ANALYSIS AND OPTIMIZATION OF SYSTEMS AVAILABILITY IN SUGAR, PAPER AND FERTILIZER INDUSTRIES

A THESIS

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By

DINESH KUMAR

DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE-247 667 (INDIA)

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"ANALYSIS AND OPTIMIZATION OF SYSTEMS AVAILABILITY IN SUGAR, PAPER AND FERTILIZER INDUSTRIES"** in fulfilment of the requirement for the award of the degree of Doctor of Philosophy, submitted in the Department of Mechanical and Industrial Engineering of the University of Roorkee is an authentic record of my own work carried out during a period from March 1988 to May 1991 under the supervision of **Dr. P.C.PANDEY and Dr. JAI SINGH.**

The matter embodied in this thesis has not been submitted by me for the award of any other degree.

(DINESH KUMAR)
Candidate's Signature

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

Dr. JAI SINGH
Sr. Lecturer
Department of Applied Mathematics
Regional Engineering College,
Kurukshetra-132119
(Haryana) INDIA

Dr. P.C.PANDEY
Professor
Department of Mechanical and Industrial Engg.
University of Roorkee
Roorkee-247667 (U.P.)
INDIA

Dated: June 4, 1991

(Signature of Supervisors)

The Ph.D. viva-voce examination of Shri Dinesh Kumar research scholar has been held on..8.9.92.....at..2.30.p.m..

8.9.92 Examiner

Signature of GUIDE(s)
8/9/92

Signature of External Examiner
8/9/92

ABSTRACT

ANALYSIS & OPTIMIZATION OF SYSTEMS AVAILABILITY IN SUGAR, PAPER AND FERTILIZER INDUSTRIES

The sugar, fertilizer, paper mills etc. are complex, repairable engineering systems comprising of a large number of subsystems interconnected in series/ parallel or both. For efficient working, it is essential that the various subsystems of the plants remain perpetually in upstate. However, in reality the subsystems are subject to random failures. These however, can be inducted back into service after repairs/ replacements. The failures of the subsystems and their components are difficult to predict precisely, as they depend upon the operating conditions and repair policy used. From economic and operational point of view it would be desirable to ensure the maximum possible level of system availability.

This thesis is devoted to the analysis and evaluation of overall as well as various subsystem availabilities of the sugar, paper and fertilizer plants. Based on the analysis appropriate maintenance strategies for all the cases have been worked out. Subject matter of the thesis has been presented in different chapters as follows:

Chapter 1 - Introduction and literature survey

Chapter 2- Availability analysis of sugar plants

Chapter 3- Availability analysis of paper mills

Chapter 4- Availability analysis of fertilizer plants

Chapter 5- Maintenance scheduling for high availability

Chapter 6- Optimum repair/ operational budget

Chapter 7- Conclusion and scope for future work.

Besides, the thesis also includes a list of available references connected with the present work.

Repairable engineering systems are characterized by a large number of interconnected components with their own failure behaviour and repair time distribution. System availability in such cases is a complex function of failure and repair time distributions of the components in the system. Survey of literature reveals that majority of the published work deals with idealized systems with limited applicability. The analysis based on Markov model apply to series, parallel combined series/parallel systems. Several computer simulation models are also available.

For the performance analysis of sugar, paper and fertilizer plants, the availability models have been designed by application of Chapman- Kolmogorov equations and the steady state subsystem/system availabilities are obtained by the use of Laplace Transform approach.

The system models for the three plants have been based on the actual study conducted in medium sized sugar, paper and fertilizers plants located around Roorkee. The failure time/repair time data as well as the current maintenance practice in the plants were studied. Chapters 2, 3 and 4 present the availability models for three industries. Based on the availability models, the sensitivity analysis for various assumed operating conditions were carried out to assess the relative importance of the various subsystems vis-a- vis their failures, repairs, reliability etc. The analysis also incorporates the effect of common cause failures. Based on these models the best plant operating policies and their preventive maintenance schedules have been worked out and compared with the existing practice.

Chapter 6 is devoted to minimizing the maintenance cost allocation to various subsystems so as to achieve optimum repair policy. For this Lagrange's multiplier technique has been employed.

The findings of this thesis have been discussed with the management of the three plants with a view to apprise them of the potential benefits that would accrue through the implementation of the results.

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CONTENTS

GENERAL NOTATIONS

s : Laplace transform parameter

$$f(s) = L\ f(t) = \int_0^\infty \exp(-st)\ f(t)\ dt$$

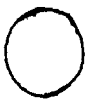
p_i : steady state probability in ith state

$p_o(t)$: probability that the system is working in full capacity without any standby unit at time 't'

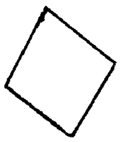
For trasition diagram :

Capital alphabats : full capacity working state

small alphabats : failed state



: operating state in full capacity



: operating state in reduced capacity

: failed state

CHAPTER-1

INTRODUCTION

In the civilized world of today it is almost unthinkable to survive without reliable power supply , telephone , transportation , medical - care and a host of other services and utilities . Reliability therefore forms an important subject of engineering research. Reliability in most general terms can be defined as the capability of a system to preserve its properties necessary to serve its intended purpose , under the normal conditions of operation over a stipulated period of time . The above description of reliability is very general in nature but helps in understanding its importance when applied to routine problems . Some of the systems whose reliability is of immediate consequence to the society in general are - power , transportation, medical, communication etc. Thus reliability appears to be everybody's concern . Unreliable systems are normally associated with high cost, lack of safety, loss of time as well as scarce resources. Unreliable defence equipment would have disastrous effect on the safety of the country and may have adverse effect on the morale of the forces. Some of the well known consequences of unreliable engineering systems that brought large scale misery and destruction can be found in recent history The famous New York black out, failures in Apollo and Challenger missions, Bhopal Gas disaster , Chernobyle nuclear power plant failure are few of the major events in this category.

The work embodied in this thesis is concerned with the reliability of process industries. The reported work deals with reliability and availability analysis of three types of process plants namely, sugar mill, fertilizer plant and the paper mill. These are complex large scale engineering systems and embrace a wide range of problems that would be encountered in ensuring a high degree of reliability both of individual elements and the system as a whole. These systems are repairable with the repair time varying randomly. In such cases, repair policy used would have a direct bearing on system reliability and operation. In some other cases the failed components if not attended, promptly, would affect the performance of other subsystems or may lead to accelerated failure of interconnected elements . Furthermore, replacements and repairs involve various types of costs and therefore , choice of an optimum repair/replacement policy is essential. Reliability modelling of the three types of process plants namely , sugar, paper and fertilizer has been based on the actual case studies of the plants situated in the neighborhood of Roorkee. Detailed analysis for reliability and availability of the subsystems and the system as a whole has been carried out. Based on this study, optimum operating and repair policies have been derived. For the modelling of systems, Chapman-Kolmogorov birth - death equations have been utilized. Results of the availability studies have next been utilized for the computation of optimum repair/operational policies for the plants.

1.1 MECHANICAL RELIABILITY

Importance of having reliable military equipment was recognized during and immediately after the second world war. It was found that to achieve high degree of reliability majority of the equipment used by army, navy and air force must be provided with major repairs. Further, these equipments were expensive to maintain. Studies were, therefore, undertaken to find ways and means of improving dependability of the defence equipment using statistical techniques.

1.2 SURVEY OF LITERATURE

The reliability research studies may be described under the following heads:

- Early concepts of reliability
- Reliability of simple systems
- Reliability of complex systems
- Redundant systems
- Reliability of missiles
- Reliability of mechanical systems
- System with common cause failures
- Reliability of large scale engineering systems (process plants)
- Software reliability

During 1940's the major statistical efforts to tackle reliability problems was in the area of quality control. Khintchine (1932) and Palm (1947) applied the reliability technology to machine maintenance with mathematical sophistication ,which was used subsequently by Erlang (1947), Feller (1957) and Morse(1958) to study the problems of telephone trunking.

In early 1950's certain areas of reliability, especially life testing of electronic components and problems related to missile reliability , started receiving greater attention. In missile industry Robert Lusser (1952), Richard Carhart (1953), Birnbaum (1961) and others worked actively in promoting reliability technology and identified problems of special interest in their fields.

During 1959-60 a class of reliability and logistic problems were solved. Hosford (1960) considered a single unit system with two states namely operating and failed, failure and repair being both of stationary type. He found the probabilities of the system being in either states at a particular instant of time. Barlow and Hunter (1961) analyzed the reliability of a single state unit while Mohan and Garg (1962) considered a two state unit system with general failure and exponential repair times.

Ososkov (1956), Khintchine (1960) have provided statistical justification for the use of Poisson distribution as the input distribution and exponential distribution for the repair time of complex systems. Mohan et al (1962) have analyzed a complex, two state system with independent failures and repair rates (distributed exponentially) for each of its n components and evaluated the probabilities of being in different states. Later

Garg (1963) considered complex systems with two types of components having exponential and general repair times. He has also considered the general waiting time distribution which were taken to be different for each component. Gaver (1963) studied the failure and availability time distributions for parallel systems. Agarawal (1964) extended this study for a complex system consisting of n components assuming that failure of any one component resulted in the failure of the system.

Reliability of redundant systems was studied by Weiss(1956). Similar studies were carried out by Flehinger (1958). Helpensin (1964) investigated into the waiting time distribution for a redundant system whereas, Kulshrestha (1966) analyzed a standby redundant complex system with general repair time distribution. Malhotra (1969) has discussed a complex system with components of two classes viz., R1 & R2 such that failure in R1 only would reduce the normal effiency of the system whereas, failure in R2 would lead to complete breakdown of the system.

Malhotra (1969), Kim et al (1972) have computed system reliability by taking components as a branch of the systems while Applebaum (1965) divided a complex system into subgroups mutually independent of each other. Majority of the work reported in the literature assumes the use of perfect switch over devices. But in practice, a perfect switching device is not always feasible. Prakash and Kumar (1970) relaxed the assumption of perfect switch over device taking exponential waiting time distribution for a complex system. Later, Dass(1972) generalized Prakash's model by assuming general waiting and repair time distributions. He devided the components into two classes L1 and L2 having k and n components respectively.

This work was further extended by Singh (1976) by assigning priorities to repair. He also extended the discussion to general failure and repair distribution for complex components. Singh (1976) studied the mission reliability of a complex system with priority repair policy having imperfect switching.

1.3 SYSTEM WITH COMMON CAUSE FAILURE

Gangloft (1975) has discussed the case of common cause failure ,he defines the common cause failure in a system when multiple units or components at any instant fail due to single common cause. Such failures may occur due to equipment design deficiency, operations and maintenance errors , external environment, natural/artificial catastrophe, common manufacturing defects, functional deficiency etc. Flemming and Hannaman (1976) have analyzed the problem of common cause failures in cooling systems. Whereas, Cate et al (1977) extended this idea to complex systems and developed a computer approach useful for qualitative and quantitative methods. Fleming (1975) and Dhillon (1977) analyzed the problem of system reliability with identical units having statistically independent and dependent (common cause) failures. Dhillon (1978) has provided an extensive bibliography for all the above cases. Sharma et al (1985), Bennet et al (1977) suggested a methodology for failure prevention and repair policies e.g. preventive maintenance for systems with common cause failures.

1.4 RELIABILITY OF PROCESS PLANTS

Freshwater and Buffham (1969) have analyzed the reliability of process plants by making the simple assumptions. Later Lenz (1970) considered the reliability for equipment design in process plants while Bently and Reid (1970) considered unreliability factors in chemical plants. The detailed equipment analysis was done by Ufford (1972) and Mcfatter (1972), Whitaker (1973) introduced the idea of the use of statistical models for process plants and obtained closed formed solutions for exponential failure and repair times for each of the subsystems. Wood et al (1974) have applied statistical modelling for determining the plant reliability. William (1974) discussed the reason for shutdown of the plant , which helped Priel (1974) and Lee (1975) in formulating a systematic maintenance organization and a methodology for failure analysis of the process. Holmes (1976) suggested a new technique for the evaluation of system availability of the plant at design stage itself. This approach was next utilized by Cherry et al (1978) for calculating the long run availability of a plant assuming constant failure and repair times for each of the components. Maintenance,replacement, reliability engineering in process industries by taking into its account various states were discussed by Mc-call (1965), Lenz (1970), Lee (1975), Holmes (1976), Neale et al(1979), Keller -

Stipho (1981), Thomas (1985) and Kumar et al (1989, 1990) giving possible cause of failure, utilization of man power and machine and utilization of the availability resources in the best possible manner. Singh (1982) and Dutta (1983) have applied mathematical theory of reliability to the problems in sugar plants (a process industry). The idea originally initiated by Singh (1980, 1982, 1984) was further extended by Kumar et al (1988, 1989, 1990) to study in detail the reliability and availability of sugar, paper and fertilizer industries.

1.5 RELIABILITY OF MECHANICAL COMPONENTS

Kececioglu and Lamarre (1980), Dhillon (1980) have discussed the reliability of mechanical components . They took into consideration factors such as-stress, load, vibrations, speed as independent variables to calculate the component failure for design and life testing. Churchley (1987), Gray and Harris (1988) have suggested a method for assessing the reliability of very high quality mechanical systems.

1.6 SOFTWARE RELIABILITY

Large scale production and reduced maintenance cost of softwares as compared to that of hardware of computer systems during late sixties and seventies has attracted attention to the life cycle management of software systems. The software reliability can be defined as the probability of a given software, operating for a specified time period, without a are error, when used within the designed limit on the priate machine. Various models have been proposed for ating the reliability by Sukert(1977) followed by Littlewood) and Shanthikumar (1980,1981). The software reliability s use the information about the number of errors debugged g the development of a software programme. This information ed to characterize the model parameters that can be used to ct the number of failures or some other measures of bility in the future.

OME DEFINITIONS

bility and availability: The probability that a device is rming its purpose within the specified tolerance of the res of performance for the specified period of time under iven operating conditions is called reliability. Statistical res of how well a system behaves under actual operating tions or meets its design objectives over a period of time provided by the concept of system reliability and ability.

wise availability: Probability that a system will be able perate or would be ready for satisfactory operation at any of time under stated conditions is called point wise ability or operational readiness. Barlow and Proschan (1967) the following definitions.

1. Interval availability: The expected fraction of a given irterval of time that the system will be able to operate within acceptable tolerance (efficiency).

2. Limiting interval availability: The expected fraction of time in the long run during which the system operates satisfactorily.

3. Interval reliability: The probability that at a specified time, the system is operating and will continue to operate for a given interval.

4. Limiting interval reliability: is the limit of interval reliability as $t \to \infty$.

5. Reliability of a process: This is defined as the probability that every equipment engaged in the process will perform the designed function satisfactorily over the required period of time under specified operating conditions.

6. Availability of a process or equipment: This is defined as the probability that all the units of the system are operating satisfactorily at any point of time (operating + active repair + administrative + logistic time) when used under given operating conditions.

7. Mean time to failure (MTTF): For a particular interval MTTF is defined as the total functioning life of a population of an item divided by the total number of failures within the population

during the measurement interval. Alternatively, if f(t) is the failure density function of an equipment then MTTF of a probability density function with continuous random variable time t is $MTTF = \int_0^{\infty} t f(t)\, dt$.

From the above mentioned definitions, it is implied that a reliable system will not fail to perform the assigned task over specified period of time.

1.8 EVALUATION OF RELIABILITY

Failure of mechanical systems depends upon a number of parameters which can be evaluated by observing the working of either a similar device or its model in the laboratory under specified conditions. For a mathematical treatment of reliability, certain statistical distributions with various parameters are used which are approximations to those actually encountered and for this reason, the reliability equations approach to reality only to extent that the actual distributions approach the assumed ones.

Reliability can be obtained by repeatedly testing a given population under the given conditions. Thus if N_o is the size of the population out of which N_S units survive the test while N_f fail, then the reliability function R(t) is given by (Barlow & Proschan 1967)

$R(t) = N_S/N_o = 1-(N_f/N_o)$

or, $dR(t)/dt = -(1/N_o)\,[dN_f/dt]$

also, the failure rate is given by:

$$\lambda = -N_o/N_s(dR(t)/dt) = -(1/R(t))dR(t)/dt$$

which gives : $R(t) = \exp(-\int_0^t \lambda\, dt)$

1.8.a MARKOV PROCESS: A stochastic process in a physical system S is known as a Markov process (or a process without an aftereffect) if the occurence of any future state of the system is independent of any past state and depends only on the present state.

Use of Markov chains to model stochastically deteriorating systems has been reported by a large number of researchers. Extensive work to utilize this technique for analysing series/ parallel production systems can be found in literature.

Since in most of the mechanical systems failures show Markov character, their failure can be approximated by poisson distribution. An important mathematical paper in this context was published by Moore and Shannon(1956). It dealt with relay network reliability.

In 1956, another report was published (G. Weise), which introduced the use of semi - Marrkov processes to solve maintainability problems.

Earlier authors associated with the study of queuing & reliability problems used Chapman- Kolmogorov (C-K) birth-death equations. The birth-death process is a special type of continuous time Markov process with discrete state space

0,1,2,...such that the probability of transition from state i to state j in time Δt is $o(\Delta t)$ whenever $|i-j|\geq 2$. In other words, changes take place through transition only from a state to its immediate neighboring state. These C-K birth-death equations are differential difference equations and can be solved using Laplace transforms and generating functions. Since in case of complex systems inversion of Laplace transform of probability functions is very difficult, Smith (1958) introduced the renewal theory approach for solving such problems. If the failure rate /service rate or both are variable, the process ceases to be a Markov process. Such problems are diffcult to solve. Cox (1955) introduced the supplementary variable technique to analyze such systems without Markov property. Several researchers(Garg, Mohan and Garg, Gaver, Agarwal,Singh, Kumar et al and others) used the supplementary variables technique for evaluating the reliability of complex systems. Singh (1976, 1980), Kumar et al (1989) analyzed several complex systems using supplementary variable technique and direct integration method (without using Laplace Transforms and generating functions).

We may categorize the various methods used for the above purpose based on the following:

1. C-K birth death equations
2. Laplace transforms and generating functions.
3. Renewal theory.
4. Supplementary variables technique.
5. Simulation technique.

$$\frac{dp_n(t)}{dt} = p_n'(t) = -(\tau+\mu)p_n(t) + \tau p_{n-1}(t) + \mu p_{n+1}(t) \ , \ n>0 \quad \text{---(1.8.3)}$$

These difference - differential equations are called Kolmogorov forward equations. To solve these equations we introduce the concept of generating function (transforms) as follows:

Let $G(z,t) = \sum_{n=0}^{\infty} p_n(t)\, Z^n, \quad (|Z| \leq 1)$ ----------------(1.8.4)

G(z,t) is the probability generating function.

Using the conditions $p_0(0)=1$, $p_n(0)=0$ and multiplying successively by $1, z, z^2, \ldots\ldots\ldots$ and adding, we obtain after simplification

$$\frac{z\delta G}{\delta t} = \{\tau z^2 - (\tau + \mu)z + \mu\}G - \mu\ (1-z)p_0(t) \quad \text{-------------(1.8.5)}$$

From 1.8.4 we have $G(z,0) = z^n (n \geq 0)$. Taking Laplace transforms of 1.8.5 and simplifying we get

$$\overline{G}(z,s) = \frac{z^{n+1} - \mu(1-z)\overline{p}_0(s)}{(\tau+\mu+s)z - \mu - \tau z^2} \quad \text{-------------(1.8.6)}$$

where, s is Laplace transform parameter.

The denominator on the right hand side of equation (1.8.6) has two zeroes namely (putting denominator equal to zero, ref J. Medhi 1982)

$$\epsilon = \frac{(\tau+\mu+s-\sqrt{(\tau+\mu+s)^2-4.\tau\mu})}{2\tau}$$

$$\eta = \frac{(\tau+\mu+s+\sqrt{(\tau+\mu+s)^2-4.\tau\mu})}{2\tau}$$

Where the square root is taken such that its real part is positive. Clearly $|\epsilon| < |\eta|$ and

$$\epsilon+\eta = \frac{(\tau+\mu+s)}{\tau} \quad ; \quad \epsilon\eta=\mu/\tau$$

By Rouche's theorem $(\tau + \mu + s)z - \mu - \tau z^2$ has only one zero in the unit circle ; this clearly shows $z = \epsilon$. Now since $G(z,s)$ converges in the region $|z| = 1$, $R_e(s) > 0$, the zeros of the numerator and denominator on right hand side of 1.8.6 must coincide, and therefore

$$\bar{p}_0(s)=\epsilon^{n+1}/\mu(1.-\epsilon)$$

Substituting the values of $\bar{p}_0(s)$ in 1.8.6 we obtain

$$\bar{G}(z,s)=\frac{(z^{n+1}-(1-z)\epsilon^{n+1}/(1.-\epsilon))}{\tau(z-\epsilon)(\eta-z)}$$

expanding the above term containing powers of z, $p_n(s)$ can be obtained as the coeff. of z^n. $p_n(t)$ is obtained by inverting the transforms $p_n(s)$. This method of analysis and the results are due to Bailey (1954).

(b). In the classical Poisson process, the intervals between successive occurrences are independently and identically distributed with a negative exponential distribution. Suppose that there is a sequence of events E such that the interval between successive occurrences of E are distributed independently and identically but have a distribution not necessarily negative exponential; we have then a certain generalization of the classical Poisson process. The corresponding process is called a renewal process. A detailed account about renewal theory can be found in Medhi (1982).

1.8.c Non Markovian Process: When we do not have a negative exponential distribution as introduced above in (b) the nature of the problem is non-Markovian. Using supplementary variables technique the problem can be changed to Markovian in character. We may analyze this problem using supplementary variables technique (instead of renewal theory approach) as follows:

Consider four identical units in a system with common cause failure where system repair time are arbitrarily distributed (Dhillon(1977)).

The supplementary variable technique is used to develop the equations for the model under the following assumptions:

-Common cause and others failures are statistically independent.

-Common cause failures can only occur with more than one unit.

-Units are repaired only when the system fails. A repaired system is as good as new.

-System repair times are arbitrarily distributed.

i= number of failed units, while the system is in working state (i=0,1,2,3).

j= 4 failed state but not due to common cause.

$p_i(t)$=Probability that system is in working state i, at time t.

$p_j(y,t)$=Probability density that the system is in failed state j, and has an elasped repair time y.

$\mu_j(y)$= Repair rate when in state j with elasped repair time of y.

β_i= Constant common cause failure rate of the system when in state i, $\beta_3=0$.

T_i=Constant failure rate of a unit, for other than common cause failures, when the system is in state i, i=0,1,2,3.

The differential equations are (Dhillon & Singh 1981):

$$\frac{dp_0(t)}{dt} + (T_0+\beta_0)p_0(t)=\int_0^{\infty} p_4(y,t)\mu_4(y)dy + \int_0^{\infty} p_{4,cc}(y,t)\mu_{4,cc}(y)dy$$

$$\frac{dp_i(t)}{dt}+(T_i+\beta_i)p_i(t)-T_{i-1}p_{i-1}(t)=0. \quad ,i=1,2,3;\ \beta_3=0.$$

$$\frac{\delta p_j(y,t)}{\delta t}+\frac{\delta p_j(y,t)}{\delta y}+\mu_j(y)p_j(y,t)=0. \quad ,j=4 \text{ or } 4,cc$$

$$p_4(0,t)=T_3p_3(t)$$

$$p_{4,cc}(0,t)=p_0(t)\beta_0+p_1(t)\beta_1+p_2(t)\beta_2$$

$p_i(0)=1.$, for i=0. otherwise $p_i(0)=0.$

$p_j(y,0)=0.$ for all j

Solution to the above problem is done using Laplace transforms and has been given by Dhillon(1977).

1.8.d Simulation Technique:

Simulation is a numerical technique for conducting experiments on a digital computer, which involves certain type of mechanical and logical relationship necessary to describe the behaviour and structure of a complex real system over extended periods of time. Simulation has often been described as the process of creating the essence of reality without ever actually attaining that reality itself. Simulation is one of the easiest tools of management science to use, having some drawbacks. It is very hard to apply and to draw accurate conclusions. The skills required to develop and operate an effective simulation model are substantial.

The variability or dispersion of simulation results is a significant problem in itself and require long and complex statistical analysis in order to draw meaningful conclusions. Simulation however is the appropriate technique when it is not feasible to experiment on the system itself or when direct analytic techniques are not available Joseph et al (1966, 1981) Shigley (1967) and Frederick (1974).

1.8.e Matrix method: For finite n state space the birth-death difference- differential equations can be written in the form of matrix differential equations. These equations are solvable by usual methods devised for solving algebraic or differential equations.Details can be found in Singh(1975), Medhi(1982), Linton(1989).

The survey of literature reveals that most of the workers have applied reliability theory to deal with the electrical and electronics systems and relatively little research work has been undertaken to apply the theory of reliability to mechanical systems particularly process industries. The work embodied in this thesis is devoted to the reliability and related studies of three main process industries e.g.sugar, paper and urea fertilizer manufacturing industries. The observed failure and repair data in each case has been utilized to develop mathematical models for the computation of system reliability, availability and mean time to system failure.

Chapter-2 is devoted to the detailed study of the problem in sugar industries. For each model the differential equation (birth-death equations) are obtained and solved using Laplace transform technique, which is an analytical and simple approach to analyze the complex systems.

Chapter-3 deals with detailed reliability analysis of paper industry.

Chapter-4 is devoted to reliability in urea based fertilizer industry.

Chapter-5 discusses some maintenance policies proposed for the above mentioned industries and suggests suitable steps to be taken.

Chapter-6 deals with the resource allocation of the system discussed in chapter 2 to 4.

Chapter-7 The work done in the chapter 2 to 6 is concluded with scope for future work in this area.

CHAPTER-2

AVAILABILITY ANALYSIS OF A SUGAR PLANT

2.1 INTRODUCTION

The work described in this chapter is based on a study of medium sized sugar plant producing 100 tones of sugar per day, situated in North India. For the production of sugar, the raw material (sugar cane) is transported to the plant by various means such as rail, tractor-trolly, trucks etc. The sugar cane as received, is fed to the cutters by a chain conveyor system for chopping. The chopped pieces are sent to crushers by another chain conveyor system where they are crushed progressively by a series of crushers so as to squeeze the sugar cane for maximum possible extraction of juice. The squeezed sugar cane (bagasse) is used up in the plant boiler as fuel. The juice so obtained normally contains impurities in the form of small pieces of bagasse and mud and hence is passed through a number of filters in series. Simultaneously, the juice is heated-up by steam to attain a definite temperature and pH value. The heated juice is stored in a tank where sulpher dioxide gas is passed through it for separation of mud (heating is also done for clear separation). The juice is next sent through a clarifier where further separation of mud by gravity process takes place. The clear juice so obtained is stored in a evaporator where a part of the water in the juice evaporates and then passes through sulphitor for final refining. The concentrated and refined juice is taken to cooking pans (heated by steam) where the water in the juice gets evaporated, converting the juice to viscous fluid.The juice in semisolid form is transferred to crystallizers (equipped with long duration slow heating) to evaporate the remaining water.

On this account the juice is converted into dark brown magma (molasses) containing yellow sugar crystals in suspended form. The output from the crystallizers is passed through centrifuges to separate out sugar crystals from magma. The yellowish colour of the sugar crystals is washed out by a chemical process. The remaining crystal free magma is recycled through sulphitor, evaporator, cooking pans, crystallizers, drier and centrifuges to achieve higher output. Finally the sugar crystals are cooled and collected in graded bags. The sugar in powder form (if any) is processed again through crystallisation process.

The sugar production process is a complex continuous process , is shown schematically through fig. 2:1 which also shows that the plant essentially consists of three major subsystems viz., feeding, refining and crystallisation.

The detailed availability analysis of the three subsystems of the sugar plant are presented in the following sections.

2.2 ASSUMPTIONS

For the purpose of system availability modelling the following assumptions have been made.

(i) Mean failure /repair rates of the units are constant over time , for equal interval of time and are statistically independent.

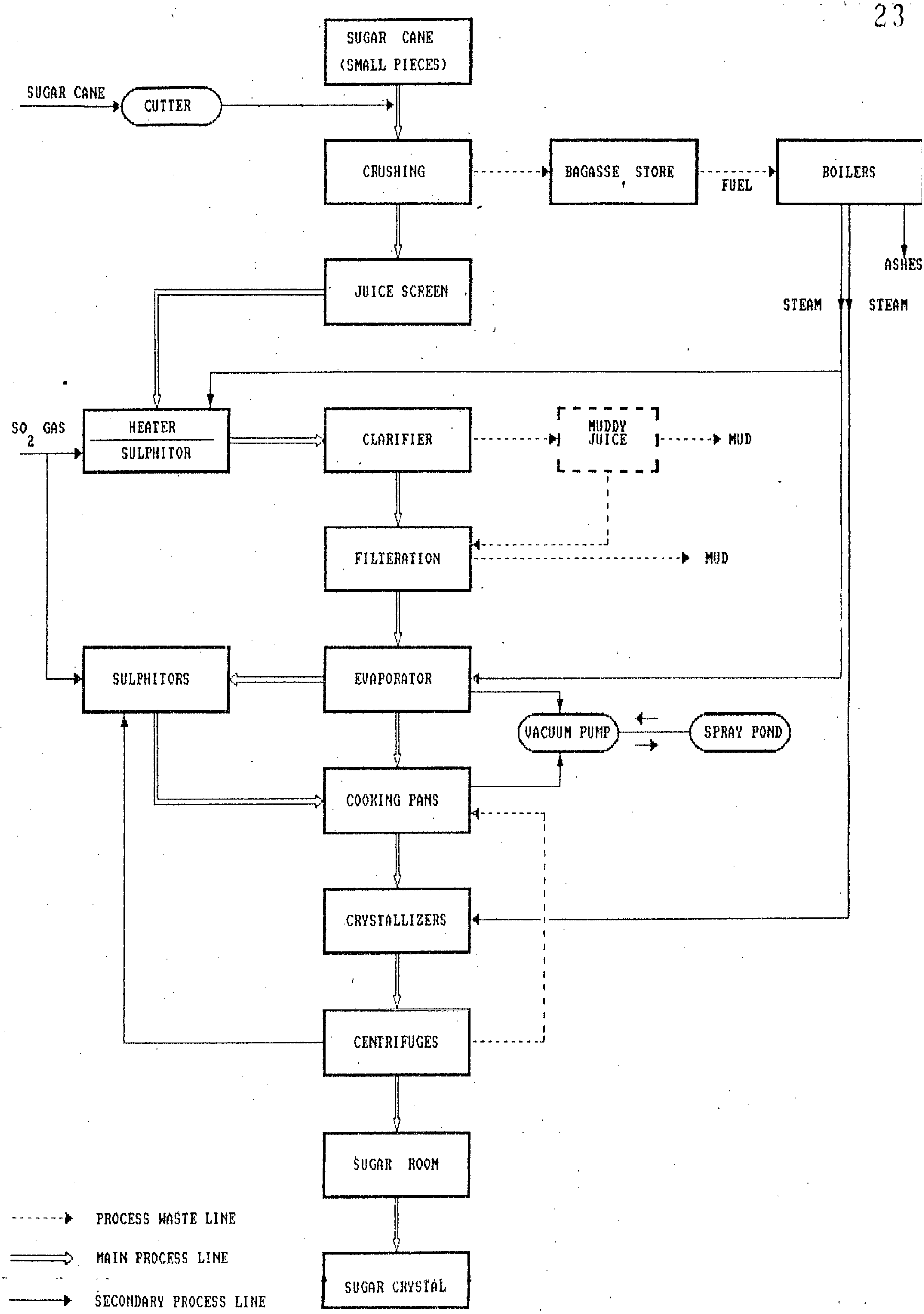


FIG. 2.1. SCHEMATIC DIAGRAM OF SUGAR PRODUCTION PROCESS

(ii) The repaired units are as good as new performance wise. Repair/replacement is under taken upon failure only.

