	4680	1104.9	8.19
1.4	4830	1996.8	2.51
0.4	4350	2757.1	1.32
2.6	4910	1544	4.19
2.4	5120	1570.6	4.05
3.7	4900	1077.6	8.61
3.8	4900	1130	7.83

Appendix 5.2

PERFORMANCE ANALYSIS FOR MEDIUM PRESSURE HEATERS (3 to 6)

$$U = 0.168\ F\ \ln\left(\frac{T_S - T_{SLI}}{T_S - T_{SLO}}\right)$$

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S °C	T_{SLI} °C	T_{SLO} °C	$T_S - T_{SLI}$ °C	$T_S - T_{SLO}$ °C	F lpm	U kcal/kg m^2 °C	$\frac{10^7}{U^2}$
Heater No.3, Cycle 1									
0	16.7	202.5	172	201.5	30.5	1.0	4980	2859.4	1.22
4	17.9	205.9	175.5	202.8	30.4	3.1	4790	1837.2	2.96
8	16.7	202.5	172	198.3	30.5	4.2	4940	1645.4	3.69
12	15.4	198.6	172	192.8	26.6	5.8	4890	1251.2	6.39
16	17.1	203.6	173	194.3	30.6	9.3	4840	968.4	10.66
20	17.1	203.6	175.5	195.5	28.1	8.1	4760	994.7	10.10
24	17.2	203.9	173.5	193.5	30.4	10.4	4970	895.6	12.47
31	16.0	200.4	175	190	25.4	10.4	4780	717.1	19.45
Heater No.3, Cycle 2									
6	18.6	207.9	180.5	202.3	27.4	5.6	5100	1360.4	5.40
9	17.6	205.0	179.8	199.8	25.2	5.2	4460	1182.5	7.15
12	17.6	205.0	177.3	198.3	27.7	6.7	4750	1132.6	7.80
15	18.7	208	179.3	199.8	28.7	8.2	4730	995.5	10.09
18	17.8	205.6	181.5	199	24.1	6.6	4890	1064	8.83

Appendix 5.2 (contd.)

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S °C	T_{SLI} °C	T_{SLO} °C	$T_S - T_{SLI}$ °C
Heater No.4, Cycle 1					
20	10.1	179.5	156.8	175	22.7
24	10.4	180.7	159	176	21.7
29	10.5	181.6	165	176.5	16.6
34	10.1	179.5	156	170.5	23.5
39	18.1	206.4	176.5	194.8	29.9
44	18.3	207	178.5	195	28.5
49	18.4	207.2	178.8	194.5	28.4
54	18.4	207.2	179.8	195.3	27.4
59	11	183.2	162.3	173.5	20.9
64	10.5	181.2	161.3	172	19.9
Heater No.4, Cycle 2					
0	11.1	183.6	165	183	18.6
4	10.8	182.4	162.3	181.8	20.1
9	17.8	205.6	177	197	28.6
14	17.8	205.6	175.5	198	30.1
19	17.3	204.2	174	198	30.2
24	16	200.4	172	193.3	28.4
28	16.9	203.1	173.5	196.3	29.6
34	10.2	179.9	156	174	23.9
39	10.1	179.5	154.8	172.5	24.7

$T_S - T_{SLO}$ °C	F lpm	U kcal/kg m^2 °C	$\frac{10^7}{U^2}$
4.5	4445	1208.5	6.85
4.7	4240	1089.7	8.42
5.1	4200	832.7	14.42
9.0	4500	725.6	18.99
11.6	4950	787.4	16.13
12	5115	743.3	18.09
12.7	4950	669.3	22.33
11.9	4980	697.8	20.53
9.7	4680	603.5	27.45
9.2	4940	640.3	24.39
0.6	4735	2731.7	1.34
0.6	4590	2707.8	1.36
8.6	4910	991.2	10.18
7.6	4870	1126.1	7.88
6.2	4900	1303.4	5.89
7.1	4715	1098.1	8.29
6.8	4800	1186.1	7.11
5.9	4750	1116.3	8.02
7	4800	1016.8	9.67

Appendix 5.2 (contd.)

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S °C	T_{SLI} °C	T_{SLO} °C	$T_S - T_{SLI}$ °C
Heater No.5, Cycle 1					
0	7.3	165.9	134	160	31.9
8	10.4	180.7	157.5	178.5	23.2
16	10.8	182.4	156.5	176.3	25.9
24	8.4	171.6	139	162.3	32.6
32	10.6	181.6	163.3	176.3	18.3
40	10.3	180.3	158.5	172.3	21.8
56	10.2	179.9	158.8	171.3	21.1
Heater No.5.Cycle 2					
0	10.6	181.6	156.5	179	25.1
6	11.0	183.2	160.8	180.8	22.4
12	7.7	168	136.8	159.3	31.2
18	6.9	163.6	133.3	155	30.3
24	10.3	180.3	158	175.5	22.3
30	11.1	183.6	154.8	175	28.8
36	10.8	182.4	158.8	174.3	23.6

$T_S - T_{SLO}$ °C	F lpm	U kcal/kg m^2 °C	$\frac{10^7}{U^2}$
5.9	4900	1389.3	5.18
2.2	5155	2040.1	2.40
6.1	4970	1207.3	6.86
9.3	4680	986.2	10.28
5.3	4750	988.8	10.23
8.0	4700	791.5	15.96
8.6	4280	645.3	24.01
2.6	4970	1893.2	2.79
2.4	4850	1819.9	3.02
8.7	4920	1055.6	8.97
8.6	4920	1040.9	9.23
4.8	5000	1290.2	6.01
8.6	4900	994.9	10.10
8.1	4670	839.0	14.21

Appendix 5.2 (contd.)

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S °C	T_{SLI} °C	T_{SLO} °C	$T_S - T_{SLI}$ °C
Heater No.6, Cycle 1					
39	8.1	170.1	141	159	29.1
44	9.4	176.4	144.5	164.5	31.9
49	7.9	169.1	135.8	155.5	33.3
54	8.0	169.6	139	156.5	30.6
59	8.7	173.1	140.3	157.5	32.8
64	8.9	174.1	139.5	157.8	34.6
Heater No.6, Cycle 2					
0	7.7	168	140.7	163.3	27.3
4	7.5	167	134.8	161.8	32.2
9	7.8	168.6	136.3	163	32.3
14	7.6	167.5	133.3	160	34.2
19	8.4	171.6	139.7	165.3	31.9
24	7.3	165.9	134.5	158.8	31.4
29	7.5	167	139	161	28
34	8.1	170.1	138	160.5	32.1
39	7.9	169.1	136.8	159.0	32.3
44	7.9	169.1	137.3	158.3	31.8

$T_S - T_{SLO}$ °C	F lpm	U kcal/kg m^2 °C	$\frac{10^7}{U^2}$
11.1	4750	769.1	16.90
11.9	4460	738.8	18.32
13.6	4100	616.8	26.28
13.1	4950	705.5	20.09
15.6	5115	638.6	24.52
16.3	4950	625.9	25.52
4.7	4750	1403.9	5.07
5.2	4870	1491.8	4.49
5.6	4760	1401.3	5.09
7.5	4970	1266.9	6.23
6.3	4680	1275.3	6.14
7.1	4280	1069	8.75
6	4270	1105.1	8.19
9.6	4760	965.3	10.73
10.1	5100	996.1	10.08
10.8	4460	809.2	15.27

Appendix 5.2 (contd.)

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S ^oC	T_{SLI} ^oC	T_{SLO} ^oC	$T_S - T_{SLI}$ ^oC	T
Heater No.6, Cycle 3						
0	7.4	166.4	138	160.5	28.4	
4	7.5	167	138	161.8	29	
9	8.6	172.6	137	159.3	35.6	
24	8.4	171.6	141.5	165	30.1	
29	7.4	166.4	133	155.8	33.4	
33	7.3	165.9	136.8	158	29.1	

S - T_{SLO} °C	F lpm	U kcal/kg m^2 °C	$\frac{10^7}{U^2}$
5.9	4940	1304.2	5.88
5.2	5120	1478.3	4.58
13.3	4850	802.2	15.54
6.6	4370	1114	8.06
10.6	4900	944.8	11.20
7.9	4750	1040.5	9.23