(iii) Each subsystem has separate repair facility and subsystems do not wait for the availability of repair facilities.

(iv) Service includes repair and /or replacement.

(v) System time to failure / repair are exponentially distributed. This would imply that there are no simultaneous failure of unit in a subsystem or among the subsystems and the probability of more than one failure /repair in a time interval Δt is zero.

Based on the above assumptions transition diagrams of the subsystems under consideration have been prepared. These are given for feeding , refining and crystallisation subsystems respectively in figs 2.4:2, 2.5:2 & 2.6:2.

2.3 NOTATIONS:

The following notations have been employed for subsystems:

State	Feeding system	Refining system	Crystallisation system
Transition diagram	fig. 2.4:2	fig. 2.5:2	fig. 2.6:2
Full capacity working	A_i	B_i	D_n
Reduced capacity working	A_{4i}	$\bar{B}_3$, $\bar{B}_4$	$\bar{D}_n$
Failed	a_i	b_i	d_n
Failure rate	α_i	α_j	σ_r
Repair rate	β_i	β_j	μ_r
Trasition state from operating to reduced	---	T_1, T_2 in B_3&B_4	T_m, m=i,j,k,l for D_1, D_2, D_3 & D_4
Probability of reduced capacity working	p_3, p_4 & p_5	p_3, p_4, p_7	$p_{1,2,3,4}$
Probability of failed state	$p_{1,2}$& $p_{6,7,--11}$	$p_{1,2,5,6}$& $p_{8,9,--15}$	$p_{5,6,--9}$
Suffix	i=1,2,3,4	i=1,2,3,4 j=i+4	n=1,2,3,4,5 r=n, c for common cause failure

2.4 _FEEDING SYSTEM

2.4.a <u>SYSTEM DESCRIPTION</u>: The feeding system consists of the following subsystems (fig. 2.4:1)

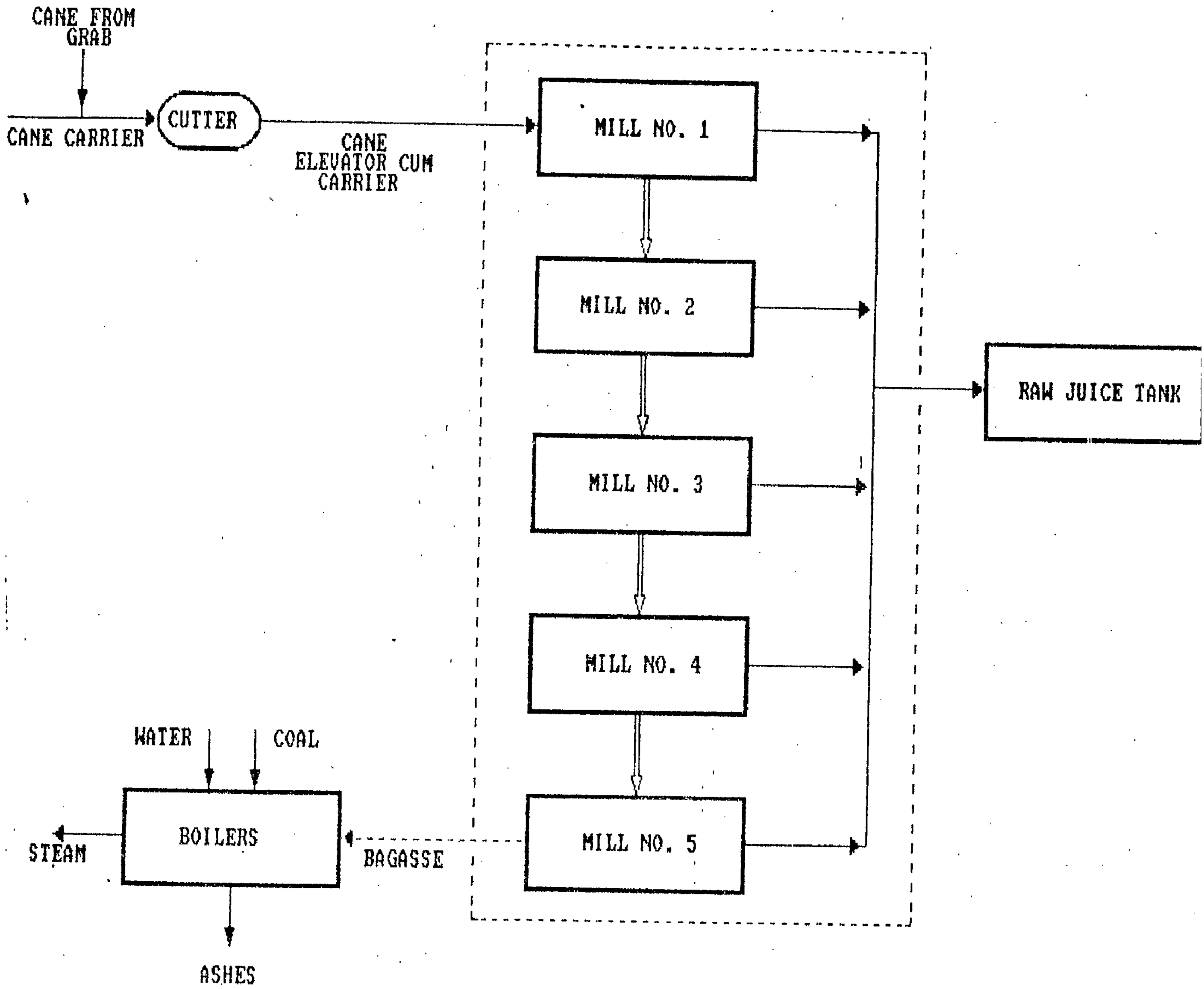


FIG.2.4:1. SCHEMATIC DIAGRAM OF THE SUGAR CANE FEEDING SYSTEM

i) The sugar supply system (A_1) comprising of 3 units (i) in series as below;

- chain conveyor to carry the sugar cane to cutters,
- cutter for chopping the sugar cane into small pieces and
- chain conveyor for carrying small pieces to crushing units.

Failure of any one unit in the supply system would mean failure of the feeding system.

ii) The crushing system (A_2) having 5 or 6 units (j) in series. crusher is equipped with three rollers in a particular configuration to squeeze the sugar cane progressively as it passes through the crushers. Failure in this subsystem would mean failure of the total feeding system.

iii) The bagasse carrying unit (A_3) having 2 or 3 units (k) having a combination of bucket elevator and conveyor in series. Failure of any one unit would lead to the pilling up of bagasse in front of crushing house, affecting fuel supply to the plant boiler and hence reduction in efficiency of the feeding system (reduced state).

iv) The heat generation subsystem (A_4) having 3 boilers (l) in parallel. These boilers generate steam at high pressure and temperature to be used by various units of the plant. A failed boiler would mean reduction in the efficiency of the heating system.

Based on the description of the feeding system and the relevant assumptions a transition diagram (fig. 2.4:2) has been prepared which presents a visual picture of the states of the system at any particular instant.

2.4.b <u>RELIABILITY OF FEEDING SYSTEM</u>:

Let $p_0(t)$ be the probability that the system is in good state at time 't',

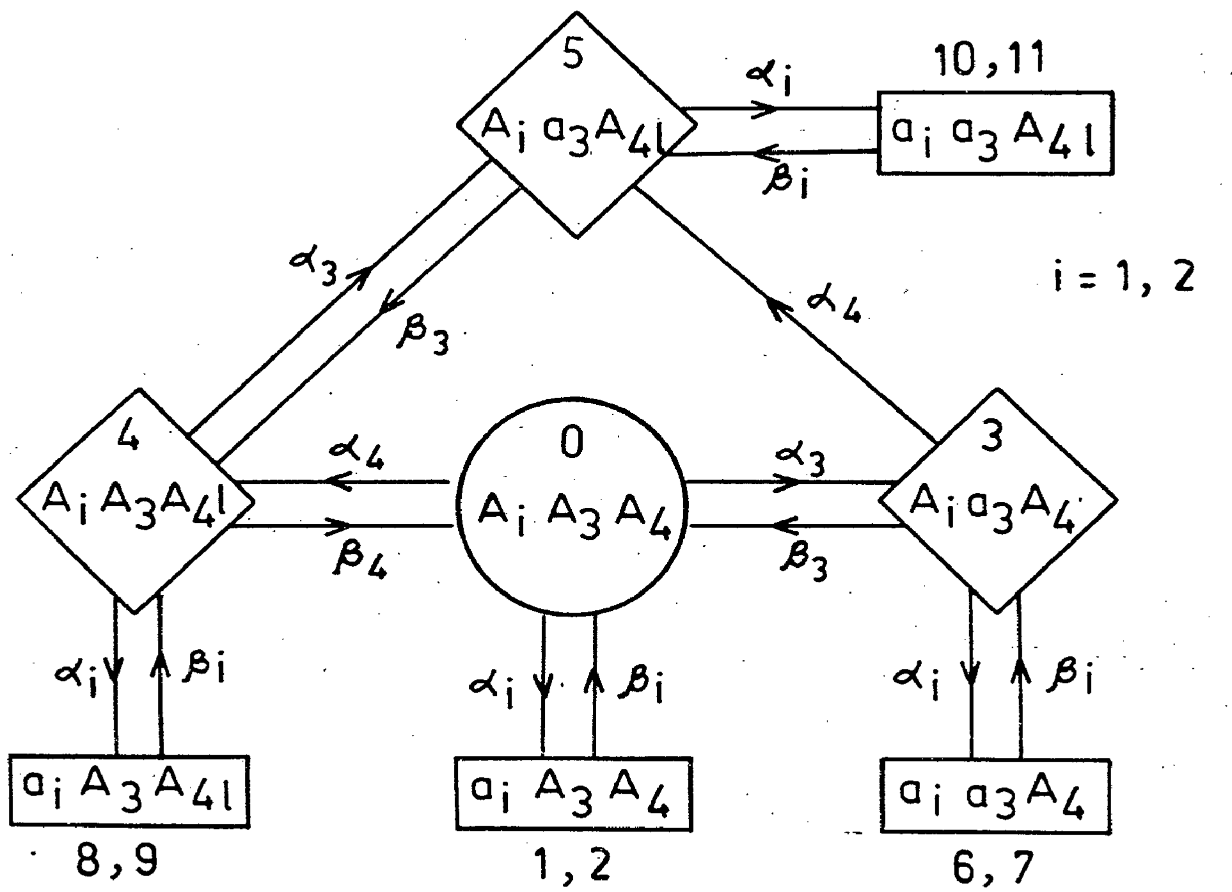


Fig.2.4:2 Transition diagram for feeding system.

Refering to the transition diagram and argueing in the same manner as above, the probability of ending up in reducecd state 3 when initially in good state is $\alpha_3 \Delta t p_o(t)$. The probabilities of ending up in reduced working state 3 from initial failed states 6 and 7 are $\beta_1 \Delta t\ p_6(t)$ and $\beta_2 \Delta t\ p_7(t)$ respectively.

The system may stay in reduced state 3 with probability $[1-(\alpha_1+\alpha_2+\alpha_4+\beta_3)\Delta t]\ p_3(t)$. since all these events are mutually independent therefore:

$$p_3(t+\Delta t)=[1-(\alpha_1+\alpha_2+\alpha_4+\beta_3)\Delta t]p_3(t)+\beta_1\Delta t\ p_6(t)+\beta_2\Delta t p_7(t) +\alpha_3\Delta t\ p_o(t).$$

or

$$\lim_{\Delta t\to 0} \frac{p_3(t+\Delta t)-p_3(t)}{\Delta t}+(\alpha_1+\alpha_2+\alpha_4+\beta_3)p_3(t)=\beta_1 p_6(t)+\beta_2 p_7(t)+\alpha_3 p_o(t)$$

or $$\left(\frac{d}{dt}+\alpha_1+\alpha_2+\alpha_4+\beta_3\right)p_3(t)=\beta_1 p_6(t)+\beta_2 p_7(t)+\alpha_3 p_o(t) \quad \text{.......(2.4.2)}$$

Similarly, we can derive the values of $p_4(t)$ & $p_5(t)$ as follows:

$$\left(\frac{d}{dt}+\sum_{i=1}^{2}\alpha_i+\beta_4\right)p_4(t) =\beta_1 p_8(t)+\beta_2 p_9(t)+\beta_3 p_5(t)+\alpha_4 p_o(t) \quad \text{......(2.4.3)}$$

$$\left(\frac{d}{dt}+\alpha_1+\alpha_2+\beta_3\right)p_5(t)=\alpha_3 p_4(t)+\alpha_4 p_3(t)+\beta_1 p_{10}(t)+\beta_2 p_{11}(t) \quad \text{.....(2.4.4)}$$

The failed state probability $p_i(t)$ is obtained from $p_k(t)$ if at time t system is in working state and failure occurs in time Δt, the probability of this event is equal to $\alpha_i \Delta t\ p_k(t)$. Another possibility is that at time t the system is in failed state and in time interval Δt ,there is no repair in the system. Probability of this event is given by $(1-\beta_i\Delta t)\ p_i(t)$.

Since all these events are independent, therefore we can write

$$p_i(t+\Delta t)=(1-\beta_i\Delta t)p_i(t)+\alpha_i\Delta t\ p_k(t)$$

or

$$\lim_{\Delta t\to 0} \frac{(p_i(t+\Delta t)-p_i(t)}{\Delta t}+\beta_i p_i(t)=\alpha_i p_k(t)$$

$$[MTTF]_1 = \frac{\left(1+\dfrac{\alpha_3}{\alpha_4+\beta_3}\right)\left(1+\dfrac{\alpha_4}{\beta_4}+\dfrac{\alpha_3\,\alpha_4}{\beta_3\beta_4}\right)}{\left(1+\sum\limits_{i=1}^{2}\dfrac{\alpha_i}{\beta_i}\right)\left[1+\dfrac{\alpha_3}{\alpha_4+\beta_3}\left\{\beta_3+\dfrac{\alpha_4}{\beta_4}\left(\dfrac{1}{(\alpha_4+\beta_3)}+\dfrac{1}{\beta_3}\right)\right\} + \left(1+\dfrac{\alpha_3}{\beta_3}\right)\left\{\dfrac{\alpha_4}{\beta_4}+\dfrac{\alpha_3\alpha_4}{\beta_4(\alpha_4+\beta_3)}\right\}\right]} \quad \text{---}(2.4.7)$$

2.4.c STEADY STATE BEHAVIOUR

Steady state probabilities of the system are obtained from the condition $t \to \infty$ when $(d/dt) \to 0$ thus from equations (2.4.1) to (2.4.5) we get:

$p_1=(\alpha_1/\beta_1)p_o$; $p_2=(\alpha_2/\beta_2)p_o$;

$p_3=\{\alpha_3/(\alpha_4+\beta_3)\}p_o$; $p_4=(\alpha_4/\beta_4)[1+\alpha_3/(\alpha_4+\beta_3)]p_o$;

$$p_5=\frac{\alpha_3\alpha_4}{\beta_3\beta_4}\left(1+\frac{\alpha_3}{(\alpha_4+\beta_3)}\right)p_o \quad ; \quad p_6=(\alpha_1/\beta_1)p_3;$$

$p_7=(\alpha_2/\beta_2)p_3$; $p_8=(\alpha_1/\beta_1)p_4$;

$p_9=(\alpha_2/\beta_2)p_4$; $p_{10}=(\alpha_1/\beta_1)p_5$;

$p_{11}=(\alpha_2/\beta_2)p_5$

Thus all the probabilities are obtained in terms of p_o.

Whereas, the probability p_o is obtained using normalizing condition;

$$\sum_{i=0}^{11} p_i=1$$

or

$$p_o=[\{1+(\alpha_1/\beta_1)+(\alpha_2/\beta_2)\}\{1+\alpha_3/(\alpha_4+\beta_3)\}\{1+(\alpha_4/\beta_4)+(\alpha_3\alpha_4/\beta_3\beta_4)\}]^{-1}$$

The steady state availability$[AV_1]$ of the system is obtained as

$$[AV_1]=p_o+p_3+p_4+p_5=[1+\sum_{i=1}^{2}\alpha_i/\beta_i]^{-1}\,..........(2.4.8)$$

Equation (2.4.8) shows that the subsystems A_1 and A_2 mainly govern the system feeding availability.

2.4.d BEHAVIOURAL ANALYSIS

For assumed values of the system parameters, the effect of failure and repair rates of subsystems A_1 and A_2 upon availability has been computed from equation 2.4.8 and the results are presented in tables 2.4-1 to 2.4-3.

Table 2.4-1: Effect of failure rate of sugar cane supply system and crushing system, β_2=0.1

β_1	α_1	Availability[AV_1]				
		α_2 = 0.0	α_2=0.025	α_2=0.05	α_2=0.075	α_2=0.1
0.1	0.00	1.0000	0.8000	0.6667	0.5714	0.5000
	0.05	0.6667	0.5714	0.5000	0.4444	0.4000
	0.10	0.5000	0.4444	0.4000	0.3636	0.3333
0.3	0.00	1.0000	0.8000	0.6667	0.5714	0.5000
	0.05	0.8571	0.7059	0.6000	0.5217	0.4615
	0.10	0.7500	0.6316	0.5455	0.4800	0.4286
0.5	0.00	1.0000	0.8000	0.6667	0.5714	0.5000
	0.05	0.9091	0.7407	0.6250	0.5405	0.4762
	0.10	0.8333	0.6897	0.5882	0.5128	0.4545

Table 2.4-2 : Effect of failure rate of sugar cane supply system and crushing system β_2=0.3(repair rate of crushing system)

β_1	α_1	Availability[AV_1]				
		α_2 =0.0	α_2=0.025	α_2=0.05	α_2=0.075	α_2=0.1
0.1	0.00	1.0000	0.9231	0.8574	0.8000	0.7500
	0.05	0.6667	0.6316	0.6000	0.5714	0.5455
	0.10	0.5000	0.4800	0.4615	0.4444	0.4286
0.3	0.00	1.0000	0.9231	0.8574	0.8000	0.7500
	0.05	0.8571	0.8000	0.7500	0.7059	0.6667
	0.10	0.7500	0.7059	0.6667	0.6316	0.6000
0.5	0.00	1.0000	0.9231	0.8574	0.8000	0.7500
	0.05	0.9091	0.8451	0.7895	0.7407	0.6977
	0.10	0.8333	0.7792	0.7317	0.6896	0.6522

Table 2.4-3 : Effect of failure rate of sugar cane supply system and crushing system β_2=0.5

β_1	α_1	Availability[AV_1]				
		α_2=0.0	α_2=0.025	α_2=0.05	α_2=0.075	α_2=0.1
0.1	0.00	1.0000	0.9524	0.9091	0.8696	0.8333
	0.05	0.6667	0.6452	0.6250	0.6061	0.5882
	0.10	0.5000	0.4878	0.4762	0.4651	0.4545
0.3	0.00	1.0000	0.9524	0.9091	0.8696	0.8333
	0.05	0.8571	0.8219	0.7895	0.7595	0.7317
	0.10	0.7500	0.7229	0.6977	0.6742	0.6500
0.5	0.00	1.0000	0.9524	0.9091	0.8696	0.8333
	0.05	0.9091	0.8696	0.8333	0.8000	0.7692
	0.10	0.8333	0.8000	0.7692	0.7407	0.7143

The tables 2.4-1 to 2.4-3 show that for a particular value of β_2 (repair rate of the crushing system) the availability decreases with increase in α_2 (the failure rate). Moreover for fixed values of β_1, α_1 and α_2 the availability of the crushing system increases with β_2. Thus the failure rate in the crushing system should be brought to the smallest possible value providing the maximum possible repairs, highly reliable system and minimizing the failure through appropriate maintenance.

The reliability analysis of the system with general repair time using Lagrange's method for solution of partial differential equations has been discussed by the author elsewhere in [55].

2.5 REFINING SYSTEM

2.5.a SYSTEM DESCRIPTION : The juice refining system consists of the following four subsystems (fig. 2.5:1)

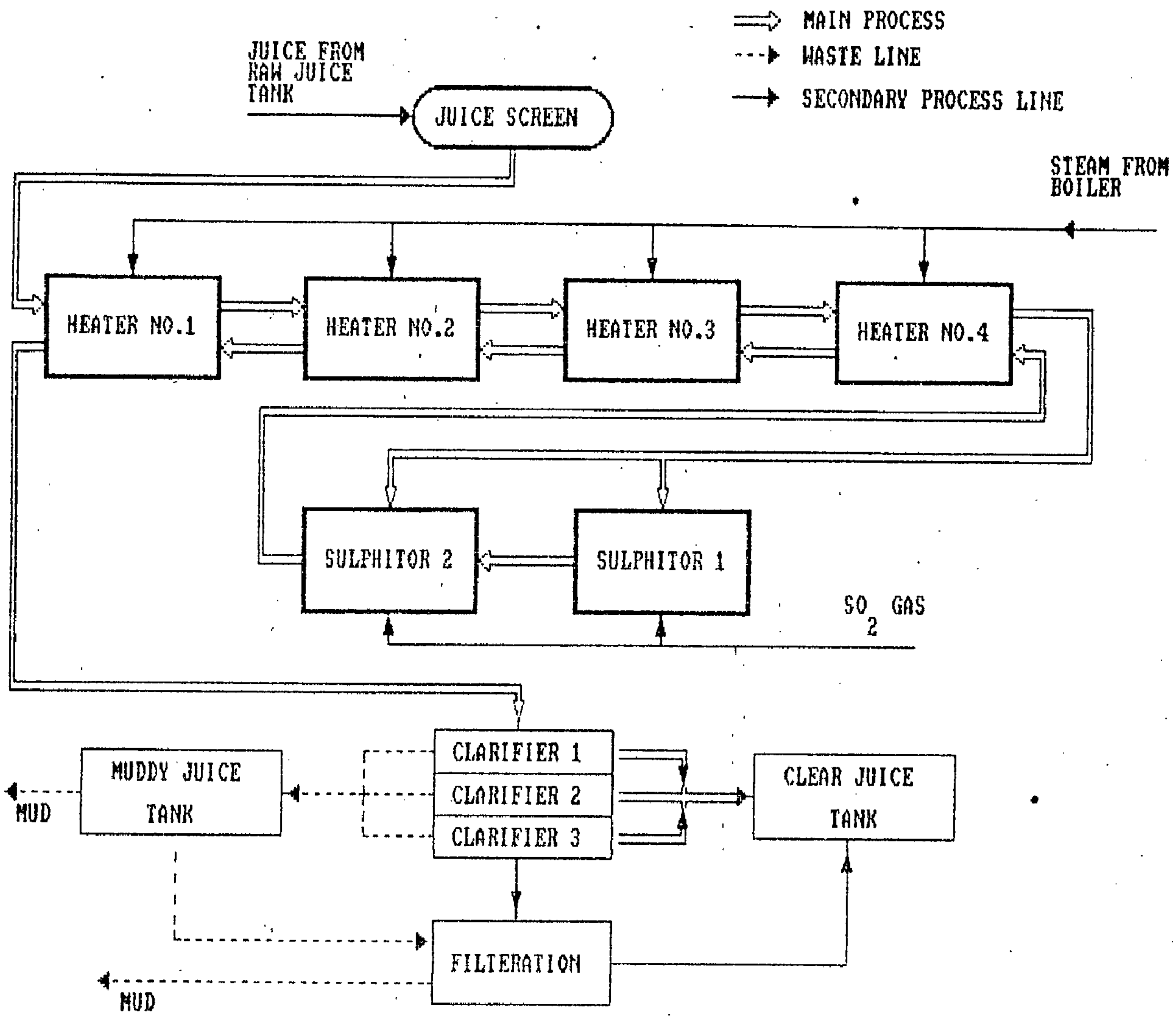


FIG.2.5:1. JUICE REFINING SYSTEM

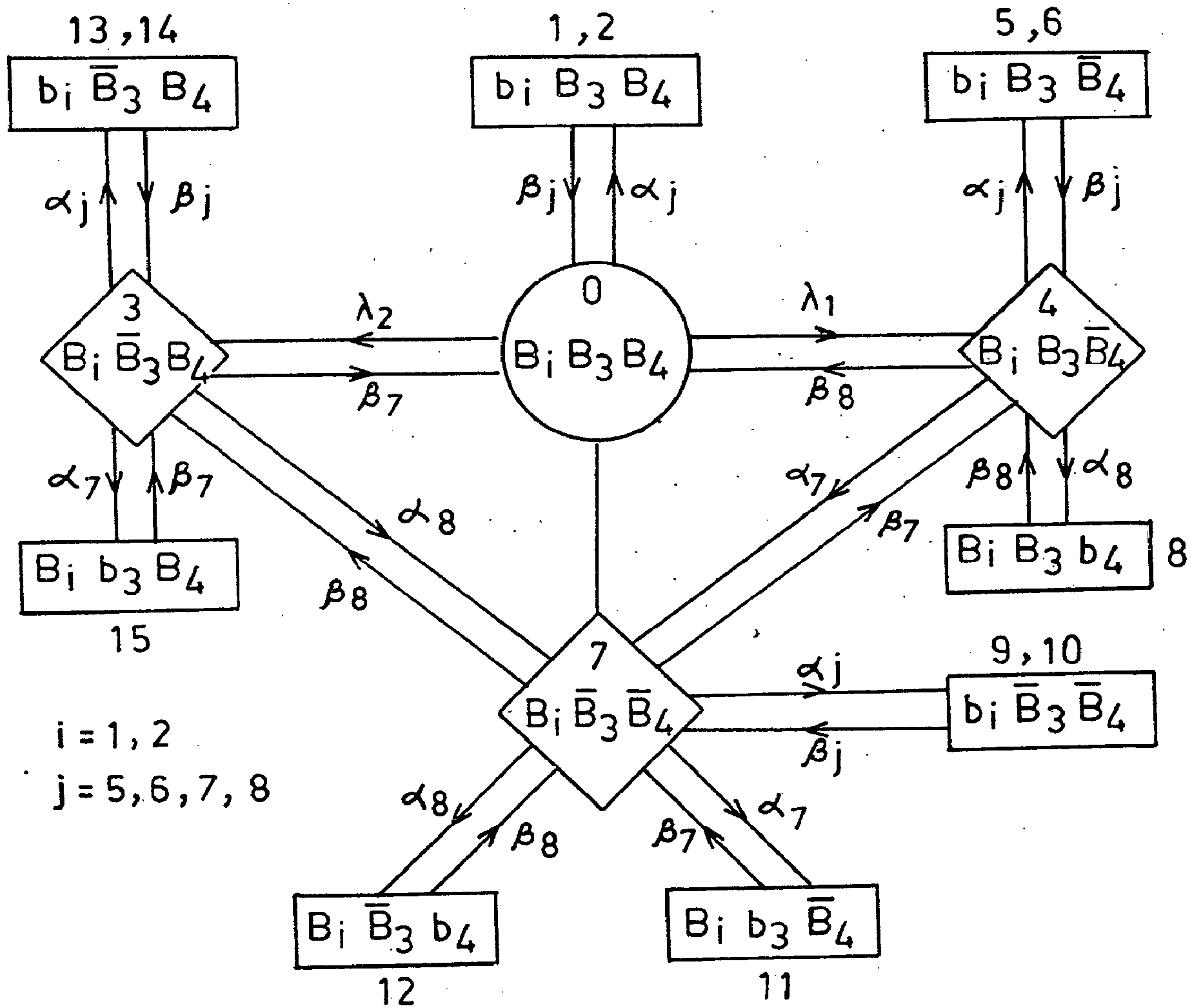


Fig. 2.5:2 Transition diagram for refining system.

$$x_5=\sum_{j=5}^{8}\alpha_j+\beta_8\quad ;x_6=\sum_{j=5}^{8}\alpha_j+\beta_7;$$

$$x_7=\sum_{j=5}^{8}\alpha_j+\beta_7+\beta_8\ ;\ x_8=\sum_{j=5}^{6}\alpha_j+T_1+T_2$$

$$y_5=\sum_{j=5}^{6}\frac{\alpha_j\beta_j}{(s+\beta_j)}+\frac{\alpha_8\beta_8}{(s+\beta_8)}\qquad ;y_6=\sum_{j=5}^{7}\frac{\alpha_j\beta_j}{(s+\beta_j)}$$

$$y_7=\sum_{j=5}^{8}\frac{\alpha_j\beta_j}{(s+\beta_j)}+\frac{\alpha_7\beta_7}{(s+x_5-y_5)}+\frac{\alpha_8\beta_8}{(s+x_6-y_6)}$$

$$y_8=\sum_{j=5}^{6}\frac{\alpha_j\beta_j}{(s+\beta_j)}+\frac{\beta_7T_2}{(s+x_6-y_6)}+\frac{\beta_8T_1}{(s+x_5-y_5)}$$

$$+\frac{\beta_7\beta_8}{(s+x_7-y_7)}\left[\frac{\alpha_7T_1}{(s+x_5-y_5)}+\frac{\alpha_8T_2}{(s+x_6-y_6)}\right]\left|\frac{1}{(s+x_5-y_5)}+\frac{1}{(s+x_6-y_6)}\right|$$

and mean time to system failure [MTTF]$=\lim_{s\to 0} sR_2(s)$ given as:

$$[MTTF]_2=\frac{1+\dfrac{T_1}{b_1}+\dfrac{T_2}{b_2}+\dfrac{1}{(b_1+b_2)}\left[\dfrac{\alpha_7T_1}{b_1}+\dfrac{\alpha_8T_2}{b_2}\right]\left[\dfrac{b_1}{\beta_7}+\dfrac{b_2}{\beta_8}+\dfrac{(b_1b_2)}{(\beta_7\beta_8)}\right]}{1+\displaystyle\sum_{j=5}^{6}\frac{\alpha_j}{\beta_j}+\frac{T_1a_1}{b_1}+\frac{T_2a_2}{b_2}+\frac{1}{(b_1+b_2)}\left[\frac{\alpha_7T_1}{b_1}+\frac{\alpha_8T_2}{b_2}\right]\left[\frac{a_2b_1}{b_2}+\frac{a_1b_2}{b_1}+\frac{a_3b_1b2}{\beta_7\beta_8}\right]}$$

--(2.5.7)

where

$b_1=\alpha_7+\beta_8$; $b_2=\alpha_8+\beta_7$; $a_1=1+(\alpha_5/\beta_5)+(\alpha_6/\beta_6)+(\alpha_8/\beta_8)$;

$a_2=1+\sum_{j=5}^{7}(\alpha_j/\beta_j)$; $a_3=1+\sum_{j=5}^{8}(\alpha_j/\beta_j)+(\alpha_7\beta_7a_1/b_1)+(\alpha_8\beta_8a_2/b_2)$

2.5.c <u>STEADY STATE BEHAVIOUR</u>:

When $t\to\infty$,$(d/dt)\to 0$. Putting $(d/dt)=0$ in equations (2.5.1) to (2.5.5) and solving recursively the steady state probabilities of the system are given by:

$p_1=(\alpha_5/\beta_5)p_0$; $p_2=(\alpha_6/\beta_6)p_0$; $p_3=\{(T_2+M_1\beta_8)/(\alpha_8+\beta_7)\}p_0$;

$p_4=\{(T_1+M_1\beta_7)/(\alpha_7+\beta_8)\}p_0$; $p_5=(\alpha_5/\beta_5)p_4$; $p_6=(\alpha_6/\beta_6)p_4$;

$p_7=[\{\alpha_7T_1(\alpha_8+\beta_7)+\alpha_8T_2(\alpha_7+\beta_8)\}/\beta_7\beta_8\{\alpha_7+\alpha_8+\beta_7+\beta_8\}]p_0=M_1p_0$;

$p_8=(\alpha_8/\beta_8)p_4$; $p_9=(\alpha_5/\beta_5)p_7$; $p_{10}=(\alpha_6/\beta_6)p_7$; $p_{11}=(\alpha_7/\beta_7)p_7$;

$p_{12}=(\alpha_8/\beta_8)p_7$; $p_{13}=(\alpha_5/\beta_5)p_3$; $p_{14}=(\alpha_6/\beta_6)p_3$; $p_{15}=(\alpha_7/\beta_7)p_3$.

All these probabilities are obtained in terms of p_0 which can be evaluated from condition $\sum_{i=0}^{15} p_i=1$. This leads to:

$$p_0=\left[\left(1+\frac{\alpha_5}{\beta_5}+\frac{\alpha_6}{\beta_6}\right)\left\{\left(1+\frac{T_2M_1\beta_8}{(\alpha_8+\beta_7)}\right)+\frac{(T_1+M_1\beta_7)}{(\alpha_7+\beta_8)}+M_1\right\}+\frac{\alpha_7}{\beta_7}\left\{\frac{(T_2+M_1\beta_8)}{(\alpha_8+\beta_7)}+M_1\right\}+\frac{\alpha_8}{\beta_2}\left\{\frac{(T_1+M_1\beta_7)}{(\alpha_7+\beta_8)}+M_1\right\}\right]^{-1}$$

or, $p_0=[L_1]^{-1}$

The steady state availability $[AV_2]$ of the system is obtained as:

$[AV_2]=p_0+p_3+p_4+p_7$

$$=[1+\{(T_2+M_1\beta_8)/(\alpha_8+\beta_7)\}+\{(T_1+M_1\beta_7)/(\alpha_7+\beta_8)\}+M_1][L_1]^{-1} \quad \text{--(2.5.8)}$$

Reliability analysis of the system with general repair time and using Lagrange's method for solution of partial differential equations has also been developed by the author and reported in (58).

2.5.d BEHAVIOURAL ANALYSIS:

The effect of failure and repair rates of filter, heater, sulphonation and clarifier upon the system availability is depicted in tables 2.5-1 to 2.5-3.

Table 2.5-1: Effect of failure rate of filter, clarifier and heating plant (β_5=.4, β_6=.1, β_7=.2, β_8=.1, T_1=.025, T_2=.02, α_7=.015)

α_5	α_8	Availability[AV_2]				
		α_6 =.00	α_6 =.025	α_6 =.050	α_6 =.075	α_6 =.10
.000	.00	.9707	.7811	.6535	.5615	.4926
	.01	.9622	.7756	.6496	.5589	.4904
	.02	.9402	.7613	.6396	.5514	.4846
.005	.00	.9590	.7736	.6482	.5578	.4895
	.01	.9507	.7682	.6444	.5550	.4874
	.02	.9293	.7541	.6345	.5476	.4817
.010	.00	.9477	.7661	.6430	.5539	.4866
	.01	.9396	.7608	.6393	.5512	.4844
	.02	.9186	.7471	.6295	.5439	.4788

Table 2.5-2: Effect of failure rates of sulphonation and clarifier subsystem (α_5=.005, α_8=.01, β_5=.4, β_6=.1, β_7=.2, β_8=.1, T_1=.025, T_2=.02)

α_7	Availability[AV_2]				
	α_6 =.00	α_6 =.025	α_6 =.050	α_6 =.075	α_6 =.10
.000	.9789	.7868	.6572	.5645	.4947
.015	.9788	.7832	.6550	.5628	.4934
.030	.9605	.7745	.6489	.5506	.4899

Table 2.5-3: Effect of repair rate of filter, clarifier and heating plant (α_5=.005, α_6=.05, α_7=.02, α_8=.01, β_7=.1, T_1=.025, T_2=.02)

β_5	β_8	Availability [AV_2]				
		β_6 =.01	β_6 =.05	β_6 =.10	β_6 =.15	β_6 =.20
.10	.01	.1508	.3797	.4688	.5085	.5310
	.05	.1587	.4348	.5556	.6122	.6452
	.10	.1607	.4496	.5800	.6420	.6783
.25	.01	.1514	.3841	.4754	.5162	.5396
	.05	.1595	.4405	.5650	.6237	.6579
	.10	.1614	.4557	.5902	.6546	.6924
.50	.01	.1517	.3856	.4777	.5190	.5425
	.05	.1597	.4425	.5682	.6276	.6623
	.10	.1617	.4578	.5937	.6589	.6972

Tables 2.5-1 and 2.5-2 show that an increase in failure rates of juice screen (α_5), sulphonation system(α_7) and heating plant (α_8) has virtually no effect on the system availability whereas increasing the failure rate of clarifier (α_6) has considerable effect on the system availability. A small increase in the failure rate of clarifier reduces the availability sharply. Therefore efforts be made to keep the clarifier operative as long as possible. Also the effect of screen failure rate upon availability can be seen to be more significant compared to the heating system. It is because failure in the heating system would reduce the plant capacity whereas the failure of screen would stop the process completely.

Table 2.5-3 shows that the effects of repair rates β_5 and β_8 upon system availability are not significant whereas a slight increase in the repair rate of the clarifier (β_6) improves the availability sharply.

2.6 CRYSTALLISATION SYSTEM

2.6.a <u>SYSTEM DESCRIPTION</u>: The crystallisation system is the most important subsystem in a sugar plant. This consist of the following five subsystems (fig. 2.6:1).

i) The evaporator (D_1) ; having 2 units (i=2) in parallel configuration. The failure of any one unit would reduce the capacity of the plant whereas a complete failure of the system would occur only when both the unit have failed.

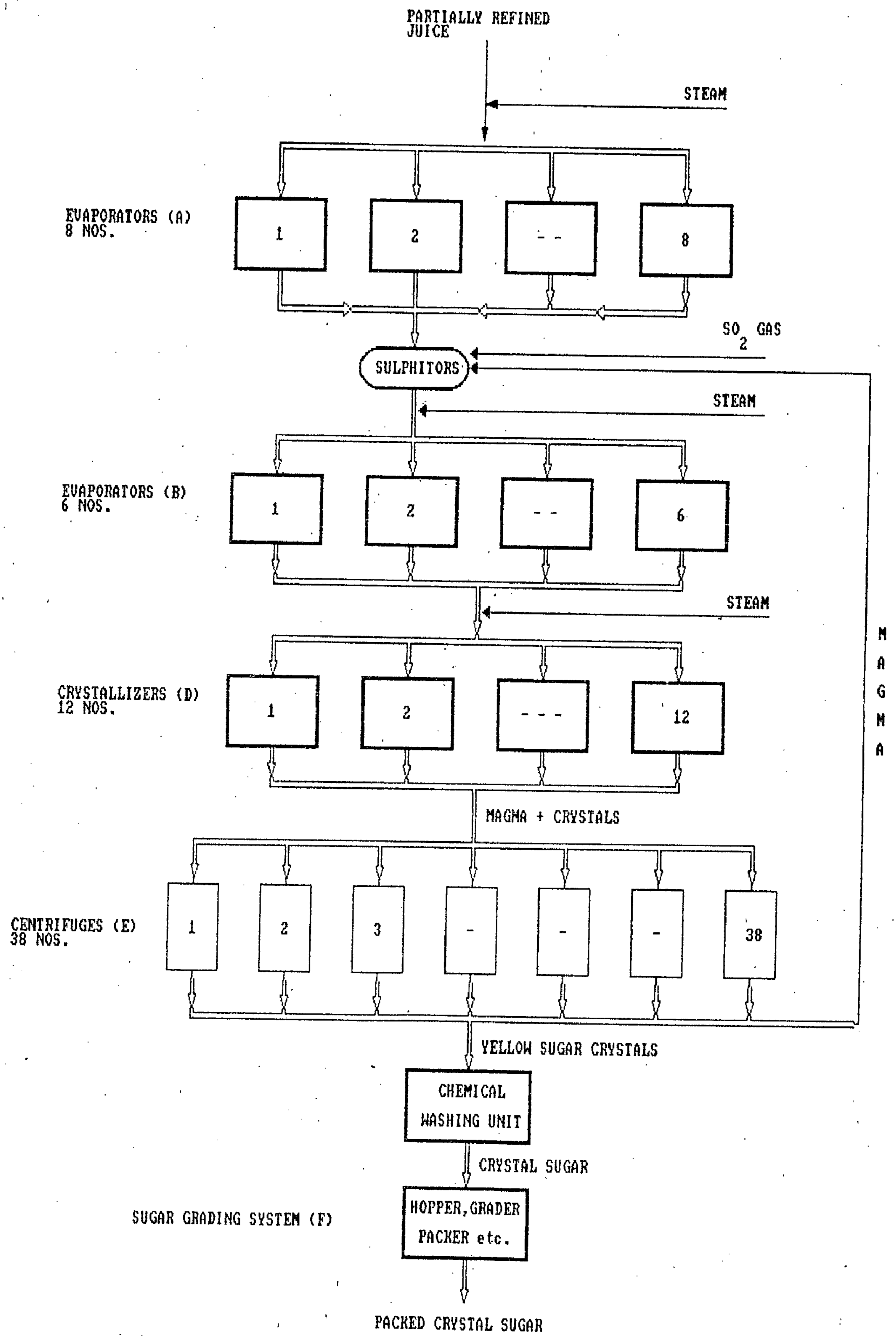


FIG 2.6:1. CRYSTALLIZATION SYSTEM OF A SUGAR PLANT

ii) The cooking pans (D_2); having 6 units (j =6) in parallel configuration. Failure of any one unit would cause a slow down of the process and hence loss of production capacity. The complete failure of the system would occur only when all the 6 units have failed,

iii) The crystallizers(D_3); has 12 units (k=12) in parallel . Failure of any one would reduce the capacity of the plant whereas complete failure of the system would occur when all of units have failed,

iv) The centrifuges (D_4); this has a total of 38 units (l=38) in parallel . Failure of any one would reduce the capacity of the plant. The complete failure of the system would occurs only when all the units have failed.

v) The subsystem (D_5) comprises of hopper, elevator, cooler and sugar grader all connected in series. Failure of any one unit would cause a complete failure of the system.

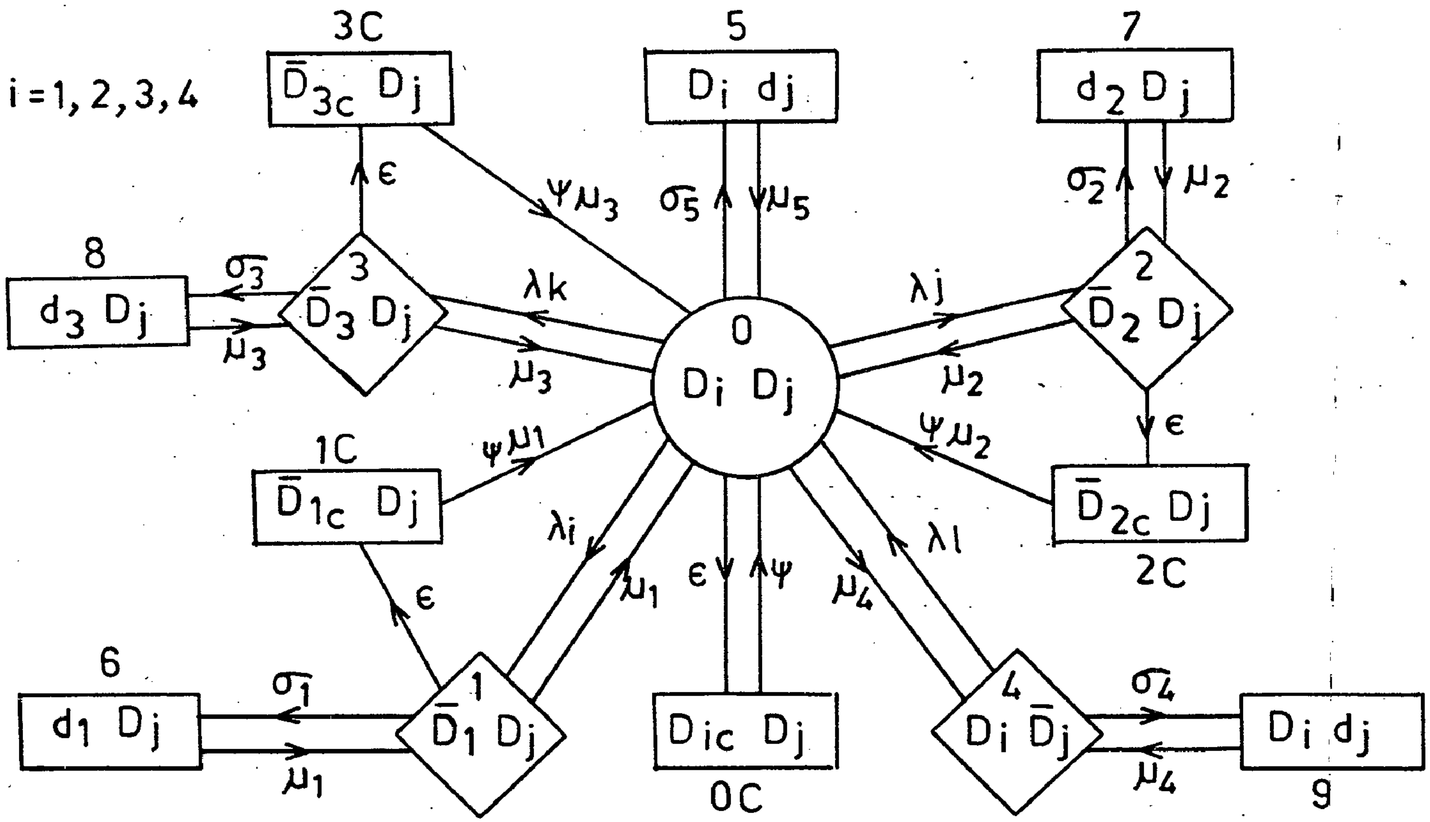
Moreover there may be common cause failure such as failure of steam supply to subsystems D_1, D_2, D_3 that would stop the plant altogether.

2.6.b RELIABILITY OF CRYSTALLISATION SYSTEM:

Using arguments as discussed under in section 2.4.b the differential equations associated with the transition diagram (fig. 2.6:2) can be derived as:

$$\left(\frac{d}{dt}+\sum_{i,j}^{k,l} T_m+\epsilon\right)p_o(t)=\sum_{r=1}^{5}\mu_r p_r(t)+\emptyset\mu_3 p_{3c}(t)+\emptyset\mu_2 p_{2c}(t)+\emptyset p_{oc}(t) \qquad \text{--(2.6.1)}$$

$$\left(\frac{d}{dt}+\sigma_r+\mu_r+\epsilon\right)p_r(t)=\mu_r p_{r+5}(t)+T_m p_o(t) \qquad \text{--(2.6.2)}$$



ϵ, ψ :— Common cause failure and repair rates.

Fig. 2.6:2 Transition diagram of crystallization system.

where m=i for r=1; m=j for r=2 ; m=k for r=3

$$\left(\frac{d}{dt}+\sigma_4+\mu_4\right)p_4(t)=\mu_4 p_9(t)+T_1 p_0(t) \qquad \text{---------(2.6.3)}$$

$$\left(\frac{d}{dt}+\mu_5\right)p_5(t)=\sigma_5 p_0(t) \qquad \text{--------(2.6.4)}$$

$$\left(\frac{d}{dt}+\mu_r\right)p_{r+5}(t)=\sigma_r p_r(t),\ r=1,2,3,4 \qquad \text{-------(2.6.5)}$$

$$\left(\frac{d}{dt}+\emptyset\right)p_{0c}(t)=\epsilon p_0(t) \qquad \text{--------(2.6.6)}$$

$$\left(\frac{d}{dt}+\emptyset\mu_r\right)p_{rc}(t)=\epsilon p_r(t),\ r=1,2,3 \qquad \text{----------(2.6.7)}$$

with initial and boundary conditions $p_0(0)=1$ otherwise =0.

Taking Laplace transforms of the equations (2.6.1) to (2.6.7) and solving recursively (using initial condition) we get the Laplace transform $R_3(s)$ of reliability function as:

$$R_3(s)=LR_3(t)=L\{p_0(t)+p_1(t)+p_2(t)+p_3(t)+p_4(t)\}$$

$$=p_0(s)+p_1(s)+p_2(s)+p_3(s)+p_4(s) \qquad \text{---(2.6.8)}$$

where

$p_0(s)=[s+x_{13}-y_{13}]^{-1}$; $p_1(s)=T_i[s+x_{12}-y_{12}]^{-1}p_0$;

$p_2(s)=T_j[s+x_9-y_9]^{-1}p_0$; $p_3(s)=T_k[s+x_{11}-y_{11}]^{-1}p_0$;

$p_4(s)=T_1[s+x_{10}-y_{10}]^{-1}p_0$; $x_9=\sigma_2+\mu_2+\epsilon$; $x_{10}=\sigma_4+\mu_4$;

$x_{11}=\sigma_3+\mu_3+\epsilon$; $x_{12}=\sigma_1+\mu_1+\epsilon$;

$$y_9=\frac{\sigma_2\mu_2}{s+\mu_2};\quad y_{10}=\frac{\sigma_4\mu_4}{s+\mu_4};\quad y_{11}=\frac{\mu_3\sigma_3}{s+\mu_3};\quad y_{12}=\frac{\sigma_1\mu_1}{s+\mu_1}$$

and mean time to system failure $[MTTF]_3=\lim_{s\to 0} sR_3(s)$ is given by

$$[MTTF]_3=\frac{1+\sum\frac{T_m}{(\mu_r+\epsilon)}+\frac{T_1}{(\mu_4)}}{1+\sum\frac{T_m}{(\mu_r+\epsilon)}+\sum\frac{T_m}{(\mu_r+\epsilon)^2}\left\{1+\frac{\sigma_r}{\mu_r}+\frac{(\mu_r+\epsilon)}{\mu_r\emptyset}\right\}+\sum T_1\left(1+\frac{\sigma_4}{\mu_4}\right)+\frac{\sigma_5}{\mu_5}+\frac{\epsilon}{\emptyset}} \qquad \text{--(2.6.9)}$$

where

$$\sum \frac{T_m}{(\mu_r+\epsilon)} = \frac{\sum T_i}{(\mu_1+\epsilon)} + \frac{\sum T_j}{(\mu_2+\epsilon)} + \frac{\sum T_k}{(\mu_3+\epsilon)} \quad ;$$

$$\sum \frac{T_m}{(\mu_r+\epsilon)^2}\left\{1+\frac{\sigma_r}{\mu_r}+\frac{\mu_r+\epsilon}{\mu_r \emptyset}\right\}$$

$$= \frac{\sum T_i}{(\mu_1+\epsilon)^2}\left\{1+\frac{\sigma_1}{\mu_1}+\frac{(\mu_1+\epsilon)}{\mu_1 \emptyset}\right\} + \frac{\sum T_j}{(\mu_2+\epsilon)^2}\left\{1+\frac{\sigma_2}{\mu_2}+\frac{(\mu_2+\epsilon)}{\mu_2 \emptyset}\right\}$$

$$+ \frac{\sum T_k}{(\mu_3+\epsilon)^2}\left\{1+\frac{\sigma_3}{\mu_3}+\frac{\mu_3+\epsilon}{\mu_3 \emptyset}\right\} .$$

2.6.c <u>STEADY STATE BEHAVIOUR</u>:

This can be derived by taking $(d/dt) \to 0$, when $t \to \infty$ in equations (2.6.1) to 2.6.7) and solving recursively. The steady state probabilities for the system are thus obtained as:

$p_1=[T_i/(\mu_1+\epsilon)]p_o$; $p_4=[T_i/\mu_4]p_o$

$p_2=[T_j/(\mu_2+\epsilon)]p_o$; $p_5=[\sigma_5/\mu_5]p_o$

$p_3=[T_k/(\mu_3+\epsilon)]p_o$; $p_6=[\sigma_1/\mu_1]p_1$

$p_7=[\sigma_2/\mu_2]p_2$; $p_8=[\sigma_3/\mu_3]p_3$

$p_9=[\sigma_4/\mu_4]p_4$; $p_{oc}=[\epsilon/\emptyset]p_o$

$p_{rc}=[\epsilon/\emptyset\mu_r]p_r$, $r=1,2,3$

All the above probabilities have been obtained in terms of p_o. p_o is evaluated as under:

$$\sum_{r=0}^{9} p_r + \sum_{r=0}^{3} p_{rc} = 1.$$

$$\text{or } p_o = \left[1+\sum \frac{T_m}{(\mu_r+\epsilon)}\left\{1+\frac{\sigma_r}{\mu_r}+\frac{\epsilon}{\mu_r \emptyset}\right\} + \frac{\sum T_i}{\mu_4}\left(1+\frac{\sigma_4}{\mu_4}\right) + \frac{\sigma_5}{\mu_5} + \frac{\epsilon}{\emptyset}\right]^{-1}$$

or $p_o=[L_2]^{-1}$

where $\sum T_m/(\mu_r+\epsilon)$ is same as in equation (2.6.8)

The steady state availability $[AV_3]$ of the crystallisation system is given by:

$$[AV_3] = \sum_{i=0}^{4} p_i = \left| 1+\Sigma\left(\frac{T_m}{(\mu_r+\epsilon)}+\frac{T_1}{\mu_4}\right) \right| [L_2]^{-1} \quad ---(2.6.9)$$

2.6.d BEHAVIOURAL ANALYSIS:

The effects of failure and repair rates of evaporator , cooking pans crystallizers, centrifuses and subsystem D_5 upon availability are depicted in tables 2.6-1 to 2.6-4.

Table 2.6-1: Effect of failure rate of crystallizers, centrifuge and subsystem D_5 (hopper, elevator, cooler and grader), μ_1=0.2, μ_2=0.5, μ_3=0.1, μ_4=0.15, μ_5=0.25, Ø=0.25, T_1=0.02, T_J=0.01, σ_1=0.06, σ_2=0.05, ϵ=0.005

σ_3	σ_4	Availability$[AV_3]$					
		σ_5 =.00	σ_5 =.02	σ_5 =.04	σ_5 =.06	σ_5 =.08	σ_5 =.10
.005	.04	.6556	.6526	.6499	.6472	.6445	.6418
	.06	.6325	.6308	.6290	.6272	.6255	.6237
	.08	.6030	.6017	.6005	.5992	.5980	.5966
	.10	.5684	.5679	.5674	.5664	.5655	.5646
.010	.04	.6370	.6346	.6322	.6298	.6274	.6251
	.06	.6256	.6239	.6222	.6205	.6189	.6172
	.08	.5986	.5974	.5962	.5950	.5938	.5926
	.10	.5667	.5658	.5649	.5640	.5631	.5622

Table 2.6-2: Effect of failure rate of crystallizers, centrifuge and common cause failure (T_1=.01, T_k=.015, σ_5=.06, T_2=.02, T_J=.015)

σ_3	σ_4	Availability$[AV_3]$				
		ϵ =.00	ϵ =.005	ϵ =.010	ϵ =.015	ϵ =.02
.005	.04	.8070	.6762	.5958	.5616	.5401
	.08	.6762	.6186	.5626	.5414	.5146
.010	.04	.8064	.6639	.5757	.5085	.4852
	.08	.6759	.6068	.5142	.4871	.4617

Using the analysis as discussed in section 2.6.c the crystallisation system performance can be derived. For the assumed values of the system parameters some of the results are given in tables 2.6-3 to 2.6-8

Table 2.6-3: Effect of failure rate of evaporator, centrifuge and common cause cause failure (σ_2=.01, σ_3=.005, σ_5=.06)

σ_4	ϵ	Availability[AV_3]			
		σ_1 =.00	σ_1 =.02	σ_1 =.03	σ_1 =.04
.04	.005	.6793	.6759	.6724	.6680
	.010	.5998	.5911	.5858	.5799
.08	.005	.6184	.6180	.6178	.6164
	.010	.5793	.5753	.5726	.5695

Table 2.6-4: Effect of failure rate centrifuge, cooking pans and common cause failure (α_3=.005, τ_1=.02, σ_5=.06)

σ_4	ϵ	Availability[AV_3]			
		σ_2 =.00	σ_2 =.01	σ_2 =.02	σ_2 =.03
.004	.005	.7523	.6759	.6108	.5553
	.010	.7093	.5911	.5096	.4497
.008	.005	.6493	.6186	.5869	.5551
	.010	.6309	.5753	.4976	.4464

In table 2.6-1 effect of σ_1 and σ_5 on system availability can be seen to be non significant whereas a change in σ_2 or ϵ has considerable influence on the system availability . Also slight change in σ_3 and σ_4 would have a large effect on system availability.

A study of tables 2.6-3 & 2.6-4 show that an increase in $\in$ or σ_2 reduces AV_3 , meaning thereby common cause failuré leads to loss of availability and hence production , similarly failure of cooking pans would reduce the sugar output from the system.

Table 2.6-5: Effect of repair rate of crystallizers, centrifuge, and hopper,elevator, cooler and grader (σ_2=.01, σ_5=.06, σ_3=.005, T_1=.02, μ_2=.05, Ø=.05, μ_1=.2)

μ_3	μ_4	Availability[AV_3]				
		μ_5 =.1	μ_5 =.2	μ_5 =.3	μ_5 =.4	μ_5 =.5
.1	.1	.6453	.6521	.6544	.6555	.6562
	.3	.6459	.6559	.6569	.6595	.6610
	.5	.6651	.6679	.6778	.6800	.6815
.3	.1	.6528	.6599	.6624	.6634	.6642
	.3	.6540	.6608	.6734	.6762	.6809
	.5	.6595	.6680	.6760	.6804	.6820
.5	.1	.6538	.6610	.6693	.6747	.6755
	.3	.6550	.6700	.6756	.6784	.6801
	.5	.6662	.6703	.6770	.6814	.6824

Table 2.6-6: Effect of repair rate of crystallizers, centrifuge and common cause repair (μ_1=.2, μ_2=.05, μ_5=.25)

μ_3	μ_4	Availability[AV_3]				
		Ø =.01	Ø =.02	Ø =.03	Ø =.04	Ø =.05
.1	.1	.6444	.6500	.6519	.6529	.6534
	.3	.6454	.6514	.6534	.6537	.6559
.3	.1	.6518	.6577	.6597	.6607	.6613
	.3	.6581	.6647	.6693	.6701	.6710

Table 2.6-7: Effect of repair rate of evaporator, centrifuge and common cause repair (μ_3=.1, μ_5=.25)

μ_4	Ø	Availability[AV_3]				
		μ_1 =.1	μ_1 =.2	μ_1 =.3	μ_1 =.4	μ_1 =.5
.1	.02	.5211	.5582	.5647	.5666	.5672
	.04	.6072	.6311	.6347	.6354	.6356
.2	.02	.4438	.4853	.4921	.4938	.4941
	.04	.5537	.5843	.5884	.5891	.5897

Table 2.6-8: Effect of repair rate of cooking pan , centrifuge and common cause repair (μ_4=.15)

μ_1	Ø	Availability[AV_3]				
		μ_2 =.1	μ_2 =.2	μ_2 =.3	μ_2 =.4	μ_2 =.5
.1	.02	.6317	.6535	.6574	.6586	.6590
	.04	.6801	.6918	.6936	.6940	.6942
.2	.02	.5830	.6141	.6203	.6220	.6224
	.04	.6574	.6760	.6785	.6795	.6797

Tables 2.6-1 to 2.6-4 show that the increasing failure rates of crystallizers (σ_3) and centrifuge (σ_4) have significant effect upon the system availability. As these comprise main parts of production process in third stage. However σ_5 and σ_1 do not have much effect upon the system output. This is because failures in units D_5 or D_1 reduce the system capacity partially and hence a loss in production. Thus it is evident that to run the crystallizers unit reliabily, the management should control common cause failure in D_1, D_2 and D_3. The failure rates in these subsystems should be controlled in the order viz- D_2, D_4, D_3, D_1 and D_5.