Appendix 5.3

PERFORMANCE ANALYSIS FOR LOW PRESSURE HEATERS (7 to 10)

$$U = 0.168\ F\ l_n\left(\frac{T_S - T_{SLI}}{T_S - T_{SLO}}\right)$$

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S °C	T_{SLI} °C	T_{SLO} °C	$T_S - T_{SLI}$ °C	$T_S - T_{SLO}$ °C	F lpm	U kcal/kg m^2 °C	$\frac{10^7}{U^2}$
Heater No.7									
85	4.1	143.2	123.5	138	19.7	5.2	4445	994.7	10.10
99	4.1	143.2	120	136	23.2	7.2	4500	884.6	12.78
119	4.7	148.8	130.3	143.3	18.5	5.5	4980	1014.9	9.70
139	3.7	140.2	123.3	134	16.9	6.2	4860	818.7	14.92
179	4.6	148	129.3	140.5	18.7	7.5	4630	710.7	19.80
199	3.8	141.1	126	137	15.1	4.1	4850	1062.3	8.86
219	4.2	144.7	127	137.3	17.7	7.4	4900	717.9	19.40
Heater No.8									
40	2.6	128.1	102.5	123.5	25.6	4.6	4445	1282	6.09
59	2.9	131.7	107.3	126.8	24.4	4.9	4900	1335	5.61
79	2.7	129.3	106.5	125.8	22.8	3.5	4680	1473.4	4.60
99	2.6	128.1	102.3	119.5	25.8	8.6	4880	900.69	12.32
159	2.8	130.6	103.8	120.8	26.8	9.8	4850	819.7	14.88
179	2.8	130.6	107	124.8	23.6	5.8	4750	1119.9	7.97

Appendix 5.3 (contd.)

No. of days in use	Steam pressure kgf/cm^2 abs.	T_S ^oC	T_{SLI} ^oC	T_{SLO} ^oC	$T_S - T_{SLI}$ ^oC	$T_S - T_{SLO}$ ^oC	F lpm	U $kcal/kg\ m^2\ ^oC$	$\frac{10^7}{U^2}$
Heater No.10									
51	1.6	112.7	83	102.5	29.7	10.2	4945	887.9	12.68
69	1.8	116.3	83.3	107.8	33	8.5	5450	1242	6.48
89	1.6	112.7	85.5	107	27.2	5.7	5260	1381	5.24
109	1.6	112.7	79	101.3	33.7	11.4	5290	963.3	10.77
169	1.9	118	83.3	104.5	34.7	13.5	5450	864.3	13.3
189	1.8	116.3	88	108.3	28.3	8	5200	1103.7	8.20

Note:- Heater No.9 was not used during the period under investigation.

Appendix 6.1

EQUIPMENT OVERHAULING SCHEDULE FOR SLURRY MIX, DIGESTION, AND EVAPORATION AREAS

Month	Week	Equipment No.	Equipment name	Frequency months	Estimated man-hours
JANUARY	1	1233-2 M	Bauxite slurry screen North	6	64
		1531-2	Hotwell pump	12	64
		1914	Caustic circulation pump	12	48
	2	1228-2	G.M.D. pump No.3	6	48
		1332W	Spent liquor injection pump	6	64
		13119-2 W	Test tank sump pump	12	48
		1513E	Hot well pump	12	64
	3	1257-2	Reject pump No.2 of B.M. No.2	6	32
		13135-2 E	Digestion sump pump	12	48
		1818W	Evaporation discharge pump	12	32
		1840-2 W	Condensate pump	6	48
	4	1235-2 N	Sump pump No.1	6	48
		1386-2 W	Spent liquor charge pump	6	72
		13111-2 W	Condensate pump	6	48
		1845-2 E	Evaporation discharge pump	6	48
FEBRUARY	1	1214N	Sump pump	6	48
		1316	Blow off pump No.1	12	48
		1330W	Spent liquor booster pump	6	64

Month	Week	Equipment No.	Equipment name	Frequency months	Estimated man-hours
FEBRUARY (CONTD)		1366	5 Ton digester hoist	12	24
	2	1202W	Bauxite grametric feeder	6	64
		1206M	G.M.D. pump No.1	6	48
		1219S	Reject pump No.1	6	32
		13124-2	Relief tank pump	12	48
		1510N	Condensate pump	12	48
	3	1355E	Digestion sump pump	12	48
		1399-2W	Spent liquor booster pump	6	72
		1816S	Evap. Circulation pump	6	48
		1822E	Evap. sump pump	12	48
	4	1219-2	Bauxiteweight feeder No.2	6	64
		1258-2	Reject pump No.4 of B.M. No.3	6	32
		1529-2 W	Condensate pump new unit	6	48
		1954-2 E	Caustic metering pump	6	48
MARCH	1	1212 N	Steam pump No.1	12	200
		1350-2	Dilute acid pump	6	48
		1363	Test tank mixer	12	32
		13102-2 E	Spent liquor injection pump	6	72
		1841-2 E	Condensate pump	6	48

Month	Week	Equipment number	Equipment name	Frequency months	Estimated man-hours
MARCH (CONTD)	2	1320S	Spent liquor charge pump	6	64
		1341S	Condensate pump	6	48
		1514E	Hose water pump	6	64
	3	1204N	Bauxite slurry screen	6	64
		1240-2S	Sump pump No.3	6	48
		1843-2E	Evap. circulation pump	6	96
	4	1215 S	Sump pump	6	48
		1224-2S	Bauxite slurry screen No.3	6	64
		1226-2N	G.M.D. pump No.1	6	48
		1532-2 N	Preg. Liq. discharge pump	6	64
		1947	C.D. area sump pump	12	48
APRIL	1	1215-2S	G.M.D. pump No.4	6	48
		1317	Blow off pump No.2	12	48
		13122-2 W	Dig. sump pump	12	48
		1847-2 N	Evap. sump pump	12	4 8
		1951-2	Caustic circulation pump	6	48
	2	1219-1 N	Reject pump No.2	6	32
		1333 E	Sp.Liq. Injection pump.	6	64
		1862-2	Evap. Condensate pump	6	48

Month	Week	Equipment number	Equipment name	Frequency months	Estimated man-hours
APRIL (CONTD)	3	1212-1 S	Steam pump No.3	12	200
		1253-2	Reject pump No.1 of B.M. No.2	6	32
		13120-2 M	Test tank sump pump	12	48
		13141-2	Electric winch	12	24
		1530-2 E	Condensate pump	6	48
	4	1207S	G.M.D. pump No.2	6	48
		1387-2 E	Sp. liquor charge pump	6	72
		13126-2	Bad water pump	6	48
		1844-2 W	Evap. discharge pump	6	48
		1911-2 N	C.D. area hoist	6	24
MAY	1	1227-2	G.M.D. pump No.2	6	48
		1254-2	Reject pump No.3 of B.M. 3	6	32
		1331 E	Sp. Liq. booster pump	6	64
		1815E	Condensate pump	12	48
	2	1362	Bad water pump	6	48
		13110-2 E	Condensate pump	6	48
		1515-W	Hose water pump	6	64
	3	1357E	Test tank sump pump	12	48
		13100-2 E	Sp. liq. booster pump	6	72
		13133-2	5 Ton crane over heater	12	32
		1817N	Evap. circulation pump	6	48

Month	Week	Equipment number	Equipment name	Frequency months	Estimated man-hours
MAY (CONTD)	4	1241-2	Grinding mill feed conveyor No.2	12	64
		1352	Dilute acid pump	6	48
		1384-2 E	Blow off pump No.2	12	64
JUNE	1	13101-2 W	Sp.liq. Injection pump	6	72
		1840-2 W	Condensate pump	6	48
		1973-2	C.D. area sump pump	6	48
	2	1319N	Sp.liq. charge pump	6	64
		13127-2 N	Test tank mixer No.1	12	32
		13134-2 M	Dig. sump pump	12	48
		1512W	Hot-well pump	12	64
	3	1220-2	Bxt. weight feeder No.3	6	64
		1842-2 W	Evap. circulation pump	6	96
		1917	Caustic make up tank mixer	12	24
		1953-2 W	Caustic metering pump	6	48
	4	1206-1 N	G.M.D. pump No.3	6	48
		1340N	Condensate pump	6	48
		1533-2 S	Preg. Liq. discharge pump	6	64
JULY	1	1213M	Steam pump No.2	12	200
		1223-2 M	Bxt. slurry screen No.2	6	64
		1845-2 E	Evap. discharge pump	6	48

Month	Week	Equipment number	Equipment name	Frequency months	Estimated man-hours
JULY (CONTD)	2	1228-2	G.M.D. pump No.3	6	48
		1332W	Sp.Liq. injection pump	6	64
	3	1512W	Hot well pump	12	64
		1821W	Evap. sump pump	12	48
		1848-2 M	Evap. sump pump	12	48
	4	1235-2 N	Sump pump No.1	6	48
		1386-2 W	Sp. Liq. charge pump	6	72
		13111-2 W	Condensate pump	6	48
		1819E	Evap. discharge pump	12	32
AUGUST	1	1214N	Sump pump	6	48
		1330W	Sp. Liq. booster pump	6	64
		1354W	Dig. sump pump	12	48
		1360	Relief tank pump	12	48
		1367	1 Ton dig. hoist	12	24
	2	1202W	Ext. grametric feeder	6	64
		1206M	G.M.D. pump No.1	6	48
		1219S	Reject pump No.1	6	32
		13132-2 S	Test tank mixer No.2	12	32
		1510N	Condensate pump	12	48
	3	1242-2	Grinding mill feed conveyor No.3	12	64
		1316-1	Blow off pump No.3	12	48
		1399-2 W	Sp.Liq. booster pump	6	72
		1816S	Evap. circulation pump	6	48