2.7 AVAILABILITY ANALYSIS OF COMPLETE SUGAR PLANT

Since the feeding, refining and crystallisation systems in a sugar plant work in series (fig. 2:1). The overall availability of the plant [AV] can be obtained from (equations 2.4.8, 2.5.8, 2.6.9) as follows:

$$[AV]=[AV_1 * AV_2 * AV_3]$$

$$=[1+(\alpha_1/\beta_1)+(\alpha_2/\beta_2)]_1^{-1}$$

$$* \left[\frac{1+\dfrac{(T_2+M_1\beta_8)}{(\alpha_8+\beta_7)}+\dfrac{(T_1+M_1\beta_7)}{(\alpha_7+\beta_8)}+M_1}{\left(1+\dfrac{\alpha_5}{\beta_5}+\dfrac{\alpha_6}{\beta_6}\right)\left\{\left(1+\dfrac{T_2M_1\beta_8}{(\alpha_8+\beta_7)}\right)+\dfrac{(T_1+M_1\beta_7)}{(\alpha_7+\beta_8)}+M_1\right\}+\dfrac{\alpha_7}{\beta_7}\left\{\dfrac{(T_2+M_1\beta_8)}{(\alpha_8+\beta_7)}+M_1\right\}+\dfrac{\alpha_8}{\beta_8}\left\{\dfrac{(T_1+M_1\beta_7)}{(\alpha_7+\beta_8)}+M_1\right\}}\right]_2$$

$$* \left[\frac{[1+\Sigma\ \{T_m/(\mu_r+\epsilon)+(\Sigma T_i/\mu_4)]}{1+\{\Sigma T_m/(\mu_r+\epsilon)\}\{1+(\sigma_r/\mu_r)+(\epsilon/\mu_r\emptyset)\}+(\Sigma T_i/\mu_4)\{1+(\sigma_4/\mu_4)\}+(\sigma_5/\mu_5)+(\epsilon/\emptyset)}\right]_3 \quad \text{--(2.7.1)}$$

where $\Sigma T_m/(\mu_r+\epsilon)$ & $\Sigma T_m/(\mu_r+\epsilon)[1+(\sigma_r/\mu_r)+(\epsilon/\mu_r\emptyset)]$ have been explained as in equation 2.6.8.

From equation 2.7.1 it can be observed that the system availability can be improved to certain extent by adopting the following measures.

i) the failure limit in every equipment can be fixed to maintain a minimum production level. Accordingly maintenance facility be provided. Practical values of the probable failure rates as stipulated by plant personal are:

crushing unit -once in 20 hrs

sugar cane supply system -once in 40 hrs

juice screen -once in 50 hrs

clarifier -once in 100 hrs

sulphonation -once in 100 hrs

heating plant once in 50 hrs

evaporator -once in 50 hrs

cooking pans -once in 100 hrs

crystallizers -once in 500 hrs

centrifuge -once in 50 hrs

hopper, elevator,cooler and sugar grader -once in 20 hrs

steam failure -once in 200 hrs

Whereas repair times for various equipment normally to very between one and ten hrs. Typical values of the average repair times for some of the equipments are of the following order.

crushing unit -10 hrs

sugar cane supply system -10hrs

filter -2 to 10 hrs

clarifier -2 hrs

sulphonation unit -10 hrs

heating unit -5 to 10 hrs

evaporator -5 hrs

cooking pans -20 hrs

crystallizers -3.3 hrs to 10 hrs

centrifuge -10 hrs

hopper, evaporator, cooler and sugar grader -5 hrs

repair in steam supply system -25hrs to 50 hrs

Using the above data, table 2.7-1 has been worked out.

Table 2.7-1: Effect of repair rate of filter , heating plant, centrifuge and steam supply system upon total sugar production process.

β_1	β_2	μ_2	Availability[AV]		
			Ø =.02	Ø =.03	Ø =.04
.10	.10	.1	.27736	.25556	.27445
		.2	.25206	.25853	.27683
		.3	.25279	.25892	.27712
	.15	.1	.24968	.25795	.27703
		.2	.25443	.26096	.27739
		.3	.25517	.26135	.27972
	.20	.1	.25048	.25878	.27792
		.2	.25525	.26180	.28033
		.3	.25599	.26219	.28062
.25	.10	.1	.27337	.28242	.30331
		.2	.27857	.28571	.30594
		.3	.27937	.28614	.30626
	.15	.1	.27623	.28538	.30648
		.2	.28148	.28870	.30914
		.3	.28230	.28913	.30946
	.20	.1	.27721	.28639	.30757
		.2	.28248	.28973	.31024
		.3	.28330	.29016	.31056
.50	.10	.1	.28230	.29268	.31433
		.2	.28869	.29610	.31706
		.3	.28953	.29654	.31802
	.15	.1	.28438	.29586	.31774
		.2	.29182	.29931	.32050
		.3	.29267	.29976	.32147
	.20	.1	.28743	.29695	.31891
		.2	.29290	.30041	.32168
		.3	.29357	.30103	.32202

Availability of the cane feeding system can be increased by providing juice tank in which the juice can be stored so that if feeding system fails the supply of juice is maintained. ✓

For the given failure and repair rates, availability of the feeding system has been shown to be as AV_1=.57143K_1 whereas k_1 is a raw juice storing constant having values

K_1=1.05 when juice storing capacity is only for one to two hrs of operation.

K_1=1.15 when juice storing capacity has been provided for 5 to 6 hrs of operation.

K_1=1.5 when juice storing capacity is for 20 hrs of operation.

Storage capacity is chosen, considering the cost of tank, maintenance of the tank and the quality of juice.

For K_1=1.5 availability of the feeding system would be equal to 0.857145.

Table 2.7-1 shows that a decrease in repair time of filter from 10 hrs to 2 hrs increases the system availability by 5% while a decrease in repair time of heating plant from 10 hrs to 5 hrs increases availability by 0.9%. The decrease in repair time of crystallizers from 10 hrs to 3.3 hrs increases its availability by 0.5%. However if reserve steam supply is available for 25 hrs to 50 hrs then the availability can be increased by 3% (approx).

In table 2.5-1 assuming the repair rates as β_1=.25, β_4=.2, μ_3=.2, Ø=.04. and providing a tank for clean juice which would supply clean juice to crystallisation system for 2 to 3 hrs of working. The availability equation for refining system is obtained as:

AV_2=0.8891K_2, where K_2 is a clean juice storing capacity constant K_2=1.1 for 2 to 3 hrs of working storage capacity.

Thus the total availability of the system can be increased by providing storage tanks. The availability for the plant with additional storage tanks as described above is given by:

$[AV]=[K_1AV_1*K_2AV_2*AV_3]$

$=[(1.15*.57143)*(1.1*.8891)*.6106156]=.511876841$

K_1 and K_2 may also be termed as factory constant.

The availability of the process can further be increased by planning for the plant maintenance in advance and ensuring that repairs are started as quickly as possible after the system failure on account of following reasons.

i) common cause failure,

ii)major breakdown in any equipment,

iii)non availability of raw material,

iv)non availability of power.

CHAPTER-3

AVAILABILITY ANALYSIS OF A PAPER MILL

3.1 Introduction:

This work is based on the study of a medium sized paper mill producing 130 tonnes of paper per day situated near Roorkee, in north India. For the production of paper,the raw material (soft + hardwood & bamboo) is chopped into small pieces of approximately uniform size (chips) and transported to the store by the use of compressed air. A chain conveyor feeding system carries these chips from the store to digesters whenever required and cooked using NaoH + Na_2s and steam at 8 Kg/cm^2 pressure and 175° c temperature. The chips when cooked are converted into pulp. The pulp is pneumatically transported to storage tanks from where it is transported for further processing through fiberizer and refiner. The pulp is filtered through filters and washed (in three-four stages) with water to remove cooking chemicals. The washed pulp discharged from the last stage of the washer is stored in a surge tank. The pulp is next processed by bleaching and screening for the production of white paper whereas, for the production of brown coarse grade of paper the pulp is screened directly . For bleaching, chlorine gas is passed through the pulp stored in a tank. The white bleached pulp, so obtained, is first passed through a screen to separate out oversize and odd shape particles or debris. The pulp is then processed through a cleaner which separates heavy material from the pulp and then sent to paper rolling machine. Here the pulp is spread evenly over an endless belt made of meshed wire running between breast and couch rolls. The paper in the form of sheets is produced by the rolling process and then sent to dryers (to smooth and iron out any irregularities). During drying the sheet paper comes into contact with the heated surface of the dryer belt. The dried sheet paper is finally rolled in the form of rolls and sent for final packing.

A schematic diagram of the paper production process is shown in fig. 3:1.

The complete paper production process/system consists of the following six subsystems- feeding, pulp preparation, washing, bleaching, screening and paper production.

a)Feeding system: It consists of-

i) chain conveyor- for carrying chips from store to digesters

ii) blower and blowing units-for pneumatic conveying of chips to the digesters,

b) Pulp preparation system: It consists of-

i) digesters- for cooking the pulp using NaoH, Na_2S and steam,

ii) fiberizer or knotter- to remove the knots from the cooked pulp,

iii) decker- to remove black liquor from the cooked pulp,

iv) opener or refiner- to open the knots,

c) Washing system: It consists of-

i) screening unit- for separating out the unwanted foreign material from the pulp,

ii) cleaners- for removing heavy material from the pulp,

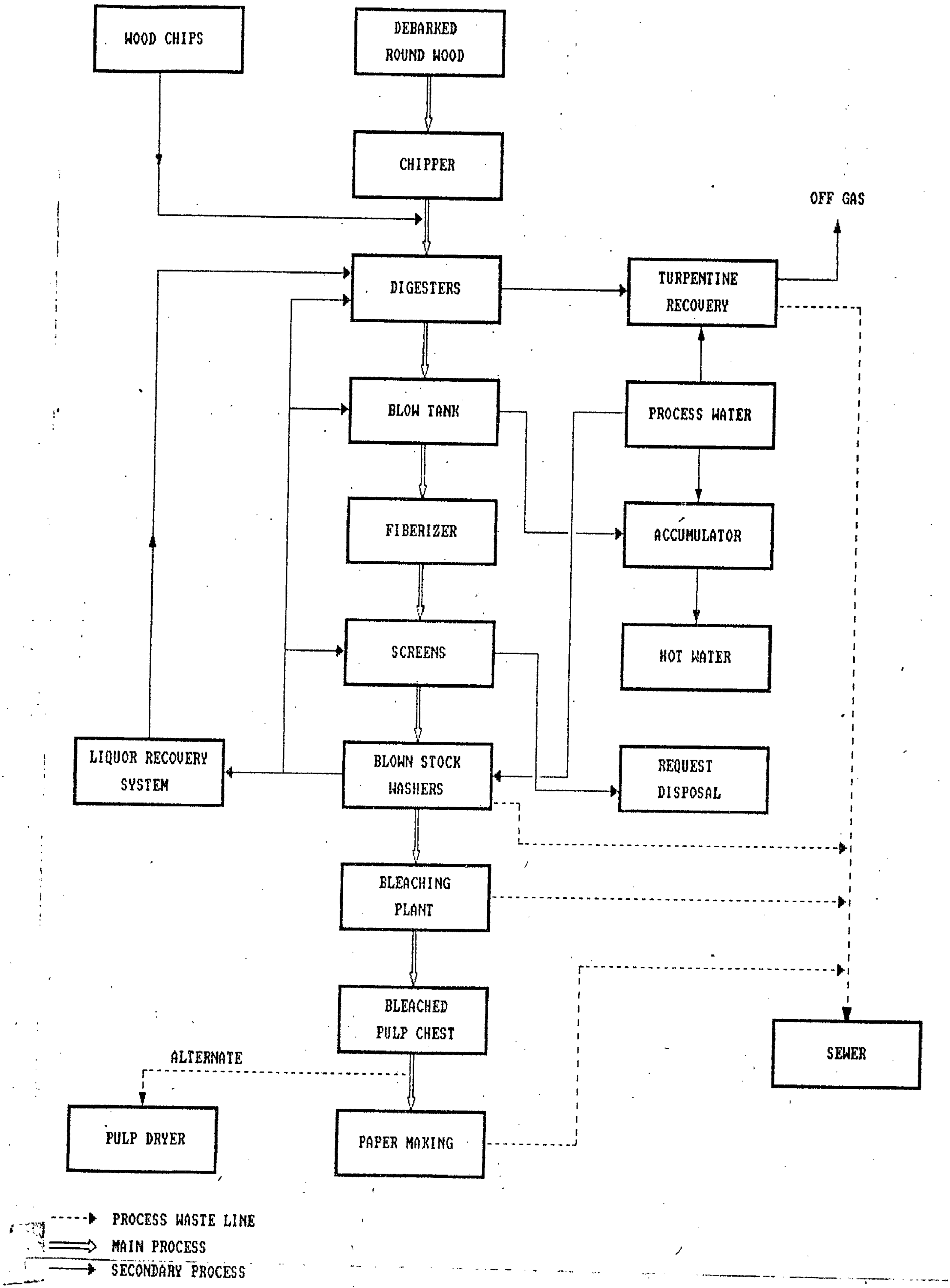


FIG.3:1. SCHEMATIC DIAGRAM OF PAPER PRODUCTION PROCESS

iii)washer-for removing chemicals through washing,

d) Bleaching system: It consists of-

i) filter- to filter the unbleached pulp,

ii) opener- to open the fibers,

e) Screening system: It consist of-

i) filter - to remove black (used) liquor,

ii) screen- to remove the knots and other undesirable material,

iii) cleaner and mixer- for cleaning the fibers and mixing of fresh water with the pulp,

iv) washer- to wash the pulp (for brightness),

f) Paper production system: It consists of-

i) fiber decomposition and water suction unit,

ii) pressing- for smoothing &ironing the paper sheet,

iii) dryers- for removing the moisture content from the rolled sheet paper.

Like sugar plant a paper mill is a complex engineering system with a large number of inter- connected subsystems and components . These , during the course of working are liable to fail . The failed units are repaired or replaced as soon as possible in order to improve upon the system availability and achieve higher paper output.

In this chapter, reliability and system availability of the various subsystems as well as the plant as a whole has been obtained. Based on the analysis an effort has been made to compute the optimum plant operating conditions. The analytical approach used for this purpose is identical to that employed for the sugar mill problem.

3.2 ASSUMPTIONS:

i) Mean failure/repair rates of the units are constant over time, for equal interval of time and are statistically independent

ii) The repaired/replaced units are as good as new performance wise. Units are repaired/replaced upon failure only.

iii) Each subsystem has separate repair facility and hence no repair waiting time is involved.

iv) Service includes repair and/or replacement.

v) System times to failure/repair are exponentially distributed This would imply that there are no simultaneous failures among subsystems and the probability of more than one subsystem failure /repair during the interval t is zero.

iv) The standby units (if any)are of the same nature and capacity as the active units.

Based on the assumptions above, transition diagrams of the six subsystems have been prepared and presented in figs. 3.3:1, 3.4:1 , 3.5:1, 3.6:1, 3.7:1 & 3.8:1.

following notations have been employed to designate the es of the subsystems in these figures

TE	FEEDING SYSTEM	PULP PREPARATION SYSTEM	WASHING SYSTEM	BLEACHING SYSTEM	SCREENING SYSTEM	PAPER PRODUCTI SYSTEM
sition ram	fig.3.3:2	fig. 3.4:2	fig. 3.5:2	fig.3.6:2	fig.3.7:2	fig. 3.8
capacity ing (without dby unit)	A, B, D_i	E_i	F_i	$\_G_1, \_G_2$ $\bar{G}_1, \bar{G}_2$	H_i	$Q_1, Q_2,$ T_m, U_i
capacity ing (with dby unit)	---	$\bar{E}_3, \bar{E}_4$	F_{31}	---	---	U_1, U_2
ced state	---	---	F_2	---	---	---
ed state	a, b, d_i	e_i	f_i	$\_g_1, \_g_2$ g_1, g_2	---	$q_{1,2}$ t_m, u_i
ure rate	α_i, α_j	α_j	$\alpha_{10}, \alpha_{11},$ T_3	α_j	$\sigma_{1,2},$ T_4, σ_4	σ_i
ir rate	β_i, β_j	β_j	β_j	β_j	μ_j	μ_i
ltaneous ure in pumps	---	---	---	---	---	T_5(two) T_6(thre
ition state operating educed	---	---	α_{12}	---	σ_3	---
ability of capacity ing (with dby unit)	---	$p_{3,4}, p_8$	p_3	---	---	p_4, p_8
ability of ced capicity ing	$p_{3,4,5}$	---	p_2, p_7	---	p_3, p_7	---
ability of ed state	$p_1, p_{6,7,8}$ $p_{9,10,11}$	$p_{1,2}, p_{5,6},$ $p_7, p_{9,-,11},$ $p_{12,--15}$	$p_1, p_{4,5,6},$ $p_{8,--11}$	$p_{1,--4}$	$p_{1,2},$ $p_{4,5,6}$ $p_{8,--11}$	$p_{1,--3}$ $p_{5,--7}$ $p_{9,--12}$
ix	i=1,2,3 j=i+2	i=1,2,3,4 j=6,7,8,9	i=1,2,3 j=i+9	j=13,14	i=1,2,3,4 j=i	l=1,2,3 i=5,6,7 sf-speci failure

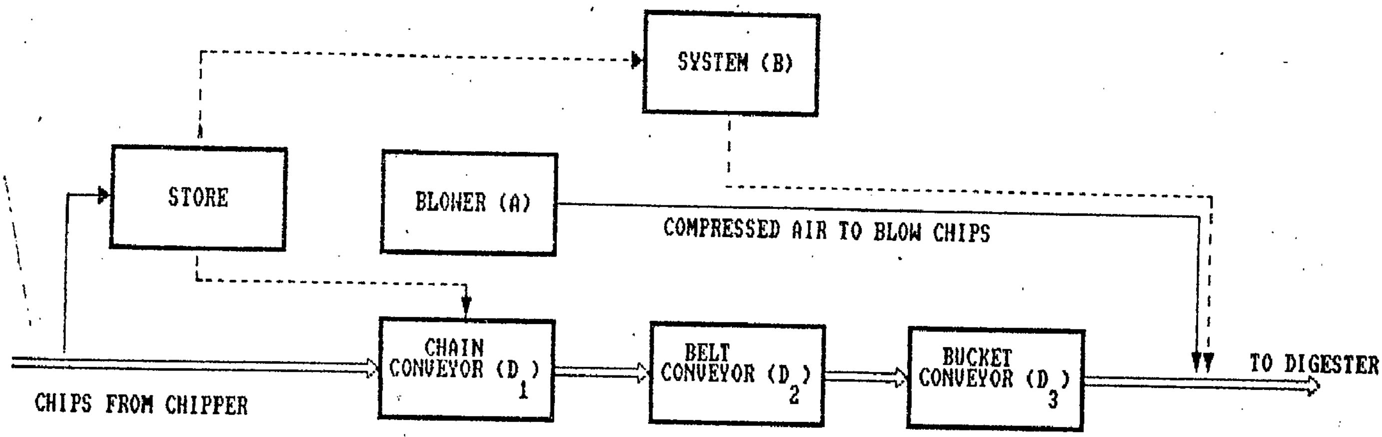


FIG 3.3:1. FEEDING SYSTEM

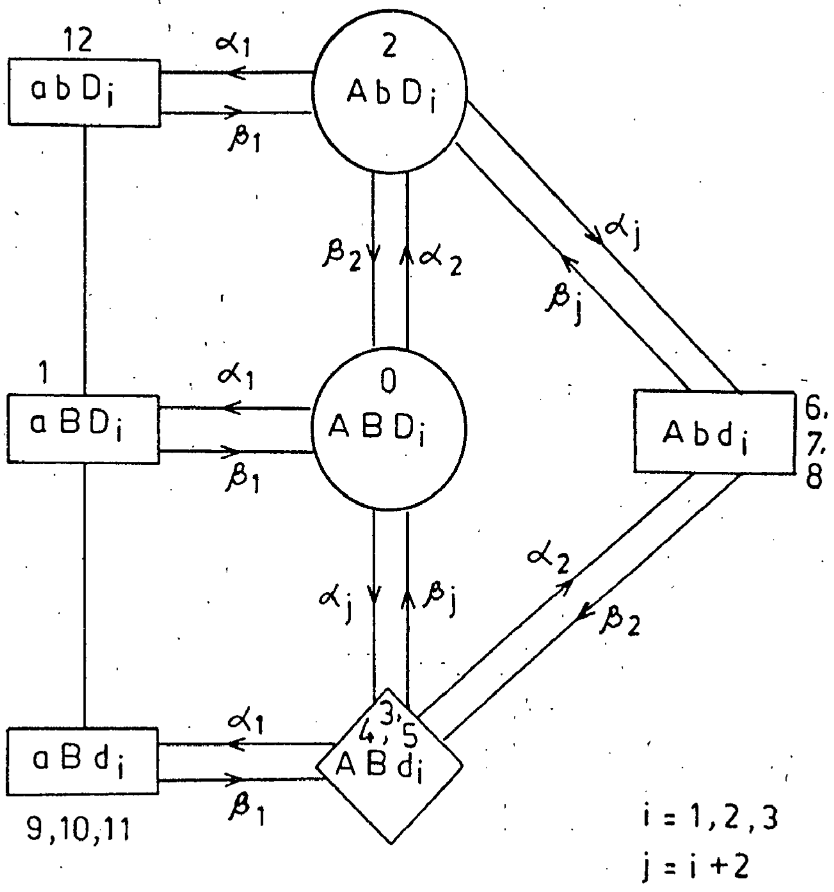


Fig.3.3:2 Transition diagram for feeding system.

$$=M_2 p_0(s)$$

$$x_1=\alpha_1+\alpha_2+\beta_j \quad ; x_2=\alpha_1+\beta_2+\sum_{j=3}^{5}\alpha_j$$

$$x_3=\sum_{i=1}^{2}\alpha_i+\sum_{j=3}^{5}\alpha_j \quad ; y_1=\frac{\alpha_1\beta_1}{s+\beta_1}+\frac{\alpha_2\beta_2}{s+\beta_2+\beta_j}$$

$$y_2=\sum_{j=3}^{5}\frac{\alpha_j\beta_j}{(s+\beta_2+\beta_j)}\left[1+\frac{\alpha_2\beta_2}{(s+\beta_2+\beta_j)(s+x_1-y_1)}\right]+\frac{\alpha_1\beta_1}{s+\beta_1}$$

$$y_3=\frac{\alpha_1\beta_1}{s+\beta_1}+\beta_2 M_1+\sum_{j=3}^{5}\beta_j M_2$$

and mean time to system failure $MTTF=\lim_{s\to 0} sR_1(s)$ is given by:

$$[MTTF]_1=\frac{1}{b_3}\left[1+\left\{1+\sum_{j=3}^{5}\frac{\beta_j^2}{(\beta_2+\beta_j)a_1}\right\}\left\{1+\frac{\beta_2\beta_j}{a_1(\beta_2+\beta_j}\right\}\frac{\alpha_2}{a_2}+\frac{\beta_j}{a_1}\right]$$

where

$$a_1=\frac{\beta_j(\alpha_2+\beta_2+\beta_j)}{\beta_2+\beta_j} \quad ; a_2=\frac{\beta_2+\sum_{j=3}^{5}(\alpha_2+\beta_2+\alpha_j+\beta_j)}{(\alpha_2+\beta_2+\beta_j)}$$

$$b_1=1+\frac{\alpha_1}{\beta_1}+\frac{\alpha_2\beta_2}{(\beta_2+\beta_j)^2}$$

$$b_2=1+\frac{\alpha_1}{\beta_1}+\frac{\alpha_j\beta_j}{(\beta_2+\beta_j)^2}\left[1+\frac{\alpha_2\beta_2}{a_1}\left\{\frac{b_1}{a_1}+\frac{1}{\beta_j+\beta_j}\left(1+\frac{1}{a_1}\right)\right\}\right]$$

$$b_3=1+\frac{\alpha_1}{\beta_1}+\frac{\alpha_2\beta_2}{a_2}\left[\frac{1}{a_1}\sum_{j=3}^{5}\frac{\beta_j^2}{\beta_2+\beta_j}\left\{\frac{1}{\beta_2+\beta_j}+\frac{b_1}{a_1}+\frac{b_2}{a_2}\right\}+\frac{b_2}{a_2}\right]$$

$$+\sum_{j=3}^{5}\frac{\alpha_2\beta_2\alpha_j\beta_j}{(\beta_2+\beta_j)^2 a_1 a_2}\left[\frac{\beta_j^2}{a_1}\left(\frac{1}{\beta_2+\beta_j}+b_1\right)\right]$$

$$+\sum_{j=3}^{5}\frac{\alpha_2\beta_2\alpha_j\beta_j}{(\beta_2+\beta_j)a_1 a_2}\left\{1+\frac{\beta_j^2}{(\beta_2+\beta_j)a_2}\right\}\left\{\frac{b_1}{a_1}+\frac{b_2}{a_2}+\frac{1}{\beta_2+\beta_j}\right\}$$

3.3.d BEHAVIOURAL ANALYSIS:

The effects of failure and repair rates of the subsystems A, B and D_1 upon availability $[AV_1]$ has been computed using equations (3.3.6) and some data has been presented in tables 3.3-1 to 3.3-2.

Table 3.3-1: Effect of failure rate of blower, chip carrying unit on system availability ($\beta_1=\beta_3=0.1, \beta_2=\beta_4=0.2$ and $\beta_5=0.3$)

α_2	α_3	α_4	α_5	Availability$[AV_1]$				
				α_1 =.002	α_1 =.004	α_1 =.006	α_1 =.008	α_1=.01
.02	.04	.04	.05	.96985	.94976	.93038	.91367	.89650
			.10	.96106	.94294	.92550	.90867	.89245
.02	.04	.08	.05	.96320	.94502	.92750	.91060	.89430
	.08	.04	.05	.96320	.94502	.92750	.91060	.89430
.04	.04	.04	.05	.95187	.93446	.91667	.89950	.88588
			.10	.94315	.92556	.91002	.89320	.87771
.04	.04	.08	.05	.94625	.92867	.91174	.89541	.87966
	.08	.04	.05	.94625	.92867	.91174	.89541	.87966

Table 3.3-2: Effect of repair rate of blower and chip carrying unit upon availability (α_2=.04, $\alpha_3=\alpha_4=\alpha_5$=.05, α_1=.004)

β_2	β_3	β_4	β_5	Availability$[AV_1]$				
				β_1 =0.1	β_1 =0.2	β_1 =0.3	β_1 =0.4	β_1 =0.5
.2	.1	.2	.3	.91337	.93036	.93617	.93909	.94086
			.5	.93684	.95724	.96084	.96393	.96579
.2	.1	.5	.3	.93884	.95681	.96295	.96605	.96792
	.3	.2		.93684	.95472	.96084	.96393	.96578
.5	.1	.2	.3	.94714	.96543	.97168	.97484	.97674
			.5	.94941	.96778	.97407	.97724	.97916
.5	.1	.5	.3	.95140	.96976	.97616	.97925	.98114
	.3	.2		.94941	.96778	.97407	.97724	.97916

Examination of tables (3.3-1) and (3.3-2) reveals that increase in failure rates of subsystem A or D_1 reduces the system availability considerably; Whereas an increase in the repair rate of these subsystems improves the availability sharply. Since the whole process of paper making depends upon the availability of the feeding system, therefore its value must be maintained at a high level through efficient maintenance planning and limiting the number of failures to the lowest possible value.

The reliability analysis of the system with general repair rate using Lagrange's method for the solution of partial differential equations has been developed by the author and reported elsewhere [56, 62].

3.4 ANALYSIS OF PULP PREPARATION SYSTEM:

A schematic diagram of the pulping system is shown in fig. 3.4:1.

3.4.a <u>SYSTEM DESCRIPTION</u>: The pulp preparation system comprises of following four subsystem.

i) the digester (E_1); here a mixture of wooden chips and NaoH+ N_2s (liquor:wood ratio 3.5:1) is heated by steam at 175° c, and 8kg/cm^2 pressure. Failure of digesters interrupts the cooking process and hence leads to total system failure, ~~and~~ (ii) The Decker (E_2) is used for the removal of black liquor from the pulp. Failure of any one

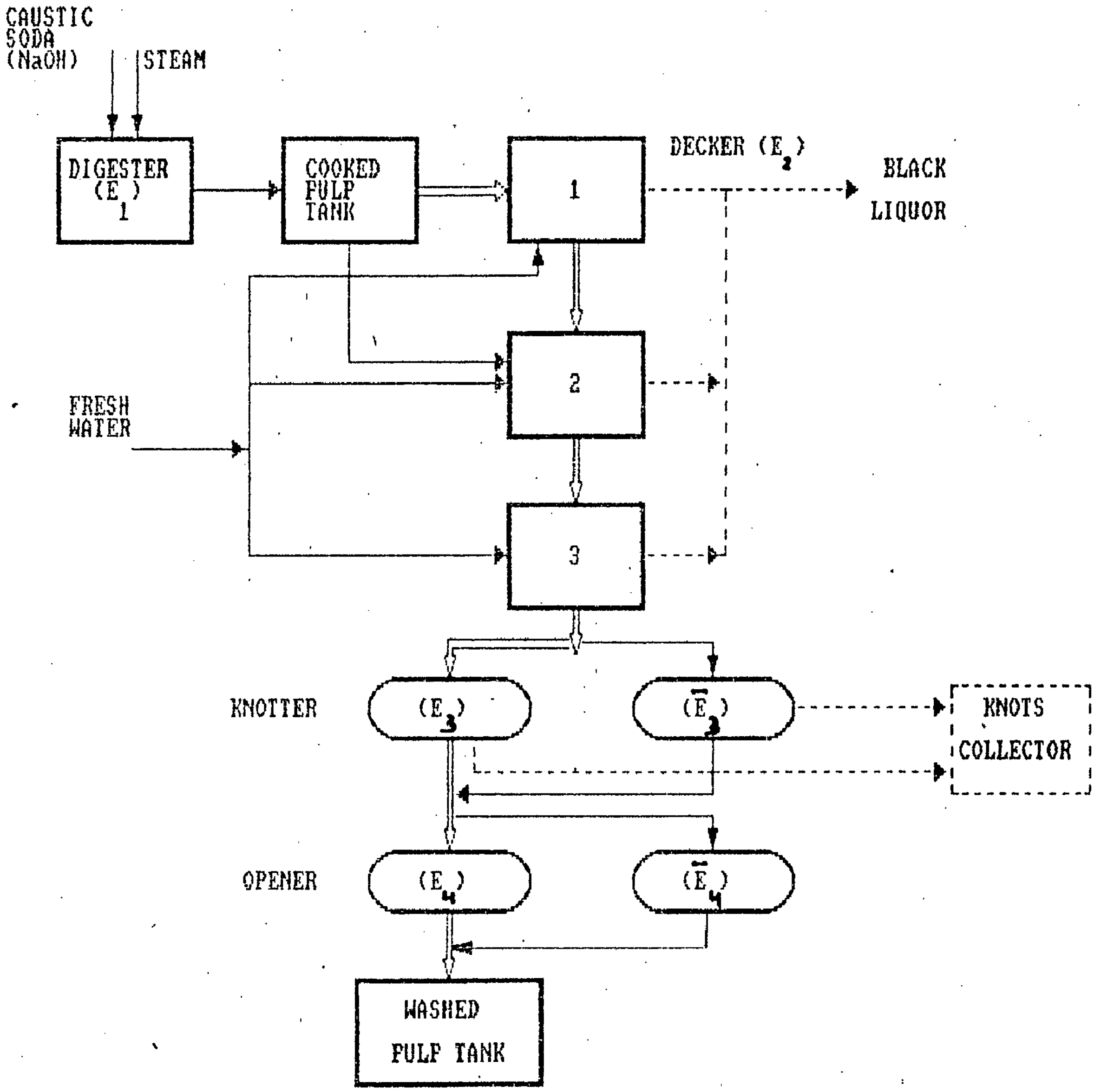


FIG 3.4:1. PULPING SYSTEM

unit causes complete stoppage of the process of black liquor removal. With only one or two units in operation it is possible to produce low quality paper which often is uneconomical,

iii) the knotter (E_3), also called fiberizer consists of one main unit and one standby. This machine is used to tear, cut and plough or abrade the fibers. Complete failure occurs when both the units fail,

iv) the opener (E_4), also called refiner consists of one main unit and one standby. This is used to break the walls of the fibers into ribbons ensuring the availability of large surface area for bonding. Complete failure of this system occurs only when both units fail.

3.4.b MATHEMATICAL FORMULATION AND ANALYSIS:

The differential equations associated with the various states of the system components as derived from the transition diagram (fig. 3.4:2) are as follows:

$$\left(\frac{d}{dt}+\sum_{j=6}^{9}\alpha_j\right)p_0(t)=\sum_{j=6}^{9}\beta_j\, p_{j-5}(t) \qquad \text{------}(3.4.1)$$

$$\left(\frac{d}{dt}+\beta_8+\sum_{j=6}^{9}\alpha_j\right)p_3(t)=\sum_{j=6}^{9}\beta_j p_{j-1}(t)+\alpha_8 p_0(t) \qquad \text{-----}(3.4.2)$$

$$\left(\frac{d}{dt}+\beta_9+\sum_{j=6}^{9}\alpha_j\right)p_4(t)=\alpha_9 p_0(t)+\beta_6 p_9(t)+\beta_7 p_{10}(t)+\beta_8 p_8(t)+\beta_9 p_{11}(t) \qquad \text{---}(3.4.3)$$

$$\left(\frac{d}{dt}+\beta_8+\beta_9+\sum_{j=6}^{9}\alpha_j\right)p_8(t)=\sum_{j=6}^{9}\beta_j p_{j+6}(t)+\alpha_8 p_4(t)+\alpha_9 p_3(t) \qquad \text{---}(3.4.4)$$

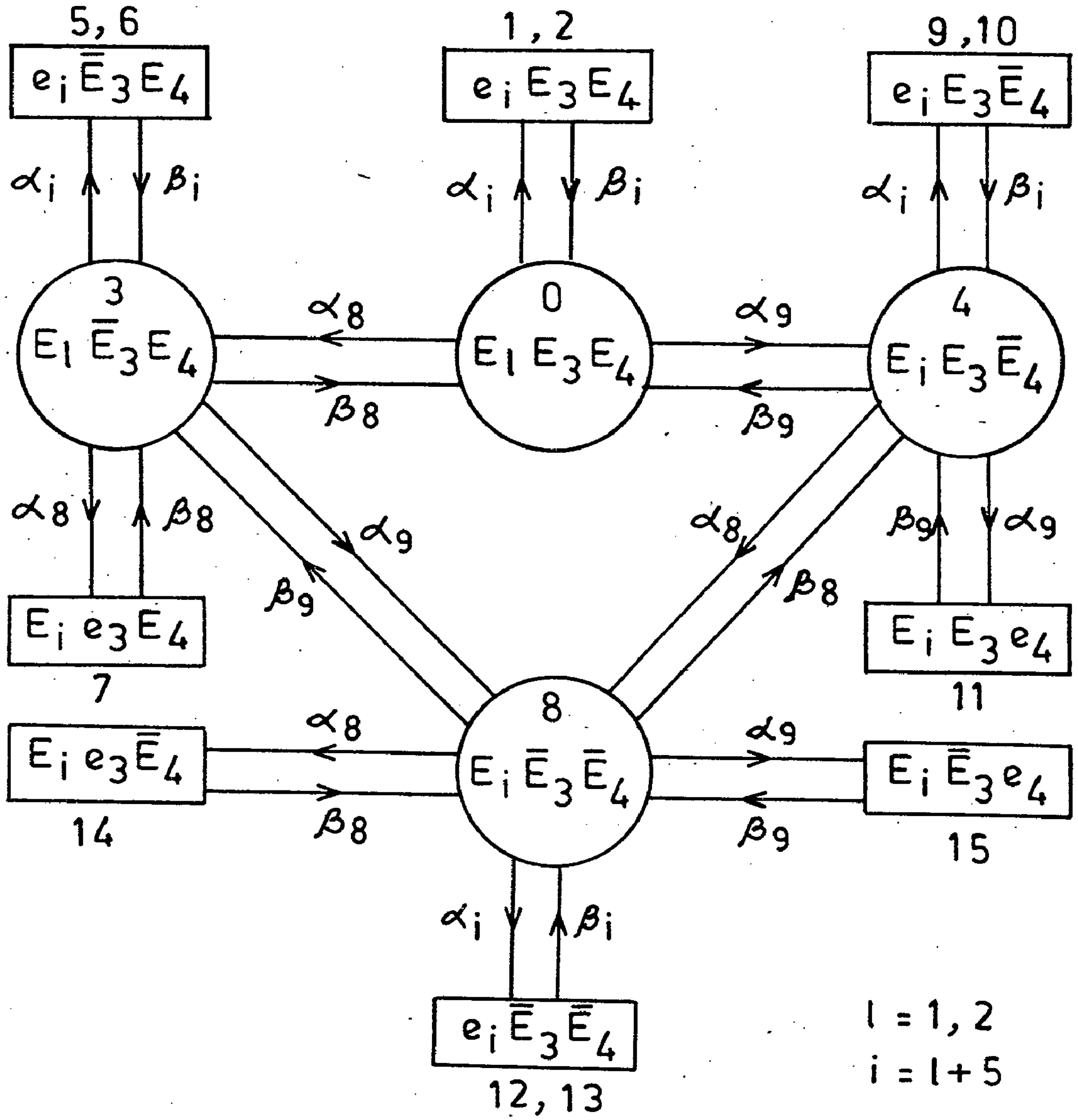


Fig. 3.4:2 Transition diagram for pulping system.

$$\left(\frac{d}{dt}+\beta_j\right)p_i(t)=\alpha_j p_k(t) \qquad ---(3.4.5)$$

with initial conditions $p_0(0)=1$. otherwise=0

where in equation (3.4.5):

for $j=6,7,k=0,i=j-5;k=3,i=j-1;k=4,i=j+3;k=8,i=j+6$,

for $j=8$, $k=3,i=j-1;k=8,i=j+6$; and for $j=9$, $k=4,i=j+2;k=8,i=j+6$.

Taking Laplace transforms of equations (3.4.1) to (3.4.5) and solving recursively (using initial condition) the Laplace transform $R_2(s)$ of the reliability function is given by:

$$R_2(s)=p_0(s)+p_3(s)+p_4(s)+p_8(s)$$

where,

$$p_0(s)=[s+x_7-y_7]^{-1} \quad ; \quad p_3(s)=[\alpha_8+\beta_9L']{[s+x_4-y_4]}^{-1}p_0(s)$$

$$p_4(s)=[\alpha_9+\beta_8L'][s+x_6-y_6]^{-1}p_0(s)$$

$$p_8(s)=\left\{\frac{\alpha_8\alpha_9}{s+x_5-y_5}\right\}\left[\frac{1}{s+x_6-y_6}+\frac{1}{s+x_4-y_4}\right]p_0(s)=M_3p_0(s)$$

and

$$x_4=x_7+\beta_8; \qquad x_5=x_7+\beta_8+\beta_9$$

$$x_6=x_7+\beta_9; \qquad x_7=\sum_{i=6}^{9}\alpha_i$$

$$y_4=\frac{\alpha_6\ \beta_6}{s+\beta_6}+\frac{\alpha_7\ \beta_7}{s+\beta_7}+\frac{\alpha_8\ \beta_8}{s+\beta_8}$$

$$y_5=y_4+\frac{\alpha_9\ \beta_9}{s+\beta_9}+\frac{\alpha_8\ \beta_8}{s+x_6-y_6}+\frac{\alpha_9\ \beta_9}{s+x_4-y_4}$$

$$y_6=\frac{\alpha_6\ \beta_6}{s+\beta_6}+\frac{\alpha_7\ \beta_7}{s+\beta_7}+\frac{\alpha_9\ \beta_9}{s+\beta_9}$$

$$y_7=\frac{\beta_9(\alpha_9+\beta_8M_3)}{s+x_6-y_6}+\frac{\beta_8(\alpha_8+\beta_9M_3)}{s+x_4-y_4}+\frac{\alpha_6\ \beta_6}{s+\beta_6}+\frac{\alpha_7\ \beta_7}{s+\beta_7}$$

$$L'=\frac{\alpha_8\alpha_9(s+x_5-y_5)^{-1}[(s+x_6-y_6)^{-1}+(s+x_4-y_4)^{-1}]}{1-(s+x_2-y_2)^{-1}[\alpha_8\beta_8(s+x_6-y_6)^{-1}+\alpha_9\beta_9(s+x_4-y_4)^{-1}]}$$

Mean time to system failure $[MTTF]_2=\lim_{s\to 0} sR_2(s)$ and is given by:

$$[MTTF]_2=\frac{\{1+(\alpha_8/\beta_8)\}\{1+(\alpha_9/\beta_9)\}}{\left[1+\sum_{j=6}^{7}\frac{\alpha_j}{\beta_j}+\left(1+\frac{\alpha_9}{\beta_9}+\sum_{j=6}^{7}\frac{\alpha_j}{\beta_j}\right)\left(\frac{\alpha_9}{\alpha_8+\beta_9}\right)\left(1+\frac{\alpha_8}{\alpha_8+\beta_9}\right)+\left(1+\sum_{j=6}^{8}\frac{\alpha_j}{\beta_j}\right)\left(\frac{\alpha_8}{\alpha_9+\beta_8}\right)\left(1+\frac{\alpha_9}{\alpha_9+\beta_8}\right)+\left(\frac{\alpha_8\alpha_9}{\beta_8\beta_9}\right)b_0\right]}$$

where

$$b_0=\left[1+\sum_{j=6}^{7}\frac{\alpha_j}{\beta_j}\right]\left[1+\frac{\alpha_8\ \beta_8}{(\alpha_8+\beta_9)^2}+\frac{\alpha_9\ \beta_9}{(\alpha_9+\beta_8)^2}\right]+\frac{\alpha_8}{\beta_8}\left[1+\frac{\alpha_9\beta_9}{(\alpha_9+\beta_8)^2}\right]+\frac{\alpha_9}{\beta_9}\left[\frac{\alpha_8\beta_8}{(\alpha_8+\alpha_9)^2}\right]$$

3.4.c STEADY STATE BEHAVIOUR:

This is obtained by using the condition as $t\to\infty$, $(d/dt)\to 0$ in equations (3.4.1) to (3.4.5) and solving recursively the steady state probabilities are obtained as (ref 59):

$p_i=(\alpha_j/\beta_j)p_k$

for $j=6,7$, $k=0, i=j-5$; $k=3, i=j-1$; $k=4, i=j+3$; $k=8, i=j+6$

$j=8$, $k=0, i=j-5$; $k=3, i=j-1$; $k=8, i=j+6$

$j=9$, $k=0, i=j-5$; $k=4, i=j+2$; $k=8, i=j+6$

$p_8=(\alpha_8\alpha_9/\beta_8\beta_9)p_0$

probability p_0 is evaluated using normalizing condition i.e.,

$\sum_{i=0}^{15} p_i=1$, and is giving by:

Table 3.4-4: Effect of repair rate of knotter, decker and digesters (β_7=0.1).

β_9	β_8	Availability[AV_2]			
		β_6 =0.05	β_6 =0.10	β_6 =0.15	β_6 = 0.20
.05	.05	.4385	.5316	.5723	.5950
	.10	.4777	.5906	.6410	.6696
	.15	.4917	.6121	.6665	.6975
	.20	.4988	.6232	.6796	.7119
.10	.05	.4777	.5906	.6410	.6696
	.10	.5146	.6480	.7092	.7444
	.15	.5259	.6659	.7308	.7683
	.20	.5310	.6742	.7407	.7792
.15	.05	.4917	.6121	.6665	.6975
	.10	.5259	.6659	.7308	.7683
	.15	.5355	.6815	.7496	.7890
	.20	.5396	.6882	.7577	.7980
.20	.05	.4988	.6232	.6796	.7119
	.10	.5310	.6742	.7407	.7792
	.15	.5396	.6882	.7557	.7980
	.20	.5433	.6941	.7649	.8086

Tables 3.4-1 & 3.4-2 reveal that if value of α_6 is doubled, the availability decreases rapidly but changes in α_8 and α_9 have little effect on availability. In practice, to maintain low failure rate in the digesters (α_6) an unskilled or semiskilled worker is usually deputed to look after its smooth functioning. Furthermore, the cooking process takes 9 to 10 hours per charge. It should therefore be ensured that the pulp would be available for operation of the plant for a minimum period of 4 to 6 hrs depending upon the plant capacity. It is also obvious from tables 3.4-1 & 3.4-2 that the failure of the decker has larger effect upon [AV_2] than the failure of knotter. Similarly failure in the opener has comparatively larger effect upon [AV_2] than failure in knotter. The failure in digesters may be minimized through

scheduled maintenance i.e. keeping it failure free for a long time. While to achieve long run availability for the knotter , decker and opener, skilled workers on each subsystem be provided. Standby units in the knotter and opener subsystems further reduce the failure rates (α_8 & α_9). The failures in these subsystems (E_3 & E_4) can further be reduced through preventive maintenance. Minimizing the repair time α_6 and α_7 gives higher values of [AV_2] as shown in table 3.4-3.

Tables 3.4-3 & 3.4-4 show that a change in repair rates (β_6, β_7, β_8, β_9) changes the availability considerably. Thus use of better maintenance facilities could lead to higher availability values. From these tables (3.4-3) & (3.4-4) it is obvious that subsystem maintenance be accorded priority in the following order - decker, opener, knotter and digesters.

3.5 ANALYSIS OF WASHING SYSTEM:

A schematic diagram of the washing system is shown in fig 3.5:1.

3.5.a SYSTEM DESCRIPTION: It comprises of the following subsystem:

i) the screen (F_1) having two units in series. This is used to remove oversize, uncooked and odd shape fibers from pulp through straining. Failure of any one unit causes complete failure of the system,

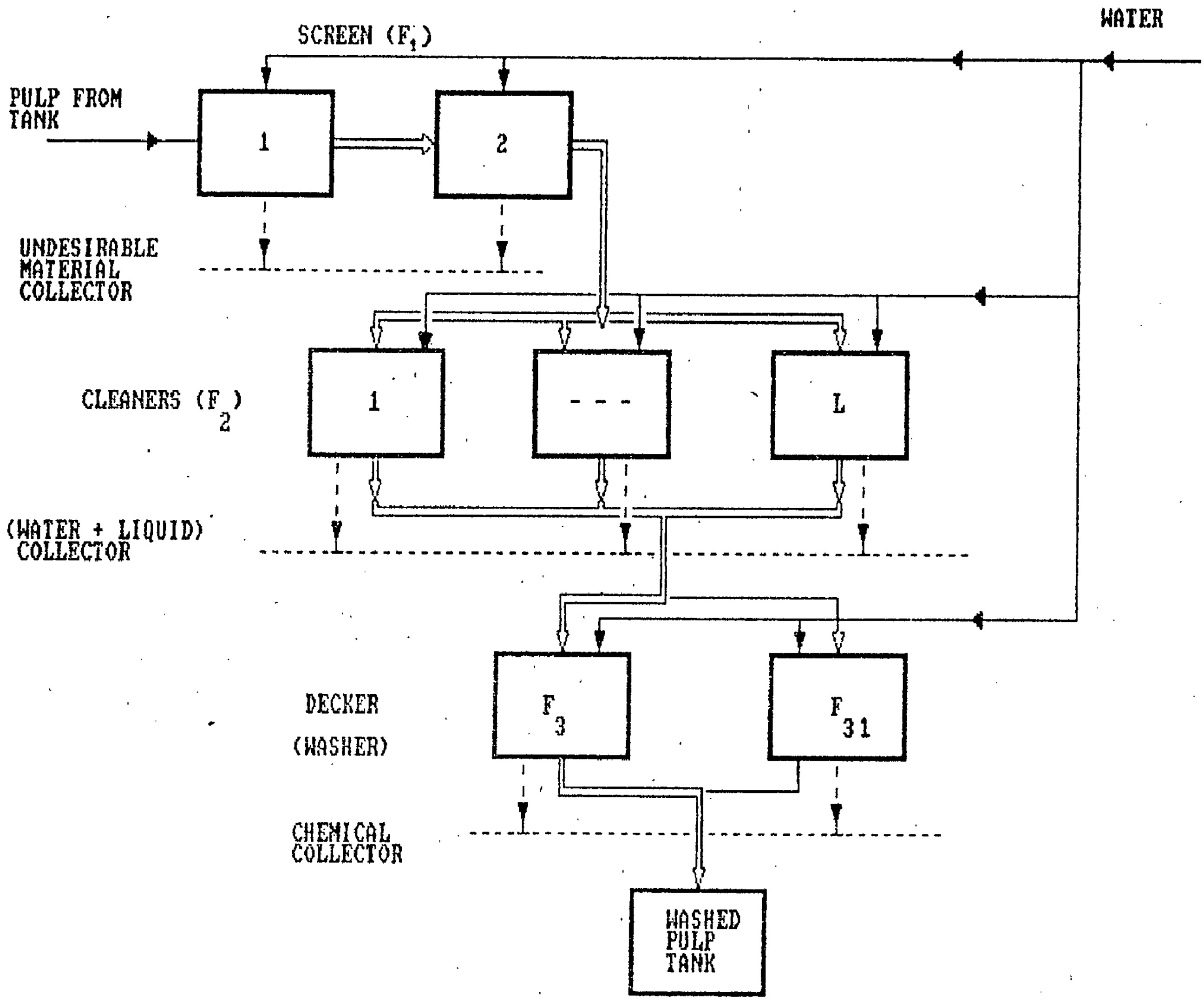


FIG 3.5:1. WASHING SYSTEM

ii)the cleaners (F_2), this has l units in parallel. Failure of any one unit reduces the cleaning efficiency of the system, which affects the quality of the paper, hence the profit. The unit can be repaired by unskilled workers in a very short period,

iii)the decker (F_3) has one main unit and a standby. Complete failure in this case occurs only when both the units fail.

3.5.b MATHEMATICAL FORMULATION AND ANALYSIS:

The differential equations associated with the various states of the system components as derived from the transition diagram (fig 3.5:2) are as follows:

$$\left(\frac{d}{dt}+\sum_{j=10}^{12}\alpha_j\right)p_0(t)=\sum_{j=10}^{12}\beta_j p_j(t) \qquad \text{--(3.5.1)}$$

$$\left(\frac{d}{dt}+\alpha_{10}+\alpha_{12}+T_3+\beta_{11}\right)p_2(t)$$
$$=\alpha_{11}p_0(t)+\beta_{11}p_5(t)+\beta_{10}p_4(t)+\beta_{12}p_6(t) \qquad \text{--(3.5.2)}$$

$$\left(\frac{d}{dt}+\sum_{j=10}^{12}\alpha_j+\beta_{12}\right)p_3(t)=\sum_{j=10}^{12}\beta_j p_{j-4}(t)+\alpha_{12}p_0(t) \qquad \text{----(3.5.3)}$$

$$\left(\frac{d}{dt}+\alpha_{10}+T_3+\alpha_{12}+\beta_{12}+\beta_{11}\right)p_7(t)$$
$$=\alpha_{12}p_2(t)+\alpha_{11}p_3(t)+\sum_{j=10}^{12}\beta_j p_{j-1}(t) \qquad \text{--(3.5.4)}$$

$$\left(\frac{d}{dt}+\beta_j\right)p_i(t)=\alpha_j p_k(t) \qquad \text{--(3.5.5)}$$

$$\left(\frac{d}{dt}+\beta_{11}\right)p_i(t)=T_3 p_k(t) \qquad \text{--(3.5.6)}$$

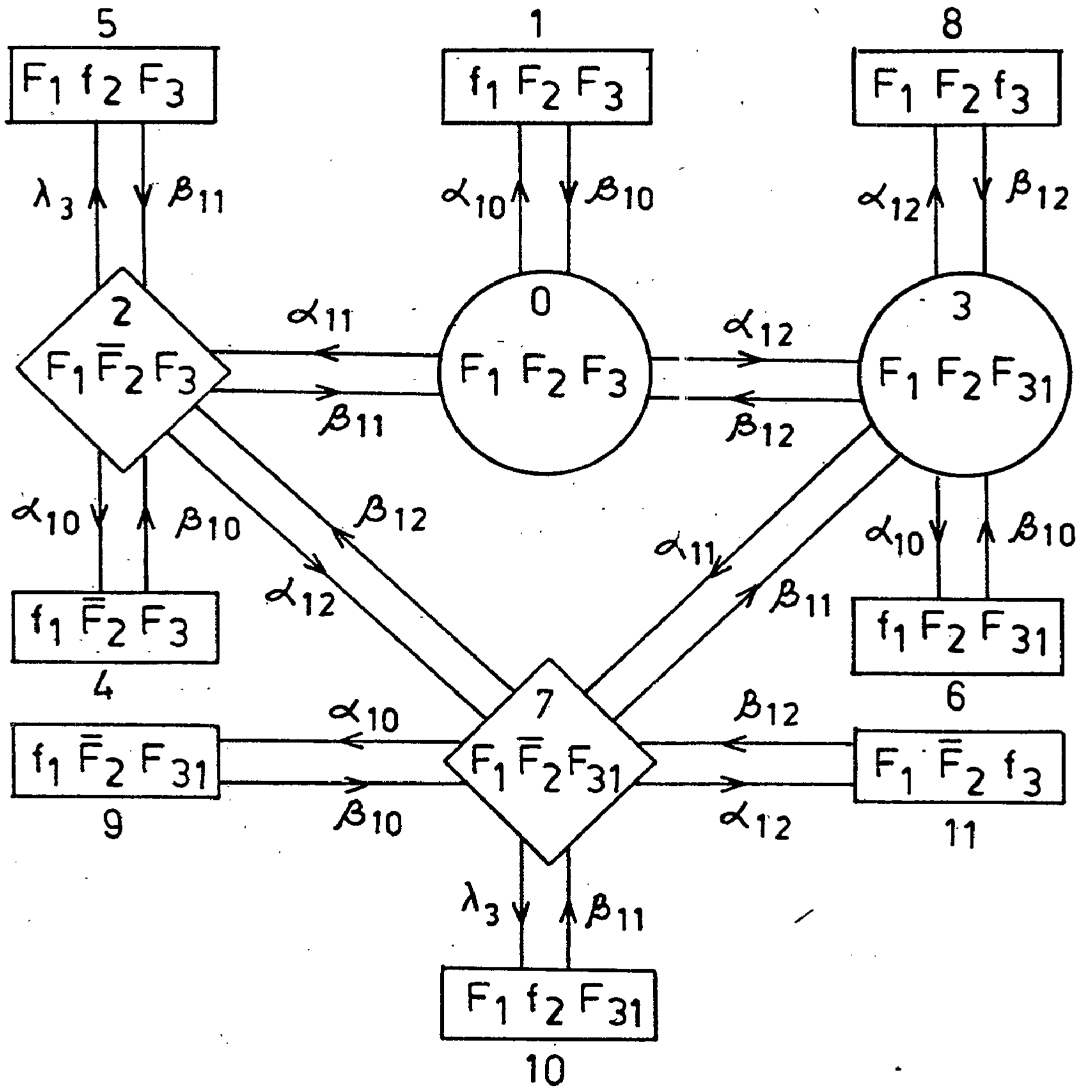


Fig.3.5:2 Transition diagram for washing process.

with initial condition $p_0(0)=1$ otherwise=0

where in equation (3.4.5) we have

for $j=10$, $k=0, i=j-9; k=2, i=j-6; k=3, i=j-4; k=7, i=j-1$

$j=12$, $k=3, i=j-4; k=7, i=j-1$.

and for equation (3.4.6) for $k=2, i=5; k=7, i=10$.