Month	Week	Equipment number	Equipment name	Frequency months	Estimated man-hours
AUGUST (CONTD.)	4	1219-2	Bauxite weight feeder No.2	6	64
		1258-2	Reject pump No.4 of B.M. No.3	6	32
		1529-2 W	Condensate pump	6	48
		1954-2 E	Caustic metering pump	6	48
SEPTEMBER	1	1259-2	Sump pump	12	48
		1350-2	Dilute acid pump	6	48
		13102-2 E	Sp.Liq. Injection pump	6	72
		1841-2 E	Condensate pump	6	48
	2	1231-2	Slurry holding tank mixer	12	24
		1320-S	Sp. liq. charge pump	6	64
		1341S	Condensate pump	6	48
		1514E	Hose water pump	6	64
	3	1204N	Bxt. slurry screen	6	64
		1211	Slurry holding tank mixer	12	32
		1240-2 S	Sump pump No.3	6	48
		1843-2 E	Evap. circulation pump	6	96
	4	1215S	Sump pump	6	48
		1224-2 S	Bxt. slurry screen No.3	6	64
		1226-2 N	G.M.D. pump No.1	6	48
		1532-2 N	Preg. liquor discharge pump	6	64

Month	Week	Equipment number	Equipment name	Frequency months	Estimated man-hours
OCTOBER	1	1210	Slurry injection tank mixer	12	24
		1215-2 S	G.M.D. pump No.4	6	48
		1951-2	Caustic Circulation Pump	6	48
	2	1219-1 N	Reject pump No.2	6	32
		1333E	Sp. liq. Injection pump	6	64
		1862-2	Evap. condensate pump	6	48
	3	1253-2	Reject pump No.1 of B.M. No.2	6	32
		1516	Preg. liq. discharge pump	12	64
		1530-2 E	Condensate pump	6	48
		1849-2 S	Evap. sump pump	12	48
	4	1207S	G.M.D. pump No.2	6	48
		1387-2 E	Sp. liq. Charge pump	6	72
		13126-2	Bad water pump	6	48
		1844-2 W	Evap. discharge pump	6	48
		1911-2 M	C.D. area hoist	6	24
NOVEMBER	1	1227-2	G.M.D. pump No.2	6	48
		1232-2	Slurry injection tank mixer	12	32
		1254-2	Reject pump No.3 of B.M. No.3	6	32
		1331 E	Sp. liq. Booster pump	6	64

Month	Week	Equipment number	Equipment name	Frequency months	Estimated man-hours
NOVEMBER (CONTD)	1	1356W	T.T. Sump pump	12	48
		1383-2 W	Blow off pump No.1	12	64
		1951-2	Caustic circulation pump	6	48
	2	1362	Bad water pump	6	48
		13110-2 E	Condensate pump	6	48
		1515W	Hose water pump	6	64
	3	13100-2 E	Sp. liquor Booster pump	6	72
		1814W	Condensate pump	12	48
		1817N	Evap. circulation pump	6	48
		1820	Excess liquer pump	12	32
	4	1352	Dilute acid pump	6	48
		1511S	Condensate pump	12	48
		1918	Caustic cleaning tank mixer	12	24
DECEMBER	1	1319N	Sp. liq. charge pump	6	64
		13101-2 W	Sp. liq. injection pump	6	72
		1840-2 W	Condensate pump	6	48
		1973-2	C.D. area sump pump	6	48
	2	1236-2 M	Sump pump No.2	12	48
		1254-2	Reject pump No.3 of B.M. No.3	6	32
		13121-2 E	T.T. sump pump	12	48

Month	Week	Equipment number	Equipment name	Frequency months	Estimated man-hours
DECEMBER (CONTD)	3	1220-2	Ext. weightfeeder No.3	6	64
		1842-2 W	Evap. circulation pump	6	96
		1953-2 W	Caustic metering pump	6	48
	4	1206-1 N	G.M.D. pump No.3	6	48
		1340N	Condensate pump	6	48
		1533-2 S	Preg. liquor discharge pump	6	64