Taking Laplace transform of (3.5.1) to (3.5.6) and solving recursively (using initial condition) the Laplace transform $R_3(s)$ of reliability function is given by:

$$R_3(s)=p_0(s)+p_2(s)+p_3(s)+p_7(s)$$

where

$$p_0(s)=[s+x_{11}-y_{11}]^{-1}$$

$$p_2(s)=\frac{\alpha_{11}+\beta_{12}M_4}{(s+x_9-y_9)}p_0(s)$$

$$p_3(s)=\frac{\alpha_{12}+\beta_{11}M_4}{(s+x_{10}-y_{10})}p_0(s) \quad ; \quad p_7(s)=M_4 p_0(s)$$

with

$$M_4=\frac{\alpha_{11}\alpha_{12}[2s+x_9+x_{10}-y_9-y_{10}]}{(s+x_{10}-y_{10})[(s+x_8-y_8)(s+x_9-y_9)-\alpha_{12}\beta_{12}]-\alpha_{11}\beta_{11}(s+x_9-y_9)}$$

$$x_8=\alpha_{10}+\alpha_{12}+\beta_{11}+\beta_{12}+T_3 \; ; x_9=\alpha_{10}+\alpha_{12}+\beta_{11}+T_3$$

$$x_{10}=\alpha_{10}+\alpha_{11}+\alpha_{12}+\beta_{12} \qquad ; x_{11}=\alpha_{10}+\alpha_{11}+\alpha_{12}$$

$$y_8=\frac{\alpha_{10}\beta_{10}}{s+\beta_{10}}+\frac{\alpha_{12}\beta_{12}}{s+\beta_{12}}+\frac{T_3\beta_{11}}{s+\beta_{11}}$$

$$y_9=\frac{T_3\beta_{11}}{s+\beta_{11}}+\frac{\alpha_{10}\beta_{10}}{s+\beta_{10}} \quad ; \quad y_{10}=\frac{\alpha_{10}\beta_{10}}{s+\beta_{10}}+\frac{\alpha_{12}\beta_{12}}{s+\beta_{12}}$$

$$y_{11}=\frac{\alpha_{10}\beta_{10}}{s+\beta_{10}}+\frac{\beta_{12}(\alpha_{12}+\beta_{11}M_4)}{(s+x_{10}-y_{10})}+\frac{\beta_{11}(\alpha_{11}+\beta_{12}M_4}{(s+x_9-y_9)}$$

Mean time to system failure $[MTTF]_3 = \lim_{s\to 0} sR_3(s)$ and is given by

$$[MTTF]_3 = \frac{\{1+(\alpha_{12}/\beta_{12})\}\{1+(\alpha_{11}/\beta_{11})\}}{\left[\begin{array}{l} 1+\dfrac{2\alpha_{11}\beta_{11}}{\alpha_{12}+\beta_{11}}\left(1+\dfrac{\alpha_{10}}{\beta_{10}}+\dfrac{T_3}{\beta_{11}}\right)+\dfrac{\alpha_{12}}{\beta_{12}}\left(1+\dfrac{\alpha_{11}}{\beta_{11}}\right)\left(1+\dfrac{\alpha_{10}}{\beta_{10}}+\dfrac{\alpha_{12}}{\beta_{12}}\right) \\ +\left(\dfrac{2T_3\alpha_{11}\alpha_{12}}{\beta_{11}^2\beta_{12}}\right)+\dfrac{\alpha_{11}\alpha_{12}}{\beta_{11}(\beta_{11}+\alpha_{12})}\left(\dfrac{\alpha_{10}}{\beta_{10}}+\dfrac{\alpha_{11}T_3}{\beta_{12}+\alpha_{11}}\right)+\dfrac{\alpha_{10}}{\beta_{10}}+\dfrac{T_3}{\beta_{11}}+\dfrac{\alpha_{12}}{\beta_{12}} \end{array}\right]}$$

3.5.c STEADY STATE BEHAVIOUR:

Steady state condition is achieved when $t \to \infty$ or $(d/dt) \to 0$. Thus putting $(d/dt)=0$ in equations (3.5.1) to (3.5.6), and solving recursively, the steady state probabilities for the system are obtained as (ref 57):

$p_1=(\alpha_{10}/\beta_{10})p_o$; $p_2=(\alpha_{11}/\beta_{11})p_o$

$p_3=(\alpha_{12}/\beta_{12})p_o$; $p_4=(\alpha_{10}\alpha_{11}/\beta_{10}\beta_{11})p_o$

$p_5=(T_3\alpha_{11}/\beta_{11}^2)p_o$; $p_6=(\alpha_{10}\alpha_{11}/\beta_{10}\beta_{12})p_o$

$p_7=(\alpha_{11}\alpha_{12}/\beta_{11}\beta_{12})p_o$; $p_8=(\alpha_{12}/\beta_{12})p_o$

$p_9=(\alpha_{10}\alpha_{11}\alpha_{12}/\beta_{10}\beta_{11}\beta_{12})p_o$

$p_{10}=(T_3\alpha_{11}\alpha_{12}/\beta_{11}^2\beta_{12})p_o$

$p_{11}=\{(\alpha_{12})^2\alpha_{11}/(\beta_{12})^2\beta_{11}\}p_o$

Whereas the probability p_o is obtained using normalizing

condition i.e., $\sum_{i=0}^{11} p_i=1$ and is given by

$$p_0=\left[\left(1+\frac{\alpha_{10}}{\beta_{10}}+\frac{\alpha_{12}}{\beta_{12}}\right)\left(1+\frac{\alpha_{11}\alpha_{12}}{\beta_{11}\beta_{12}}\right)+\frac{\alpha_{12}}{\beta_{12}}\left(\frac{\alpha_{10}}{\beta_{10}}+\frac{\alpha_{12}}{\beta_{12}}\right)+\frac{\alpha_{11}}{\beta_{11}}\left\{1+\frac{\alpha_{10}}{\beta_{10}}+\frac{T_3}{\beta_{11}}\left(1+\frac{\alpha_{12}}{\beta_{12}}\right)\right\}\right]^{-1}$$

or , $p_0=[L_5]^{-1}$

The steady state availability $[AV_3]$ for the washing system is obtained as:

$[AV_3]=p_0+p_2+p_3+p_7$

$$=[\{1+(\alpha_{12}/\beta_{12})\}\{1+(\alpha_{11}/\beta_{11})\}][L_5]^{-1} \quad --(3.57)$$

3.5.d BEHAVIOURAL ANALYSIS:

The effects of failure and repair rates of subsystem F_1 on the system availability $[AV_3]$ have computed for different values of the system parameters and given in tables 3.5-1 & 3.5-2.

Table 3.5-1: Effect of failure rate of screen, cleaner and decker on availability($\beta_{10}=\beta_{12}=0.2$, $\beta_{11}=0.5$, $\alpha_{11}=0.06$ number of parallel units in F_2 are l=3)

T_3	α_{12}	Availability$[AV_3]$				
		$\alpha_{10}=0.0$	$\alpha_{10}=.01$	$\alpha_{10}=.04$	$\alpha_{10}=.07$	$\alpha_{10}=0.1$
0.0	.00	1.0	.9524	.8333	.7407	.6667
	.05	.9524	.9091	.8000	.7143	.6452
0.025	.00	.9935	.9465	.8288	.7372	.6638
	.05	.9465	.9037	.7958	.7110	.6425
0.05	.00	.9774	.9319	.8176	.7283	.6566
	.05	.9319	.8904	.7688	.7027	.6357
0.075	.00	.9555	.9119	.8022	.7160	.6466
	.05	.9119	.8722	.7713	.6913	.6263

Table 3.5-2: Effect of repair rate of screen ,cleaner and decker (T_3=.02, α_{10}=.01, α_{11}=.06, α_{12}=.025)

β_{11}	β_{12}	Availability[AV_3]				
		β_{10}=0.1	β_{10}=0.2	β_{10}=0.3	β_{10}=0.4	β_{10}=0.5
.1	.1	.81633	.85106	.86333	.86950	.87336
	.3	.84644	.88385	.89708	.90382	.90790
	.5	.84934	.88701	.90824	.91510	.91926
.3	.1	.84644	.88385	.89708	.90382	.90790
	.3	.89484	.93674	.95161	.95921	.96384
	.5	.89810	.94030	.95528	.96294	.96667
.5	.1	.84934	.88700	.90824	.91510	.91926
	.3	.89484	.93674	.95161	.95921	.96384
	.5	.90361	.94637	.96151	.96931	.97403

Table 3.5-3: Effect of failure rate on MTTF(β_{10}=β_{12}=0.2,β_{11}=0.5, T_3=.02,α_{10}=.01, α_{11}=.06, α_{12}=.025)

α_{12}	Mean time to failure [MTTF]$_3$]			
	T_3 =0.0	T_3 =0.05	T_3 =0.1	T_3 =0.15
0.0	83.333	62.50	51.948	45.238
0.1	62.654	61.45	59.450	54.769

Table 3.5-1 shows that increasing the failure rate of the screen has a pronounced effect on system availability compared to cleaner and the decker. Also the decker has more impact upon system availability than the cleaner. Hence operationwise the various units can be accorded the following order of preference screen, decker, cleaner.

Table 3.5-2 shows that an increase in repair rate of the screen from 0.1 to 0.2 increases the availability by about 4% and there is only a marginal improvement in availability with further increase in repair rate.

3.6 ANALYSIS OF BLEACHING SYSTEM:

A schematic diagram of the system is shown in fig. 3.6:1.

3.6.a <u>SYSTEM DESCRIPTION</u>: It has two subsystems;

i) the filter (G_1) consists of two units, and is said to have failed (due to fall in quality) when one of the two units have failed. Its primary function is to remove chlorine and unbleached mass from the pulp received from the washing process,

ii) the opener (G_2) comprises of two units and is said to have failed (due to fall in quality) when one of the units fails. Its function is to open up the fibers through combing action.

G_1 is similar as $\bar{G}_1$ and G_2 is similar to $\bar{G}_2$. Also G_1 is in series with G_2, $\bar{G}_1$ is in series with $\bar{G}_2$.

3.6.b <u>MATHEMATICAL FORMULATION AND ANALYSIS</u>:

The differential equations associated with the transition diagram of this system (fig 3.6:2) are:

$$\left(\frac{d}{dt}+2\sum_{j=13}^{14}\alpha_j\right)p_0(t)=2\sum_{j=13}^{14}\beta_j p_{j-12}(t) \qquad \text{---(3.6.1)}$$

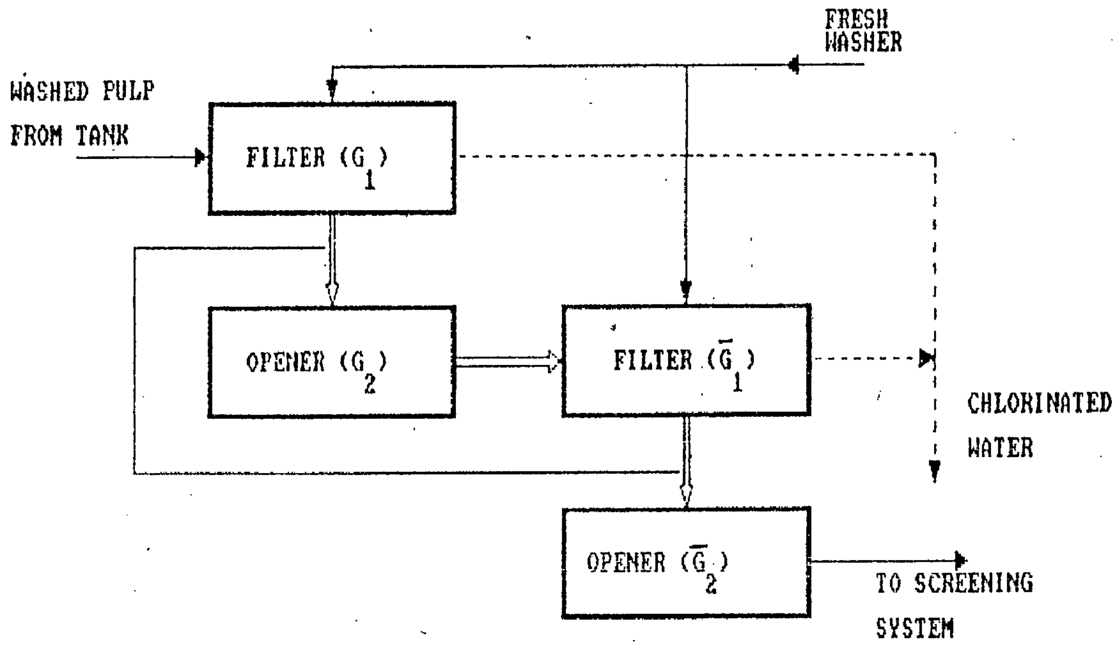


FIG 3.6:1. BLEACHING SYSTEM

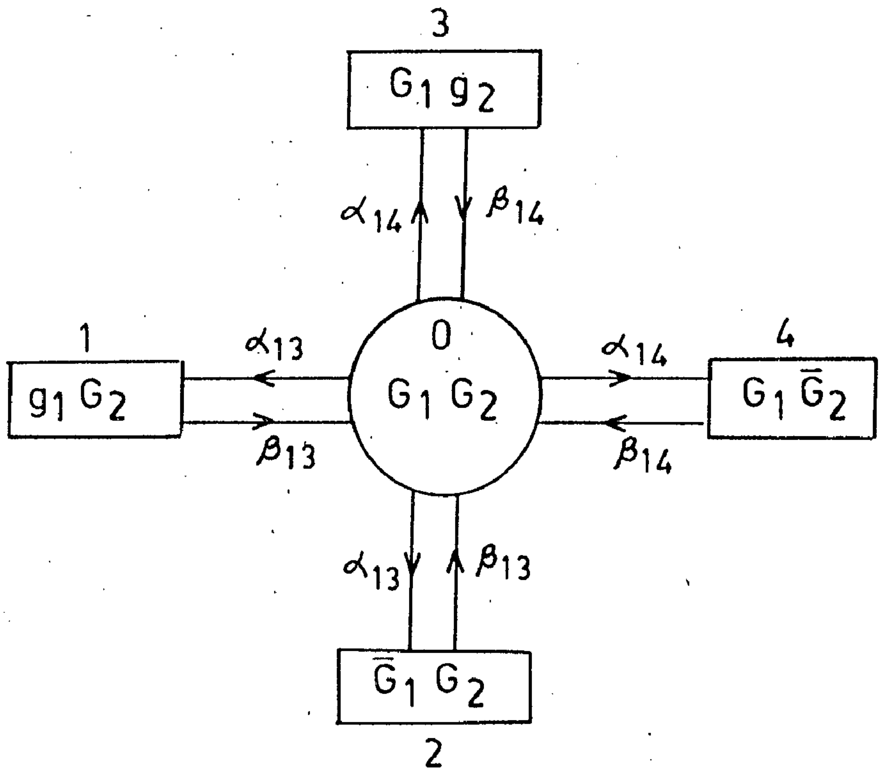


Fig. 3.6:2 Transition diagram of bleaching system.

$$\left(\frac{d}{dt}+\beta_j\right)p_i(t)=\alpha_j p_k(t) \qquad \text{---(3.6.2)}$$

with initial condition $p_o(0)=1$. otherwise=0.

where in equation (3.6.2) the values are:

for k=0, i=1,2, j=13; i=3,4,j=14

Taking Laplace transforms of equations(3.6.1) to (3.6.2) and solving (using initial condition) we get the Laplace transform $R_4(s)$ of reliability function as follows:

$R_4(s)=LR_4(t)=L\{p_o(t)\}=p_o(s)$

where

$$p_o(s)=\frac{(s+\beta_{13}))(s+\beta_{14})}{s[s^2+s(\beta_{13}+\beta_{14}+2\alpha_{13}+2\alpha_{14})+\beta_{14}(\beta_{13}+2\alpha_{13})+2\alpha_{14}\beta_{13}}$$

Mean time to failure $[MTTF]_4=\lim_{s\to 0} sR_4(s)$ and is given by:

$[MTTF]_4=[\beta_{13}\beta_{14}+2\alpha_{13}\beta_{14}+2\alpha_{14}\beta_{13}]^{-1}$

3.6.c STEADY STATE BEHAVIOUR:

This is obtained from the condition, when $t\to\infty$,$(d/dt)\to 0$. Putting $(d/dt)=0$ in equations (3.6.1) to (3.6.2) and solving, the steady state probabilities for the system are obtained as:

$p_{1or2}=(\alpha_{13}/\beta_{13})p_o$;$p_{3or4}=(\alpha_{14}/\beta_{14})p_o$

p_o is obtained by using normalizing condition i.e., $\sum_{i=0}^{4} p_i=1$.

$p_o=[1+2(\alpha_{13}/\beta_{13})+2(\alpha_{14}/\beta_{14})]^{-1}$

and the steady state availability $[AV_4]$ of the bleaching system is given as:

$[AV_4]=[1+2(\alpha_{13}/\beta_{13})+2(\alpha_{14}/\beta_{14})]^{-1}$

3.6.d BEHAVIOURAL ANALYSIS:

Table 3.6-1: Effect of failure rate of opener and filter upon availability ($\beta_{13}=\beta_{14}=0.2$)

α_{13}	Availability$[AV_4]$				
	α_{14} =0.0	α_{14} =0.025	α_{14} =0.05	α_{14} =0.075	α_{14} =0.1
0.00	1.0000	.8000	.6667	.5714	.5000
0.02	.8333	.6897	.5882	.5128	.4546
0.04	.7143	.6061	.5263	.4651	.4167
0.06	.6250	.5405	.4762	.4255	.3846
0.08	.5556	.4878	.4348	.3921	.3571
0.10	.5000	.4444	.4000	.3636	.3333

Table 3.6-2: Effect of repair rates of opener and filter upon availability (α_{14}=.02, α_{13}=.03)

β_{13}	Availability $[AV_4]$				
	β_{14} =0.1	β_{14} =0.2	β_{14} =0.3	β_{14} =0.4	β_{14} =0.5
0.1	.5000	.5556	.5769	.5882	.5952
0.2	.5882	.6667	.6977	.7143	.7246
0.3	.6250	.7143	.7500	.7692	.7813
0.4	.6452	.7407	.7792	.8000	.8130
0.5	.6579	.7576	.7979	.8197	.8333

Table 3.6-3: Effect of failure rate on MTTF (α_{13}=0.3, α_{14}=0.02, β_{13}=β_{14}=0.2)

α_{13}	Mean time to failure [MTTF]$_4$]		
	α_{14} =0.0	α_{14} =0.05	α_{14} =0.10
0.00	25.0	16.6	12.5
0.05	16.6	12.5	10.0
0.10	12.5	10.0	8.3

Table 3.6-4: Effect of repair rates on mean time to failure

β_{13}	mean time to failure [MTTF$_4$]		
	β_{14} =0.1	β_{14} =0.3	β_{14} =0.5
0.1	50.0	19.2	11.9
0.3	20.8	8.3	5.2
0.5	13.2	5.4	3.3

Tables (3.6-1) and (3.6-2) show that failure and repair rates of G_1 has larger effect upon system availability than failure and repair rates of G_2. Mean time to failure is also affected likewise. It is therefore obvious that G_1 requires larger attention during operation than G_2. Keeping in view the cost constraints, repair is arranged on the criterion of minimum failure in the subsystems.

3.7 ANALYSIS OF SCREENING SYSTEM:

A schematic diagram of this system is shown in fig. 3.7:1.

3.7.a <u>SYSTEM DESCRIPTION</u>: it comprises of

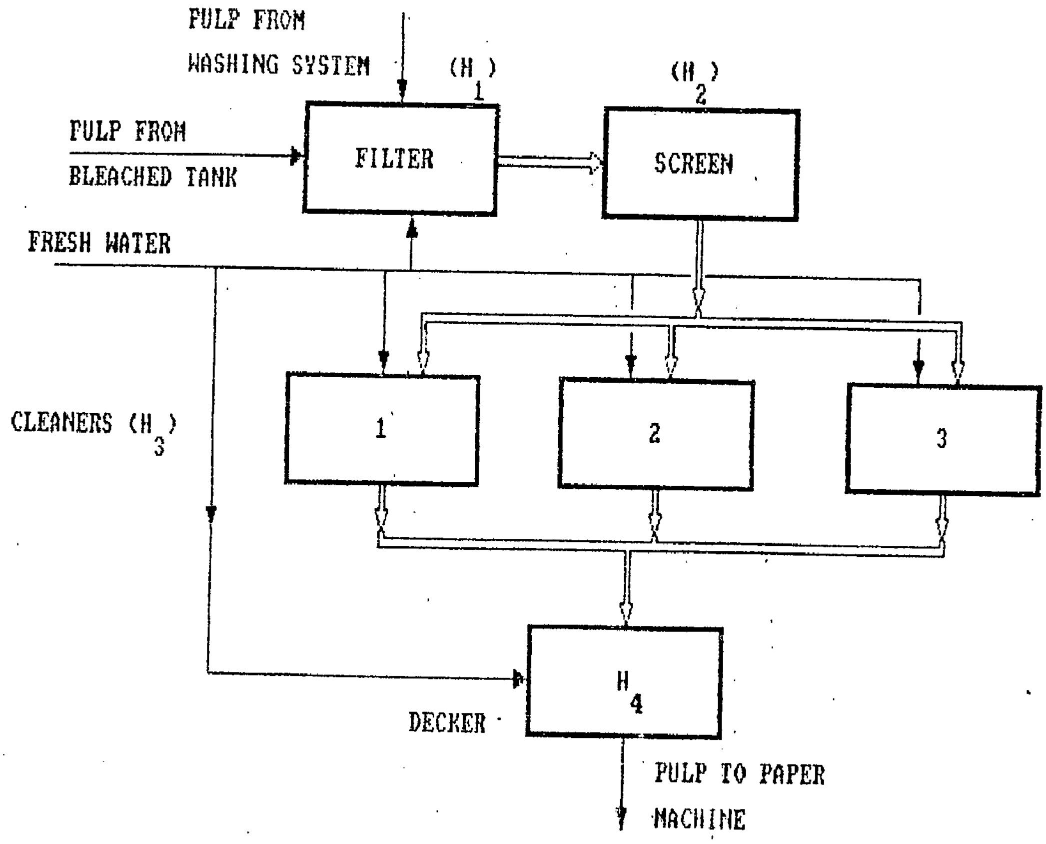


FIG 3.7:1. SCREENING SYSTEM

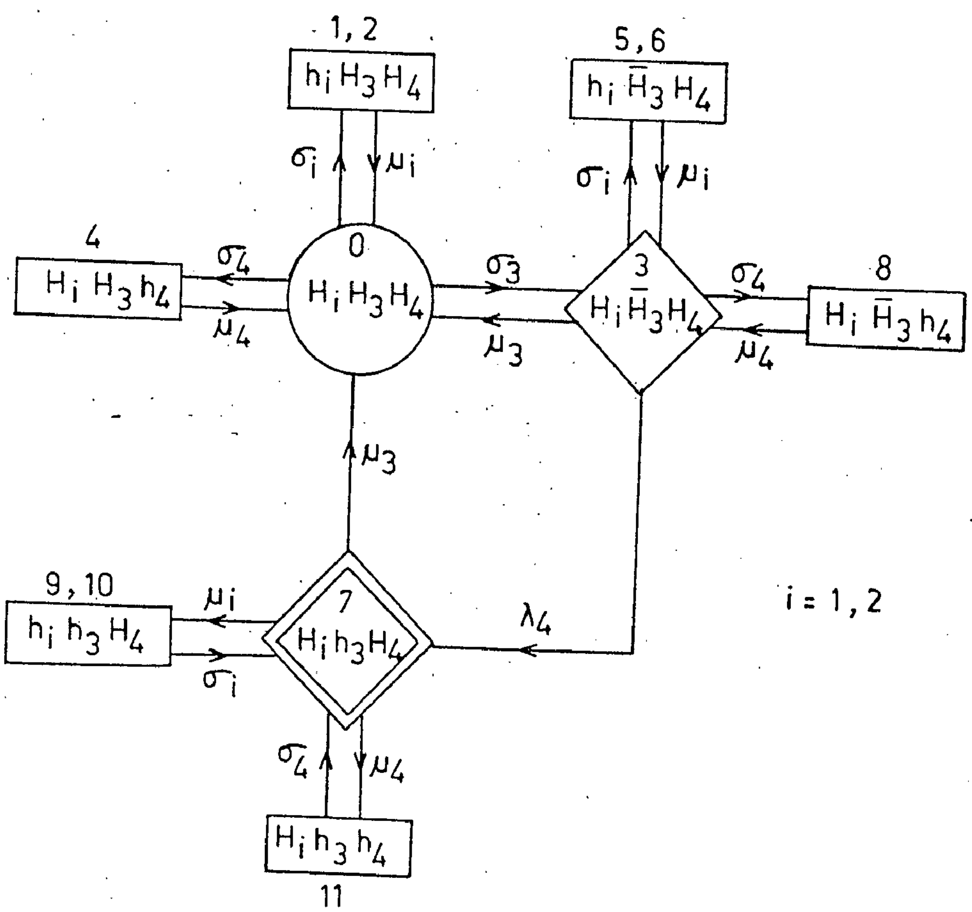


Fig.3.7:2 Transition diagram for screening system.

i) the filter (H_1), is employed for the removal of black liquor from the pulp. Its failure causes complete failure of the system,

ii) the screen (H_2), removes the knots and other undesirable foreign materials from the pulp. Its failure causes complete failure of the system.

iii) the cleaner (H_3), has three units in parallel. Failure of any one unit reduces the efficiency of the plant. Complete failure of this subsystem reduces the efficiency of the plant but the system remains operative (slow process). Here water is mixed with the pulp through centrifugal action. Also manual operation is possible during the repair of H_3,

iv)the decker (H_4), reduces blackness of the pulp by controlling its water content. Its failure causes complete failure of the system.

3.7.b MATHEMATICAL FORMULATION AND ANALYSIS:

Deferential equations associated with various states of the system as depicted by the transition diagram (fig.3.7:2) can be written as:

$$\left(\frac{d}{dt}+\sum_{j=1}^{4}\sigma_j\right)p_0(t)=\sum_{j=1}^{4}\mu_j\ p_j(t) \qquad \text{---(3.7.1)}$$

$$\left(\frac{d}{dt}+\mu_3+\sum_{i=1}^{2}\sigma_i+\sigma_4+T_4\right)p_3(t)$$

$$=\sigma_3 p_0(t)+\sum_{j=1}^{2}\mu_j p_{j+4}(t)+\mu_4 p_8(t) \qquad \text{---(3.7.2)}$$

$$\left(\frac{d}{dt}+\sum_{j=1}^{2}\sigma_j+\mu_3+\sigma_4\right)p_7(t)$$

$$=T_4p_3(t)+\mu_4p_{11}(t)+\sum_{j=1}^{2}\mu_jp_{j+8}(t) \qquad ---(3.7.3)$$

$$\left(\frac{d}{dt}+\mu_j\right)p_i(t)=\sigma_jp_k(t) \qquad ---(3.7.4)$$

with initial conditions $p_o(0)=1$. otherwise=0.

whereas in equation (3.7.4) the values are:

for $j=1,2$, $k=o,i=j$; $k=3,i=j+4$; $k=7,i=j+8$.

$j=4$, , $k=0,i=j$; $k=3,i=j+4$; $k=7,i=j+7$.

Taking Laplace transforms of equations (3.7.1) to (3.7.4) and solving recursively (using initial condition) we get the Laplace transform$R_5(s)$ of the reliability function as follows:

$$R_5(s)=L\{p_o(t)+p_3(t)+p_7(t)\}$$

$$=p_o(s)+p_3(s)+p_7(s)$$

where

$$p_o(s)=[s+x_{13}-y_{13}]^{-1} \quad ; \quad p_3(s)=\sigma_3[s+T_4+x_{12}-y_{12}]^{-1}p_o(s)$$

$$p_7(s)=T_4\sigma_3[(s+x_{12}-y_{12})(s+T_4+x_{12}-y_{12})]^{-1}p_o(s)$$

$$x_{12}=\mu_3+\sigma_1+\sigma_2+\sigma_4 \quad ; x_{13}=\sum_{i=1}^{4}\sigma_i$$

$$y_{12}=\sigma_1\mu_1(s+\mu_1)^{-1}+\sigma_2\mu_2(s+\mu_2)^{-1}+\sigma_4\mu_4(s+\mu_4)^{-1}$$

$$y_{13}=y_{12}+\sigma_3\mu_3[s+T_4+x_{12}-y_{12}]^{-1}\,[1+T_4/(s+x_{12}-y_{12})]$$

Mean time to system failure $MTTF=\lim_{s\to 0} sR_5(s)$ is given by:

$$[MTTF]_5=2(T_4+\mu_3)^2[\mu_3(T_4+\mu_3)^2+T_4\mu_3^2+T_4^2(T_4+2\mu_3)]^{-1}$$

3.7.c STEADY STATE BEHAVIOUR:

When t->∞, (d/dt)->0. Putting (d/dt)=0 in equations (3.7.1) to (3.7.4) and solving recursively the steady state probabilities for the system are obtained as (ref 63):

$p_1=(\sigma_1/\mu_1)p_0$; $p_2=(\sigma_2/\mu_2)p_0$

$p_3=[\sigma_3/(T_4+\mu_3)]$; $p_4=(\sigma_4/\mu_4)p_0$

$p_5=\{\sigma_1\sigma_3/\mu_1(T_4+\mu_3)\}p_0$; $p_6=\{\sigma_2\sigma_3/\mu_2(T_4+\mu_3)\}p_0$

$p_7=\{T_4\sigma_3/\mu_3(T_4+\mu_3)\}p_0$; $p_8=\{\sigma_4\sigma_3/\mu_4(T_4+\mu_3)\}p_0$

$p_9=(\sigma_1\sigma_4/\mu_1\mu_4)p_0$; $p_{10}=(\sigma_2\sigma_4/\mu_2\mu_4)p_0$

$p_{11}=(\sigma_4/\mu_4)^2p_0$

whereas p_0 is obtained using the normalizing condition i.e.,

$$\sum_{i=1}^{11} p_i=1.;$$

$$p_0=[\{1+\sigma_3(1+T_4/\mu_3)/(T_4+\mu_3)\}\{1+\sum_{j=1}^{2}(\sigma_j/\mu_j)+(\sigma_4/\mu_4)\}]^{-1}$$

or $p_0=[L_6]^{-1}$

The steady state availability $[AV_5]$ of the system is given by:

$[AV_5]=p_0+p_3+p_7$

$$[1+\sigma_3\{1+T_4/\mu_3\}/(T_4+\mu_3)][L_6]^{-1}$$

3.7.d BEHAVIOURAL ANALYSIS:

Using equation (3.7.5) the effect of failure and repair rates of the subsystem upon availability has been computed and given in tables 3.7-1 to 3.7-2:

Table 3.7-1: Effect of failure rate of filter, screen and decker ($\mu_1=\mu_2=\mu_4=0.2, T_4=0.005, \sigma_3=0.015$)

σ_2	σ_4	Availability[AV_5]				
		σ_1 =0.0	σ_1 =0.025	σ_1 =0.05	σ_1 =0.075	σ_1 =0.10
.00	.000	1.0000	.8889	.8000	.7273	.6667
	.025	.8889	.8000	.7273	.6667	.6154
	.050	.8000	.7273	.6667	.6154	.5714
	.100	.6667	.6154	.5714	.5333	.5000
.025	.000	.8889	.8000	.7273	.6667	.6154
	.025	.8000	.7273	.6667	.6154	.5714
	.050	.7273	.6667	.6154	.5714	.5333
	.100	.6154	.5714	.5333	.5000	.4706
.050	.000	.8000	.7273	.6667	.6154	.5714
	.025	.7273	.6667	.6154	.5714	.5333
	.050	.6667	.6154	.5714	.5333	.5000
	.100	.5714	.5333	.5000	.4706	.4444
.10	.000	.6667	.6154	.5714	.5333	.5000
	.025	.6154	.5714	.5333	.5000	.4706
	.050	.5714	.5333	.5000	.4706	.4444
	.100	.5000	.4706	.4444	.4211	.4000

Table 3.7-2: Effect of repair rate of filter, screen and decker ($\sigma_1=\sigma_2=\sigma_4=0.02$)

μ_2	μ_4	Availability[AV_3]				
		μ_1 =0.1	μ_1 =0.2	μ_1 =0.3	μ_1 =0.4	μ_1 =0.5
.05	.01	.2778	.2857	.2885	.2899	.2907
	.05	.5000	.5263	.5357	.5405	.5435
	.10	.5556	.5882	.6000	.6061	.6098
	.20	.5882	.6250	.6383	.6452	.6494
.075	.01	.2885	.2970	.2999	.3015	.3024
	.05	.5357	.5660	.5769	.5825	.5859
	.10	.6000	.6383	.6522	.6593	.6637
	.20	.6383	.6818	.6976	.7059	.7109
.10	.01	.2941	.3030	.3061	.3077	.3086
	.05	.5556	.5882	.6000	.6061	.6098
	.10	.6250	.6667	.6818	.6897	.6944
	.20	.6667	.7143	.7317	.7407	.7462

Table 3.7-1 shows that an increase in failure rates of filter (σ_1) and screen (σ_2) has a large negative effect upon system availability. Similarly the decker failure rate (σ_4) decreases the availability sharply. Thus all the three equipments require a careful operation so as to avoid an early failure.

Table 3.7-2 shows that reducing the time for filter from 10 hrs to 5 hrs per repair improves the availability by about 2.8%. Such an improvement is possible by keeping a periodic check on the level of lubricating oil & shaft alignment. Decreasing the repair time of screen from 20 hours to 10 hours increases availability only by 1.6% whereas in case of decker reducing repair time from 100 hours to 50 hours would improve the availability by about 22%. Hence better maintenance planning be undertaken for decker, filter and screen in the order.

3.8 ANALYSIS OF PAPER FORMATION SYSTEM:

A schematic diagram of the system is shown in fig. 3.8:1.

3.8.a SYSTEM DESCRIPTION: The paper production system consists of four subsystems e.g.,

i) the wire mat (Q_1), this is used for depositing the suspended fiber on the top of the wire mesh and sucking the water in the pulp by the suction. It also controls the width of the paper sheet produced. Its failure causes complete failure of the system,

ii) the synthetic belt (Q_2), provides support to run the fiber mat through press section and drying sections. Its failure causes complete failure of the system,

iii) the rollers (T_m), consist of m rollers in series, which help the wire mat and the synthetic belt to roll on them smoothly. Failure of any one would mean system failure,

iv) the vacuum pump (U_1), comprises of four units in parallel, and is used for sucking water from the pulp through wire mat. It has two additional units as standby. Failure of more than three pumps at a time causes complete failure of the system.

All the four subsystem as mentioned under 3.8 require a common steam supply. Failure of steam supply causes completely system failure.

Apart from the failure of subsystems as described above a special type of failure is also possible in this case. This could be best understood as follows:

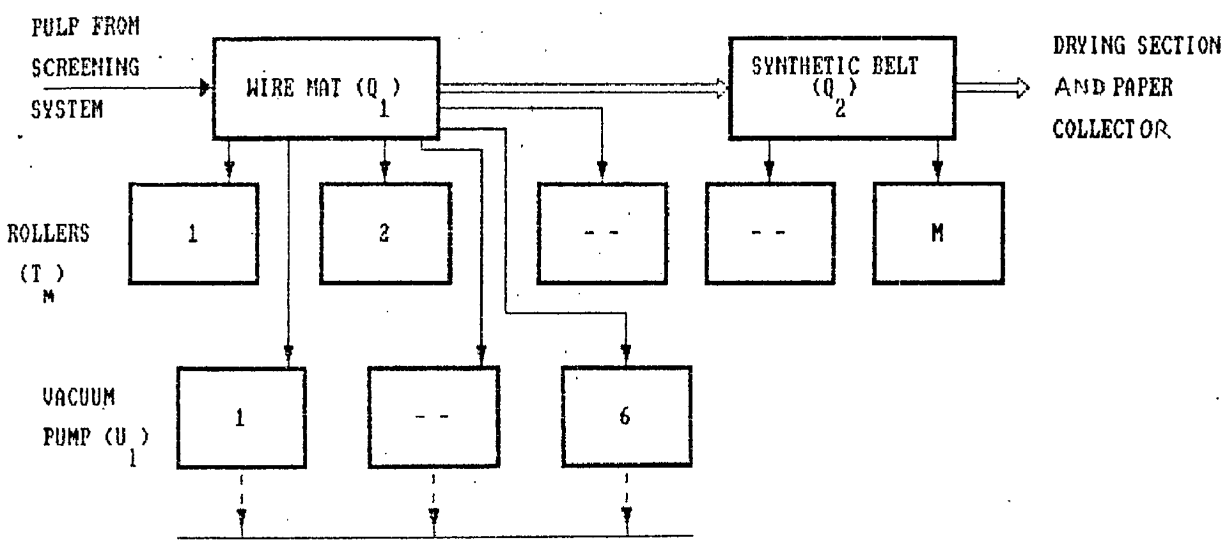


FIG 3.8:1. PAPER PRODUCTION PROCESS

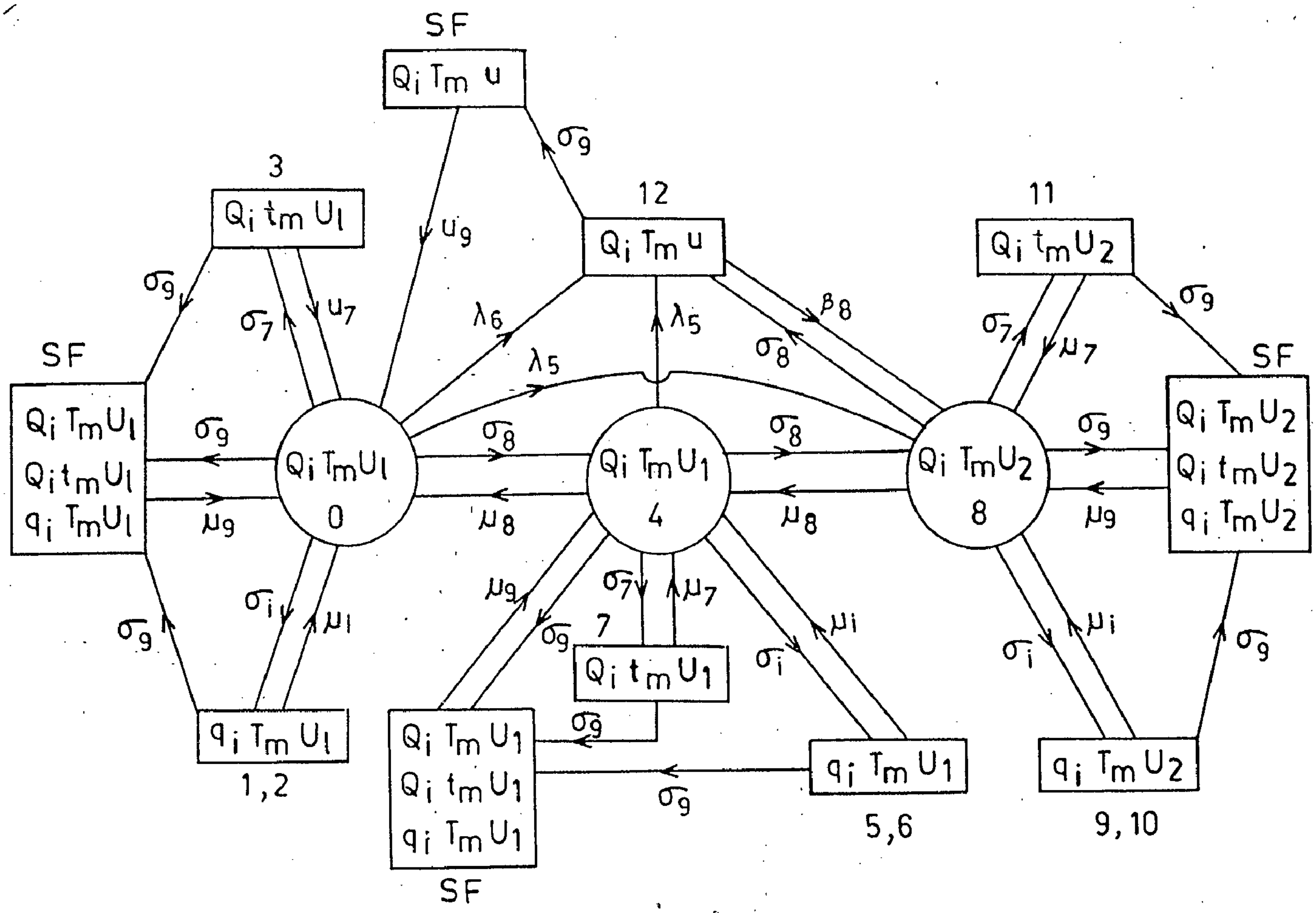


Fig. 3.8:2 Transition diagram for paper production system.

Suppose a subsystem which also requires steam for its operation is in failed state and is going to require a time of t units for repairs. After an interval $t=(t_1<t)$ the steam supply system fails. This would mean that the other subsystems which also require steam for their operation come to a standstill withholding the functioning of the system.

3.8.b MATHEMATICAL FORMULATION AND ANALYSIS:

The differential equations associated with the various states of the system are derived from transition diagram (fig. 3.8:2) as:

$$\left(\frac{d}{dt}+\sum_{i=5}^{9}\sigma_i+T_s+T_6\right)p_o(t)$$

$$=\sum_{i=5}^{8}\mu_i p_{i-4}(t)+\mu_9\sum_{j=0}^{3}p_{j*f}(t)+\mu_9 p_{12*f}(t) \qquad \text{--(3.8.1)}$$

$$\left(\frac{d}{dt}+\mu_a+T_s+\sum_{i=5}^{9}\sigma_i\right)p_4(t)$$

$$=\sigma_a p_o(t)+\sum_{i=5}^{8}\mu_i p_i(t)+\mu_9\sum_{j=4}^{7}p_{j*f}(t) \qquad \text{--(3.8.2)}$$

$$\left(\frac{d}{dt}+\mu_a+\sum_{i=5}^{9}\sigma_i\right)$$

$$=T_s p_o(t)+\sigma_a p_4(t)+\sum_{i=5}^{8}\mu_i p_{i+4}(t)+\mu_9\sum_{j=8}^{11}p_{j*f}(t) \qquad \text{---(3.8.3)}$$

$$\left(\frac{d}{dt}+\mu_i+T_s\right)p_n(t)=\sigma_i p_k(t) \qquad \text{--(3.8.4)}$$

$$\left(\frac{d}{dt}+\sigma_9+\mu_8\right)p_{12}(t)=T_6p_0(t)+T_5p_4(t)+\sigma_8p_8(t) \qquad \text{--(3.8.5)}$$

$$\left(\frac{d}{dt}+\mu_9\right)p_{j\ast f}(t)=\sigma_9p_i(t),\ j=i=1,2,\text{-----},12 \qquad \text{--(3.8.6)}$$

with initial condition $p_0(0)=1$. otherwise=0.

where in equation (3.8.4) the values are

for $i=5,6,7,\ k=0,n=i-4;\ k=4,n=i;\ k=8,n=i+4$.

Taking Laplace transforms of equations (3.8.1) to (3.8.6) and solving recursively (using initial conditions) we get the Laplace transform $R_6(s)$ of reliability function as follows:

$$R_6(s)=p_0(s)+p_4(s)+p_8(s)$$

where

$$p_0(s)=[s+x_{16}-y_{16}]^{-1}$$

$$p_4(s)=[\mu_8(s+x_{14}-y_{14})^{-1}\{T_6\mu_8(s+\mu_8+\sigma_9)^{-1}+T_5\}+\sigma_8]/(s+x_{15}-y_{15})$$

$$p_8(s)=\frac{[\mu_8\{(s+x_{14}-y_{14})(s+\mu_8+\sigma_9)\}^{-1}\{T_5T_6\mu_8^2(s+\mu_8+\sigma_9)^{-1}+T_5^2+\sigma_8T_6\}+T_5\mu_8(s+\mu_8+\sigma_9+\sigma_8)^{-1}+\sigma_8]p_0(s)}{\{(s+x_{14}-y_{14})(s+x_{15}-y_{15})\}}$$

with

$$x_{14}=\sum_{i=5}^{9}\sigma_i+\mu_8\quad ;x_{15}=x_{14}+T_5\ ;\ x_{16}=x_{14}+T_5+T_6$$

$$y_{14}=\sum_{i=5}^{8}\{\sigma_i\mu_i/(s+\mu_i+\eta)\}+\sigma_9\mu_9(s+\mu_9)^{-1}[1+\sum_{i=5}^{7}\sigma_i/(s+\mu_i+\eta)]$$

$$y_{15}=\sum_{i=5}^{7}\{\sigma_i/(s+\mu_i+\eta)\}[\mu_i+\{\sigma_9\mu_9/(s+\mu_9)\}]$$
$$+\mu_8(s+x_{14}-y_{14})^{-1}[\{T_5\mu_8/(s+\mu_8+\sigma_9)\}+\sigma_8+\sigma_9\mu_9(s+\mu_9)$$

$$y_{16}=\sum_{i=5}^{7}\sigma_i(s+\mu_i)^{-1}\{\mu_i+\sigma_9\mu_9/(s+\mu_9)\}+\{\sigma_9\mu_9/(s+\mu_9)\}+T_1'+T_2'$$

3.8.c STEADY STATE BEHAVIOUR:

When $t \to \infty$, $(d/dt) \to 0$. Putting $(d/dt)=0$ in equations (3.8.1) to (3.8.6) and solving recursively the steady state probabilities for the system are given by (ref. 67):

$p_{j+r}=(\sigma_9/\mu_9)p_j$, $j=1,2,---,12$

$p_1=\{\sigma_5/(\mu_5+\sigma_9)\}p_0$; $p_2=\{\sigma_7/(\mu_7+\sigma_9)\}p_0$

$p_3=\{\sigma_6/(\mu_6+\sigma_9)\}p_0$; $p_4=M_5p_0$

$p_5=\{\sigma_5/(\mu_5+\sigma_9)\}M_5p_0$; $p_6=\{\sigma_7/\mu_7+\sigma_9)\}M_5p_0$

$p_7=\{\sigma_6/(\mu_6+\sigma_9)\}M_5p_0$; $p_8=M_6p_0$

$p_9=\{\sigma_5/(\mu_5+\sigma_9)\}M_6p_0$; $p_{10}=\{\sigma_7/(\mu_7+\sigma_9)\}M_6p_0$

$p_{11}=\{\sigma_6/(\mu_6+\sigma_9)\}M_6p_0$; $p_{12}=[\sigma_8M_5+T_5M_6+T_6][\mu_8+\sigma_9]^{-1}p_0$

The probability p_0 is obtained using normalizing condition

$$\sum_{i=0}^{12} p_i + \sum_{j=0}^{12} p_{j+r}=1. \text{ as:}$$

$$p_0=[(1+\frac{\sigma_9}{\mu_9})\{1+\sum_{i=5}^{7}\frac{\sigma_i}{(\mu_i+\sigma_9)})(1+M_5+M_6)+\frac{\sigma_8M_5+T_5M_6+T_6}{\mu_8+\sigma_9}\}]^{-1}$$

or, $p_0=[L_7]^{-1}$

The steady state availability $[AV_6]$ of the system is given by:

$[AV_6]=p_0+p_4+p_8$

$$=[1+M_5+M_6][L_7]^{-1} \qquad --(3.8.7)$$

where

$$M_5=\frac{\mu_8T_5(T_5+\sigma_8)+(\sigma_8+\mu_8)[\mu_8(T_5+T_6)+T_5(T_5+\sigma_9)+\sigma_8^2]}{\mu_8^3+\mu_8\sigma_9(\sigma_9+2\mu_8+2\sigma_8+2T_5)+(\sigma_8+\sigma_9)(\sigma_8+T_5)\sigma_9}$$

$$M_6=\frac{\mu_8^2(T_5+T_6+\sigma_8)+\sigma_9\mu_8(T_5+\sigma_8)+\sigma_8^2\sigma_9}{(\mu_8^2+\mu_8\sigma_9+\sigma_8\sigma_9)[\sigma_9(\mu_8+\sigma_8)(T_5+\sigma_8)+\mu_8(\mu_8^2+\sigma_8\sigma_9)]}$$

3.8.d BEHAVIOURAL ANALYSIS:

Using equation (3.8.7) the effect of failure and repair rates of the vacuum pump and special cause failures have been computed and depicted in tables 3.8-1 & 3.8-2

Table 3.8-1: Effect of special cause failure and repair on availability($\sigma_5=\sigma_7=.001$, $\mu_5=\mu_6=0.1$, $\mu_7=0.2$, $\sigma_8=0.1$, $\mu_8=0.5$)

μ_9	Availability [AV_6]					
	σ_9 =0.0	σ_9 =0.02	σ_9 =0.04	σ_9 =0.06	σ_9 =0.08	σ_9 =0.1
0.1	.9712	.8126	.6987	.6121	.5457	.4919
0.2	.9712	.8865	.8151	.7542	.7017	.6559
0.3	.9712	.9142	.8631	.8170	.7755	.7379
0.4	.9712	.9287	.8892	.8526	.8186	.7871
0.5	.9712	.9376	.9057	.8751	.8468	.8199
0.6	.9712	.9437	.9170	.8913	.8668	.8433

Table 3.8-2: Effect of failure and repair rate of vacuum pump ($\sigma_5=\sigma_6=\sigma_7=.001$, $\mu_5=\mu_6=0.1$, $\mu_7=0.2$, $\sigma_9=.02$, $\mu_9=0.5$)

μ_8	Availability[AV_6]				
	σ_8 =0.0	σ_8 =.025	σ_8 =.050	σ_8 =.075	σ_8 =.100
0.1	.9398	.9302	.9170	.8931	.8599
0.2	.9399	.9366	.9333	.9271	.9170
0.3	.9400	.9386	.9372	.9346	.9322
0.4	.9401	.9397	.9388	.9374	.9352
0.5	.9402	.9401	.9398	.9388	.9374

Table 3.8-1 shows that small increase in failure rate (σ_9) decreases the system availability sharply whereas reducing the repair time increases the availability exponentially. This however becomes almost constant beyond a repair rate of 0.4. Table 3.8-2 shows that increase in failure rate of vacuum pump (i.e. failure of single unit only) does not have much effect. Furthermore increase in repair rate (μ_8) contributes little to system availability.

3.9 AVAILABILITY OF PAPER MILL AS A WHOLE:

In the foregoing analysis we have analyzed the behaviour of different subsystems of a paper mill (six in numbers). Since the feeding, pulping, washing, bleaching, screening and paper formation systems are working in series for the industrial rocess the availability of the paper mill as a whole [AV] can be obtained as:

$$[AV]=[AV_1*AV_2*AV_3*AV_4*AV_5*AV_6]$$

Substituting from equations 3.3.6, 3.4.6, 3.5.7, 3.6.3, 3.7.5 and 3.8.7 we get

$$[AV] = \left[\frac{(1+L_1)+\Sigma\alpha_j L_2}{L_3}\right]_1 * \left[\frac{(1+\alpha_8/\beta_8)(1+\alpha_9/\beta_9)}{L_4}\right]_2$$

$$* \left[\frac{(1+\alpha_{11}/\beta_{11})(1+\alpha_{12}/\beta_{12})}{L_5}\right]_3 * \left[\frac{1}{1+(2\alpha_{13}/\beta_{13})+(2\alpha_{14}/\beta_{14})}\right]_4$$

$$* \left[\frac{1+\{\sigma_3/(\tau_4+\mu_3)\}(1+\tau_4/\mu_3)}{L_6}\right]_5 * \left[\frac{1+M_5+M_6}{L_7}\right]_6 \qquad (3.9.1)$$

In order to improve upon the overall system availability, failure rate in each of the subsystems be controlled by providing standby units and taking certain maintenance related managerial decisions. It should however be noted that providing frequent maintenance and efficient repair facilities would mean increased costs.

Tables 3.3-1 & 3.3-2 show that availability of the feeding system is very high. This is because of standby units are available.

The failure rate of digesters (α_6) is very small but slight increase in α_6 would mean sharp decrease in AV_2. Thus use of two digesters would be advisable so that feeding and cooking remains more or less continuous. Also, the digester capacity must be so planned that cooked pulp is sufficient to run the plant for 8 to 10 hours. The availability can further be increased by keeping one digester as standby. In the decker, maintaining proper oil level,lubrication of various parts and running at low speeds has been found to helpful in achieving low failure rates. The failure rate (α_{10}) of screen has significant effect upon availability. Since the subsystem have two units in series, hence the effect of failures is significant. However this subsystem has parts rotating at low speed therefore probability of any major failure is small. By regular checking of oil level, lubrication etc. its failure rate can be controlled. Cleaners have no immediate effect upon system availability but the failure of few cleaners may reduce the quality of the pulp under such circumtances we can still produce coarse paper, chocking (if any) is removed immediately by an unskilled worker. Standby unit in decker at this stage reduces the system failure to very small. In paper production process wire mat and synthetic belt have a life time of about 1000 hours for regular running and are replaced by new one after every 1000 run (called scheduled maintenance) and the probability of their early failure is very small. Checking of rollers (lubrication, alignment, covering rubber smoothness etc) is done as per routine. Two vacuum pumps are provided as standbyes thus reducing the failure rate (σ_8) to once in 100 hours. Also, keeping a regular watch at every stage , steam supply remains continuous unless there is a failure in the steam generation unit. A steam generation unit ready in all respect is kept as standby.

The average failure rate for the various subsystems of the plant have been studied and the following average values have been recorded:

blowers (A) - once in 1000 hours

standby feeding unit (B) - once in 100 hours

main feeding system (D_1) - once in 25 hours

digesters (E_1) - once in 1000 hours

decker (E_2) - once in 100 to 200 hours

fiberizer or knotter (E_3) - once in 50 to 100 hours

refiner or opener (E_4) - once in 50 to 100 hours

screen (F_1) - once in 50 to 100 hours

cleaners (F_2 & H_3) - thrice in 500 hours

decker (F_3 & H_4) - once in 200 hours

filter (G_1 & H_1) - once in 200 hours opener (G_2) - once in 100 hours

wire- mat (Q_1) - once in 1000 hours

synthetic belt (Q_2) - once in 1000 hours

rollers (T_m) - once in 1000 hours

vacuum pump (U_1) - once in 50 to 100 hours

The mean repair time observed in various subsystems are:

blowers - 10 hours

standby feeding system - 2 hours

main feeding system - 4 to 5 hours

digesters - 5 hours

decker - 5 hours

fiberizer - 5 hours

refiner - 5 hours

screen - 5 hours

cleaners - 2 hours

filter - 2 hours

wire mat - 10 hours

synthetic belt - 10 hour

rollers - 10 hours

vacuum pump - 5 hours

Taking the above data the effect of failure on total system availability has been worked out and given in table 3.9-1.

3.9.a <u>SPECIAL CASE</u>:

a) For white paper production the availability [WAV],using given failure and repair parameters corresponds to-

$$[WAV] = \frac{1.02436(1+M_5+M_6)[1.02+5\alpha_{14}]^{-1}}{[(1.1188+5.5125\alpha_7)(1.017025+5.1865\alpha_{10})L_7]}$$

Table 3.9-1: Effect of failure rate of decker of pulping system, screen of washing system and vacuum pump without preventive maintenance in decker

($\alpha_1=\alpha_6=\sigma_5=\sigma_6=\sigma_7=\sigma_9=T_6=.001$, $\alpha_{11}=\sigma_3=.006$, $\alpha_2=\alpha_8=\alpha_9=\alpha_{14}=.01$, $\alpha_j=.04$, $\alpha_{12}=\alpha_{13}=\sigma_1=\sigma_2=\sigma_4=.005$, $T_3=T_4=T_5=.002$, $\beta_1=\beta_6=\mu_5=\mu_6=\mu_7=0.1$, $\beta_2=\beta_{11}=\beta_{13}=\mu_3=0.5$, $\beta_j=\beta_7=\beta_8=\beta_9=\beta_{10}=\beta_{12}=0.2$, $\mu_1=\mu_2=\mu_4=\mu_8=0.2$, $\beta_{14}=0.4$, $\mu_9=.01$ ($j=3,4,5$)

α_7	α_{10}	Availability[WAV]			
		α_8 =0.0	α_8 =0.01	α_8 =0.015	α_8 =0.02
0.0	0.00	.74163	.73974	.73873	.73830
	0.01	.71051	.70870	.70773	.70732
	0.02	.67543	.67371	.67280	.67240
0.05	0.00	.59503	.59352	.59271	.59236
	0.01	.56236	.56580	.56502	.56469
	0.02	.55232	.55091	.55017	.54984
0.1	0.00	.50636	.50507	.50438	.50409
	0.01	.48270	.48147	.48082	.48054
	0.02	.46116	.45999	.45936	.45909

Table 3.9-1 shows that the failure rate (σ_8) of the vacuum pump has low effect upon availability. i.e. by increasing failure rate from once in 100 hours to once in 50 hours the decrease in availability is by o.156% only. This is due to the provision of standby units which keep the system operative. The switch over device for standbyes has been found to require negligible time. Increase in failure rate of screen (α_{10}) from

once in 100 hours to once in 50 hours would decrease the system availability by 4.12% which is reasonable, hence proper and timely maintenance would be satisfactory. Regular checking of bearings, lubrication, vibration, alignment etc. would also reduce the probable failures. Increase in failure rate (α_7) of decker in the pulping system from once in 200 hours to 100 hours decreases the system availability by 1.75%. The harmfull effect of decker failure can be reduced by providing a pulp tank in which enough pulp can be stored to cater for 8 to 10 hours of working.

Table 3.9-2: Effect of failure rate of decker in pulping system, screen in screening system and opener in bleaching system with failure time of vacuum pump (σ_8) as once in 100 hours (minimum possible) giving [AV_6]=0.8755.

α_7	α_{10}	Availability[WAv]			
		α_{14} =0.0	α_{14} =0.01	α_{14} =0.015	α_{14} =0.02
0.0	0.00	.77599	.73973	.72284	.70670
	0.01	.73974	.70517	.68907	.67369
	0.02	.70672	.67370	.65832	.64362
0.05	0.00	.62260	.59351	.57996	.56701
	0.01	.59352	.56578	.55286	.54052
	0.02	.56703	.54053	.52819	.51640
0.10	0.00	.51984	.49555	.48424	.47343
	0.01	.49556	.47240	.46162	.45131
	0.02	.47344	.45132	.44102	.43117

Table 3.9-2 shows that increase in failure rate of opener (α_{14}) reduces the availability sharply whereas a slight increase in failure rate from .01 to .015 decreases the system availability by 2%.

b) Brown paper production:

For the production of brown paper the pulp from pulping system is washed and then sent for screening i.e. for the production of brown paper bleaching would not be required.

Hence AV_4=1.0 and availability of the brown paper manufacturing process [BAV] is given by:

$$[BAV]=\frac{1.049975(1+M_5+M_6)}{[(1.118775+5.5125\alpha_7)(1.017025+5.1865\alpha_{10})L_7]}$$

If the failure rate for the vacuum pump is taken as once in 100 hours the value of [BAV] is obtained as:

$$[BAV]=0.919269139/[(1.118775+5.5125\alpha_7)(1.037987+5.0865\alpha_{10}]$$

Table 3.9-3: Effect of failure rates in decker and screen upon availability for brown paper production process .

α_7	Availability[BAV]			
	α_{10} =0.0	α_{10} =0.01	α_{10} =0.015	α_{10} =0.02
0.0	.79160	.75463	.73740	.72095
0.05	.63513	.60546	.59164	.57844
0.10	.53031	.50553	.49399	.48297

A comparison of data in table 3.9-3 with table 3.9-1 reveals that availability of brown paper production process is higher by about 1.8%.Decker of pulping system and screen of washing system have significant impact upon availability as in case of white paper production process.

DISCUSSION:

In order to improve the overall system availability following steps are suggested:

i) install a large number of standby units wherever feasible,

ii) provide for efficient maintenance facilities so as to reduce the rate of failure,

iii)reduce the down time of failed units by installing efficient repair facilities,

All the three measures would mean a substantial investment and therefore achieving 100% system availability may not be advisable. The best decision under the circumstances would be to arrive at a compromise decision which would minimize the combined costs of installation, standby, repair and maintenance facilities and the cost of system downtime.

CHAPTER-4

AVAILABILITY ANALYSIS OF A FERTILIZER PLANT

4.1 INTRODUCTION:

This chapter presents a study of the factors that control the availability of fertilizer plants. For this purpose a study was carried out in a plant situated in North India producing 100 tons urea per day. For the production of urea, carbon dioxide (CO_2) and ammonia (NH_3) are the prime inputs. These gases react at a particular temperature and pressure to form urea. The urea in gaseous form is cooled down to yield urea crystals.A schematic diagram of the urea manufacturing process is shown in fig. 4:1.

Thus urea production process is quite complex and continuous in nature. To facilitate the availability analysis of this plant the production system is divided into four subsystems- Synthesis, Decomposition, Crystallisation and Prilling.

The synthesis process comprises of a centrifugal pump (to compress CO_2 gas), two reciprocating pumps (one for CO_2 and another for NH_3, to boost the pressure) and heaters (to heat NH_3 gas).

The decomposition process- is carried out by heating (using the reboiler and falling film heater), absorber (high and low pressure), gas separator and heat exchanger.

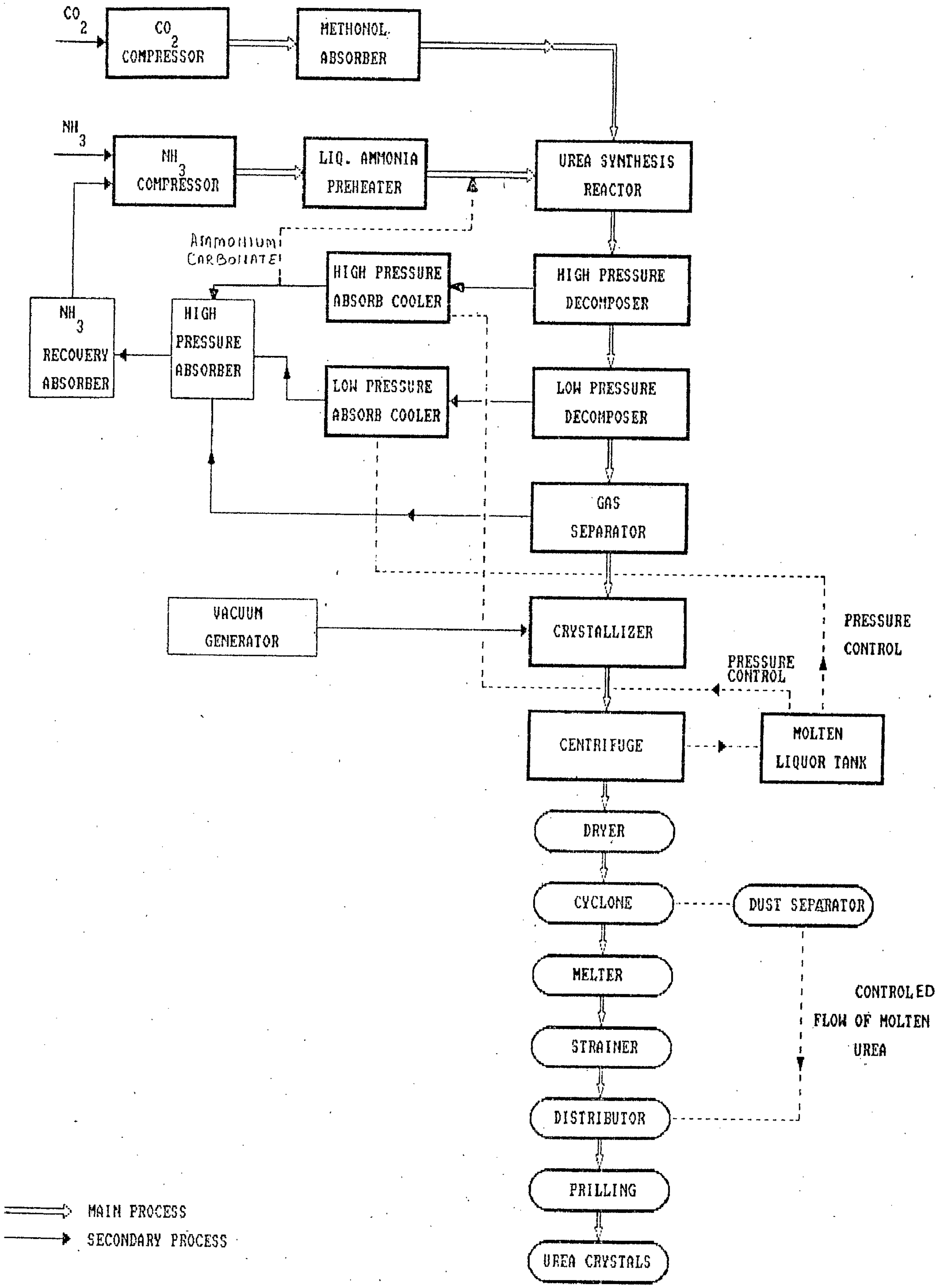


FIG 4:1. SCHEMATIC DIAGRAM OF UREA PRODUCTION PROCESS

The crystallisation section consists of vacuum generator (used to control the level in crystallizer), crystallisation (having a close clearance type agitator) and centrifuges (used to separate out the urea crystals from mother liquor).

The prilling process- consists of a distributor used to drop the liquid urea through small holes and conveyor to carry the product to the trommer.

The reliability and availability analysis for the various subsystems of the urea plant and the plant as a whole have been carried out by considering the plant as a complex repairable system. The methodology and the various assumptions used in this chapter are same as used for sugar and paper plants.

The analysis presented herein is based on the assumptions that are valid for sugar and paper plants. Some of the additional assumptions used in this chapter are:

i) intermittent service may be performed in the various subsystems indicated above in second para,

ii) cold standby units in liquid ammonia feed pump , recycle isolution feed pump, heat exchanger and distributers (B,D,F & V) subsystems have the same nature and capacity as the active units,

iii) simultaneous failures in B and/or in D can not occur,

iv) in centrifuge (G_3), all the units are working simultaneously and the failure of any one can not be tolerated (since inflow of liquid urea in centrifuge can not be controlled hence reduced capacity operation is not possible).

Based on the above assumption the transition diagrams for the rious subsystems are given in fig. 4.2:2, 4.3:2, 4.4:2, 4.5:2.

ie notations employed to represent the various states of e subsystems are:

TATE	UREA SYNTHESIS	DECOMPOSITION	CRYSTALLI-SATION	PRILLING
ansition diagram	fig. 4.2:2	fig. 4.3:2	fig. 4.4:2	fig. 4.5:2
ll capacity rking (without andby)	A_j,B,D	E_i,E_j E_5, F	G_i,H,Q	U_j,V,W
ll capacity rking (with andby)	B_1,B_2, D_1	F_1	H_1, Q_1	V_1
iled state	a_j,b,d	e_i, e_j e_5, f	g_i,h,q	u_j,v,w
ilure rate	α_i	α_k	τ_i,$\tau_{4,5}$	τ_i
pair rate	β_i	β_k	μ_i,$\mu_{4,5}$	μ_i
obability of full pacity working th standby units	$p_{4,5}$, $p_{9,10}$, p_{15}	p_6	$p_{4,5}$, p_{13}	p_2
obability of iled state	p_k	p_r	p_r	p_1, $p_{3,4}$, $p_{5,6}$
ffix	j=1,2,3 i=1,2--5 k=1,2,3,6,7,8, 16,17,---,28.	i=1,2 &j=3,4 k=6,7,-11 r=1,2-5, r=7,8,--12	i=1,2,3 r=1,2,3, 6,7--,12, 15,--,19	j=1,2,-4 i=j+5

2 THE UREA SYNTHESIS SYSTEM

A schematic diagram of the urea synthesis system is given in g. 4.2:1.

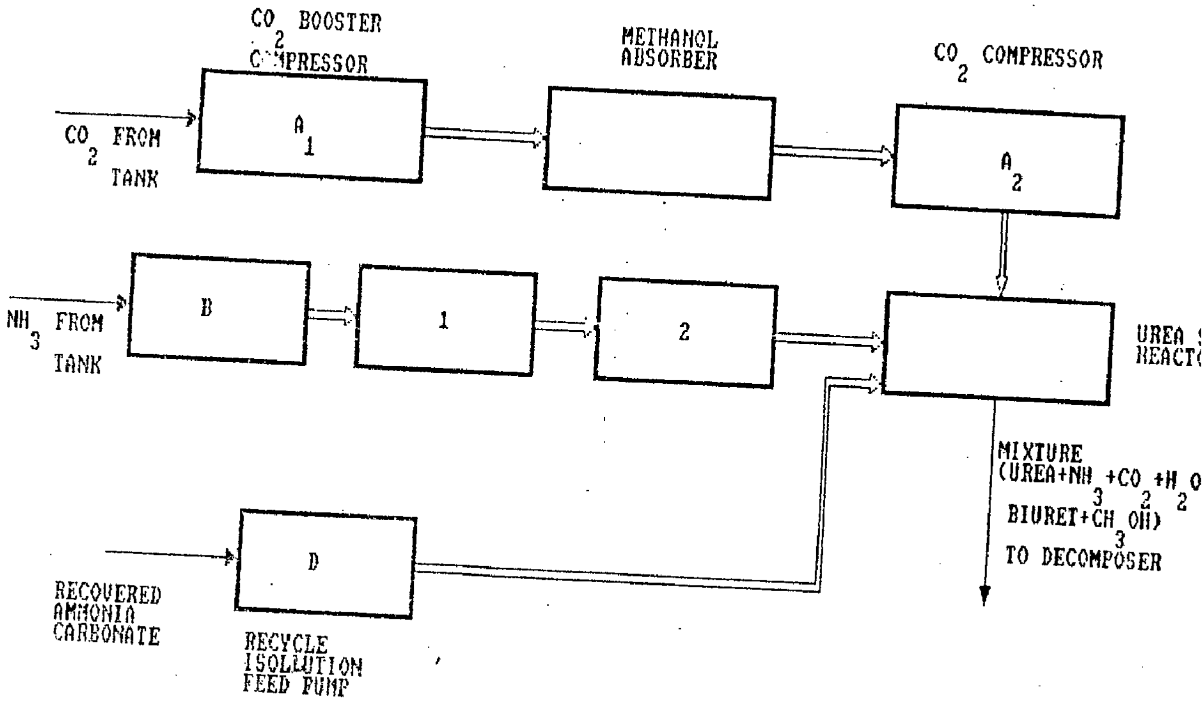


FIG 4.2:1. SCHEMATIC DIAGRAM OF UREA SYNTHESIS PROCESS

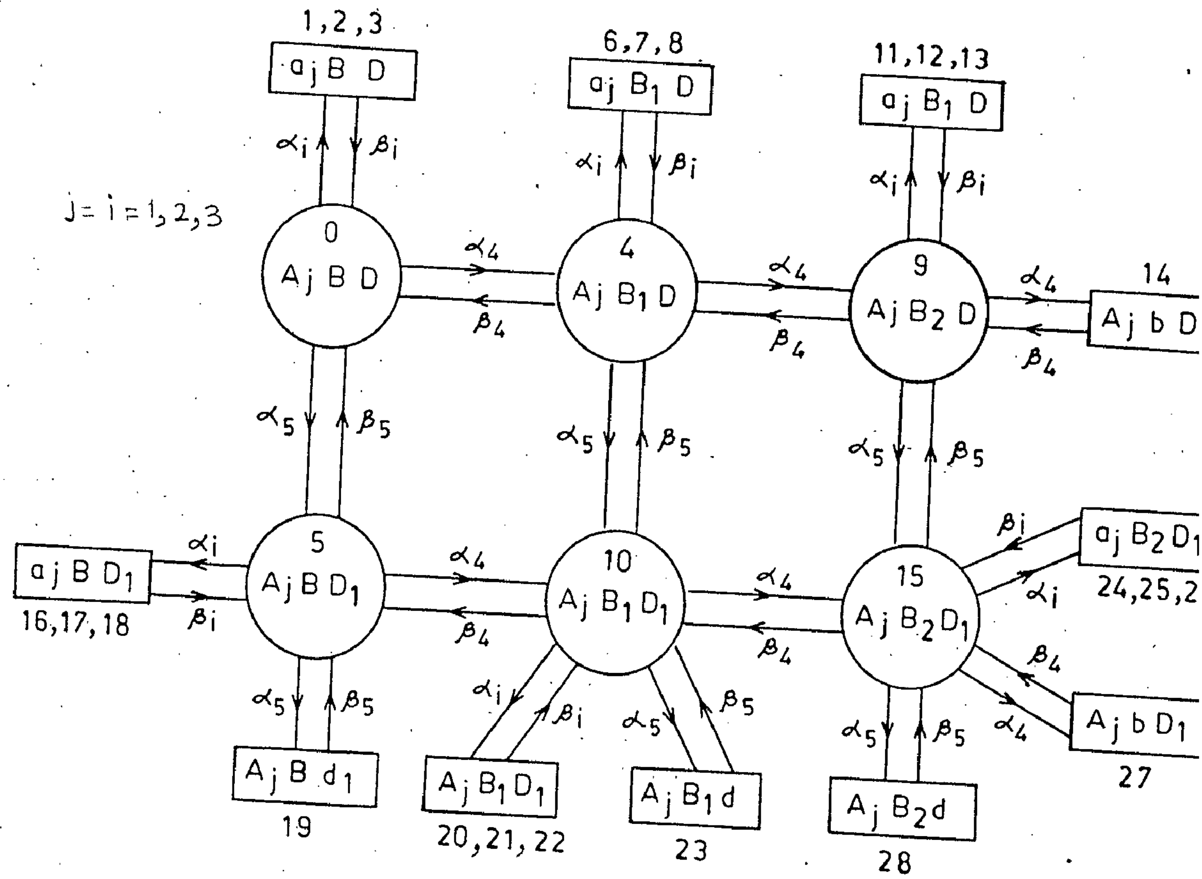


Fig. 4.2:2 Urea synthesis system.

4.2.a SYSTEM DESCRIPTION:

The urea synthesis system is an important subsystem of the plant and consists of the following five subsystems.

i) the CO_2 booster compressor (A_1), is a centrifugal type compressor, which raises the pressure of CO_2 from 0.1 atm to 29.5 atm. Its failure would lead to complete failure of the subsystem,

ii) CO_2 high pressure compressor (A_2),is of reciprocating type, which raises the pressure of CO_2 from 29.5 atm to 250 atm. Its failure would cause complete failure of the system,

iii) the ammonia preheater (A_3), this has two units in series. The first raises the temperature of the gas upto 53.2 deg.c whereas the second unit heats the gas to 82.3 deg.C. Failure of either of the units would mean complete failure of the system,

iv) the liquid ammonia feed pump (B), where reciprocating type pumps are used. These would raise the pressure of ammonia from 16.5 atm to 250 atm. For this purpose two pumps are operated simultaneously in parallel and two in cold standby. Simultaneous failure of the three pumps causes complete failure of the system,

v) the recycle solution feed pump (D), is a multistage centrifugal pump, which raises the pressure of ammonium carbonate from 17 atm to 250 atm. It has one unit in cold standby. The system fails only when both the units fail.

4.2.b RELIABILITY OF THE UREA SYNTHESIS SYSTEM:

The differential equations associated with the various states of the system in transition diagram (fig. 4.2:2) are:

$$\left(\frac{d}{dt}+\sum_{i=1}^{5}\alpha_i\right)p_0(t)=\sum_{i=1}^{5}\beta_i p_i(t) \qquad \text{--(4.2.1)}$$

$$\left(\frac{d}{dt}+\beta_4+\sum_{i=1}^{5}\alpha_i\right)p_4(t)=\alpha_4 p_0(t)+\sum_{i=1}^{5}\beta_i p_{i+5}(t) \qquad --(4.2.2)$$

$$\left(\frac{d}{dt}+\beta_5+\sum_{i=1}^{5}\alpha_i\right)p_5(t)$$

$$=\alpha_5 p_0(t)+\sum_{i=1}^{3}\beta_i p_{i+15}(t)+\beta_4 p_{10}(t)+\beta_5 p_{19}(t) \qquad --(4.2.3)$$

$$\left(\frac{d}{dt}+\beta_4+\sum_{i=1}^{5}\alpha_i\right)p_9(t)=\alpha_4 p_4(t)+\sum_{i=1}^{5}\beta_i p_{i+10}(t) \qquad --(4.2.4)$$

$$\left(\frac{d}{dt}+\beta_4+\beta_5+\sum_{i=1}^{5}\alpha_i\right)p_{10}(t)$$

$$=\alpha_5 p_4(t)+\alpha_4 p_5(t)+\sum_{i=1}^{3}\beta_i p_{i+19}(t)+\beta_4 p_{15}(t)+\beta_5 p_{23}(t) \qquad -(4.2.5)$$

$$\left(\frac{d}{dt}+\beta_5+\beta_4+\sum_{i=1}^{5}\alpha_i\right)p_{15}(t)$$

$$=\alpha_5 p_9(t)+\alpha_4 p_{10}(t)+\sum_{i=1}^{5}\beta_i p_{i+23}(t) \qquad --(4.2.6)$$

$$\left(\frac{d}{dt}+\beta_i\right)p_j(t)=\alpha_i p_k(t) \qquad --(4.2.7)$$

where in equation (4.2.7) i,j,k are :

i=1,2,3, k=0,j=i;k=4,j=i+5;k=5,j=i+15;k=9,j=i+10;k=10,j=i+19;

k=15,j=i+23.

for i=4, k=9,j=14; k=15,j=27.

and for i=5, k=i,j=19; k=2i,j=23; k=3i,j=28.

with initial conditions, $p_0(0)=1$. otherwise =0.

Taking Laplace transforms of equations 4.2.1 to 4.2.7 and solving recursively (using initial condition), Laplace transform $R_1(s)$ of reliability function is obtained as follows:

$$R_1(s)=LR(t)=p_0(s)+p_4(s)+p_5(s)+p_9(s)+p_{10}(s)+p_{15}(s)$$

where

$p_0(s)=[s+x_6-y_6]^{-1}$; $p_4(s)=[s+x_5-y_5]^{-1}p_0(s)$

$p_5(s)=\alpha_5\beta_4N_1[(s+x_2-y_2)(s+x_3-y_3)]^{-1}p_4(s)$

$p_9(s)=\alpha_4N_2[s+x_4-y_4]^{-1}p_4(s)$

$p_{10}(s)=\alpha_5N_3[s+x_2-y_2]^{-1}p_4(s)$

$p_{15}(s)=\alpha_4\alpha_5(N_2+N_3)[s+x_1-y_1]^{-1}p_4(s)$

$N_1=1+\alpha_4\beta_4N_2[(s+x_1-y_1)(s+x_5-y_5)]^{-1}$

$N_2=[1+\alpha_5\beta_5/(s+x_1-y_1)(s+x_2-y_2)][1+\alpha_4\beta_4/(s+x_2-y_2)(s+x_3-y_3)]$

$N_3=1+\alpha_4\beta_4N_1[\{(s+x_2-y_2)(s+x_3-y_3)\}^{-1}+\{(s+x_1-y_1)(s+x_5 5-y_5)\}^{-1}]$

$x_1=x_2=\beta_5+\beta_4+\sum_{i=1}^{5}\alpha_i$; $x_3=x_4=\beta_4+\sum_{i=1}^{5}\alpha_i$; $x_6=\sum_{i=1}^{5}\alpha_i$; $y_1=\sum_{i=1}^{5}\frac{\alpha_i\beta_i}{(s+\beta_i)}$

$y_2=\sum_{i=1}^{3}\frac{\alpha_i\beta_i}{s+\beta_i}+\frac{\alpha_5\beta_5}{s+\beta_5}+\frac{\alpha_4\beta_4}{s+x_1-y_1}$; $y_3=\sum_{i=1}^{3}\frac{\alpha_i\beta_i}{(s+\beta_i)}+\frac{\alpha_4\beta_4}{(s+x_2-y_2)}$

$$y_4=\sum_{i=1}^{4}\frac{\alpha_i\beta_i}{(s+\beta_i)}+\frac{\alpha_5\beta_5}{(s+x_1-y_1)}+\frac{\alpha_4\beta_4\alpha_5}{(s+x_1-y_1)^2(s+x_2-y_2)}\{\beta_5+\frac{\alpha_4\beta_4/(s+x_3-y_3)}{(s+x_2-y_2)}\}$$

$$y_5=\sum_{i=1}^{3}\frac{\alpha_i\beta_i}{(s+\beta_i)}+\frac{\alpha_4\beta_4N_2}{(s+x_4-y_4)}+\frac{\alpha_5\beta_5N_3}{(s+x_2-y_2)}$$

$$y_6=\sum_{i=1}^{3}\frac{\alpha_i\beta_i}{(s+\beta_i)}+\frac{\alpha_4\beta_4}{(s+x_5-y_5)}[1+\frac{\alpha_5\beta_5N_1}{(s+x_2-y_2)(s+x_3-y_3)}]$$

Mean time to system failure $[MTTF]_1$ is obtained as $\lim_{s\to 0} sR_1(s)$ and is given by:

$$[MTTF]_1=1/a_6[1+(\alpha_4/d_1)\{1+(\alpha_5\beta_4cf_2/b)+(\alpha_4f_1/d)+(\alpha_5f_3c/a)+\alpha_4\alpha_5(f_1+f_2)/c\}]$$

where

$a=(\beta_4+\beta_5)^2+\alpha_4\beta_5$,

$b=(\beta_4+\alpha_5)(\beta_4+\beta_5)^2+\alpha_4\beta_5(1+\beta_4+\beta_5)$,

$c=\beta_4+\beta_5$

$d=\beta_4+\alpha_4-\alpha_5\beta_5/(\beta_4+\beta_5)\{1+\alpha_4\beta_4/a\}-(\alpha_4\beta_4/a)^2(\alpha_5/b)$

$a_1=1+\sum_{i=1}^{5}(\alpha_i/\beta_i)$; $a_2=1+\sum_{i=1}^{3}(\alpha_i/\beta_i)+(\alpha_5/\beta_5)+(\alpha_4\beta_4/c^2)$

$$a_3=1+\sum_{i=1}^{3}(\alpha_i/\beta_i)+\{\alpha_4\beta_4(c/a)^2\}$$

$$a_4=1+\sum_{i=1}^{4}(\alpha_i/\beta_i)+(\alpha_5\beta_5/c^2)+(\alpha_4\beta_4\alpha_5\beta_5)/a[(2a_1/c^2)+(a_2/a)]$$
$$+(\alpha_4\beta_4)^2(\alpha_5/b)[2a_1/(a*c)+(2a_2c/a)+(a_3/b^2)]$$

$$a_5=1+\sum_{i=1}^{3}(\alpha_i/\beta_i)+(\alpha_4\beta_4/d)[(f_1a_4/d)+c_1]+(\alpha_5\beta_5c/a)[(f_3a_2c_1/a)+e_3]$$

$$a_6=1+\sum_{i=1}^{3}(\alpha_i/\beta_i)+\{\alpha_4\beta_4a_5/d_1^2\}$$
$$+(\alpha_4\beta_4\alpha_5\beta_5c/bd_1)[f_2\{a_3+1/d_1\}+(f_2a_2c/a)+e_2/c]$$

$$f_1=1+(\alpha_5\beta_5/a)[1+\alpha_4\beta_4c/b] \quad ; \quad f_2=1+(\alpha_4\beta_4f_1/cd)$$

$$f_3=1+\alpha_4\beta_4[(f_2c/b)+(f_1/cd)]$$

$$e_1=(\alpha_5\beta_5/a)[(a_1/c)+(a_2c/a)]$$
$$+(\alpha_4\alpha_5\beta_4\beta_5/b)[(a_1/a)+(a_3c/b)+2a_2(c/a)^2]$$

$$e_2=(\alpha_4\beta_4/cd)[(a_1e_1/c)+(a_4f_1/d)+e_1]$$

$$e_3=(\alpha_4\beta_4c/b)[f_2a_2+e_2+(f_2a*a_3/b)]$$

$$d_1=\beta_4+\alpha_4+\alpha_5-(\alpha_4\beta_4f_1/d)-(\alpha_5\beta_5f_3c/a)$$

4.2.c STEADY STATE BEHAVIOUR:

This is obtained by using the condition, when $t\to\infty$, $(d/dt)\to 0$, therefore putting $(d/dt)=0$ in equations 4.2.1 to 4.2.7 and solving recursively the state probabilities for the system are obtained as (ref. 57):

$$p_j=(\alpha_i/\beta_i)p_k$$

where for $i=1,2,3$ $k=0, j=i$; $k=4, j=i+4$; $k=13, j=i+13$; $k=17, j=i+18$.

$i=1,2$ $k=8, j=i+8$; $k=22, j=i+23$.

$i=3$ $k=8, j=i+9$; $k=22, j=i+24$.

$i=4$ $k=8, j=i+7$; $k=22, j=i+22$.

$i=5$ $k=13, j=i+13$; $k=17, j=i+18$; $k=22, j=i+23$.

$$p_4=I_6p_0 \quad ; p_8=(I_4/M_2)p_0 \quad ; \quad p_{13}=I_5p_0$$

$$p_{17}=[I_1+(I_2I_4/M_2)]/M_1p_0 \quad ; \quad p_{22}=I_7p_0$$

whereas the probability p_0 is obtained using normalizing condition (i.e the sum of all the probabilities is equal to one).

thus $\sum_{i=0}^{28} p_i=1.$ and is given by $p_0=[L_1]^{-1}$

where

$$L_1=[\{1+I_5+I_6+I_7+I_4/M_2(1+I_2/M_1)\}(1+\sum_{i=1}^{3}\alpha_i/\beta_i)$$

$$+(\alpha_4/\beta_4)\{I_7+(I_4/M_2)\}+(\alpha_5/\beta_5)\{I_5+I_7+(I_1+I_2I_4/M_2)/M_1\}]$$

and;

$$I_1=\alpha_4\alpha_5[(\alpha_4+\beta_5)^{-1}+(\alpha_4+\alpha_5+\beta_4)^{-1}]$$

$$I_2=\alpha_5\beta_4[(\beta_4+\beta_5)^{-1}+(\beta_4+\alpha_4+\alpha_5)^{-1}]$$

$$I_3=\alpha_4\beta_5[(\beta_4+\beta_5)^{-1}+(\beta_4+\alpha_4+\alpha_5)^{-1}]$$

$$I_4=[\alpha_4^2/(\beta_4+\alpha_4+\alpha_5)]+[I_3I_1/M_1]$$

$$I_5=[\alpha_5+(\beta_4/M_1)\{I_1+(I_2I_4/M_2)\}][\alpha_4+\beta_5]^{-1}$$

$$I_6=[\alpha_4+(\beta_5/M_1)\{I_1+(I_2I_4/M_2)\}+(\beta_4I_4/M_2)][\beta_4+\alpha_4+\alpha_5]^{-1}$$

$$I_7=[(\alpha_5I_4/M_2)+(\alpha_4/M_1)\{I_1+(I_2I_4/M_2)\}][\beta_4+\beta_5]^{-1}$$

$$M_1=[\alpha_4+\beta_5+\beta_4-\alpha_4\beta_4\{(\alpha_4+\beta_5)^{-1}+(\beta_4+\beta_5)^{-1}\}-\alpha_5\beta_5/(\beta_4+\alpha_4+\alpha_5)]$$

$$M_2=[\beta_4+\alpha_5-\{\alpha_4\beta_4/(\beta_4+\alpha_4+\alpha_5)\}-\{\alpha_5\beta_5/(\beta_4+\beta_5)\}-(I_2I_3/M_1)]$$

the steady state availability $[AV_1]$ of the system is given by:

$$[AV_1]=p_0+p_4+p_5+p_9+p_{10}+p_{15}$$

or, $$[AV_1]=[1+I_5+I_6+I_7+(I_4/M_2)(1+I_2/M_1)+(I_1/M_1)][L_1]^{-1} \quad -(4.2.8)$$

Equation 4.2.8 shows that the subsystems B and D play an important role in achieving good system availability, hence their failure rates be controlled by providing efficient repairs.

4.2.d BEHAVIOURAL ANALYSIS:

With the use of equation 4.2.8 the effect of failure and repair of various subsystems upon system availability can be studied. Some of the results are given in tables 4.2-1 to 4.2-4

Table 4.2-1: Effect of failure and repair rates of liquid ammonia pump on system availability ($\alpha_1=\alpha_2=\alpha_5=.005$, $\beta_1=\beta_2=\beta_5=0.1$, $\alpha_3=.001$, $\beta_3=0.5$)

β_4	Availability[Av_1]					
	α_4 =0.0	α_4 =.002	α_4 =.004	α_4 =.006	α_4 =.008	α_4 =0.01
0.1	.9067	.8990	.8905	.8890	.8871	.8837
0.2	.9067	.8992	.8911	.8892	.8873	.8839
0.3	.9067	.8996	.8913	.8895	.8877	.8843
0.4	.9067	.9000	.8920	.8898	.8880	.8848
o.5	.9067	.9007	.8925	.8903	.8885	.8852

Table 4.2-2: Effect of failure and repair rates of recycle solution feed pump on system availability ($\alpha_1=\alpha_2=\alpha_4=.005$, $\beta_1=\beta_2=\beta_4=0.1$, $\alpha_3=.001$, $\beta_3=0.5$)

β_5	Availability[AV_1]					
	α_5 =0.0	α_5 =.002	α_5 =.004	α_5 =.006	α_5 =.008	α_5=0.01
0.1	.9476	.9299	.9130	.8966	.8808	.8656
0.2	.9476	.9387	.9299	.9214	.9130	.9048
0.3	.9476	.9417	.9358	.9299	.9242	.9186
0.4	.9476	.9431	.9387	.9343	.9299	.9257
0.5	.9476	.9440	.9404	.9369	.9335	.9299

Table 4.2-3: Effect of failure rates of CO_2 compressor, CO_2 high pressure compressor and ammonia preheater on availability [AV_1] ($\alpha_4=\alpha_5=0.1$, $\beta_i=0.1, i=1,2,3,4,5$)

α_3	α_1	Availability[AV_1]				
		α_2 =0.0	α_2 =.025	α_2 =.05	α_2 =.075	α_2 =0.1
.00	.000	.9978	.8006	.6685	.5738	.5026
	.025	.8006	.6685	.5738	.5026	.4472
	.050	.6685	.5738	.5026	.4472	.4027
.025	.000	.8006	.6685	.5738	.5026	.4472
	.025	.6685	.5738	.5026	.4472	.4027
	.050	.5738	.5026	.4472	.4027	.3663
.05	.000	.6685	.5738	.5026	.4472	.4027
	.025	.5738	.5026	.4472	.4027	.3663
	.05	.5026	.4472	.4027	.3663	.3359

Table 4.2-4: Effect of repair rates of CO_2 compressor, CO_2 high pressure compressor and ammonia preheater on [AV_1] ($\alpha_3=\alpha_4=\alpha_5=0.01$, $\alpha_1=\alpha_2=0.02$, $\beta_4=\beta_5=0.1$)

β_3	β_2	Availability [AV_1]				
		β_1 =0.1	β_1 =0.2	β_1 =0.3	β_1 =0.4	β_1 =0.5
0.1	0.1	.6685	.7158	.7330	.7420	.7475
	0.3	.7330	.7902	.8110	.8230	.8290
	0.5	.7475	.8070	.8290	.8405	.8475
0.3	0.1	.6993	.7512	.7702	.7801	.7861
	0.3	.7702	.8336	.8571	.8694	.8769
	0.5	.7861	.8523	.8769	.8897	.8976
0.5	0.1	.7058	.7587	.7781	.7882	.7944
	0.3	.7781	.8428	.8669	.8794	.8871
	0.5	.7944	.8620	.8871	.9003	.9083

From tables 4.2-1 and 4.2-2 it is observed that failure and repair rates of liquid ammonia feed pump and recycle solution feed pump do not have significant effect upon the availability mainly because these subsystems have standby units. A study of the table 4.2-3 shows that the effect of α_2 on system availability is more pronounced than that of α_1 and α_3. Thus, Co_2 high pressure compressor would require more maintenance care than CO_2 compressor and ammonia preheater.

Table 4.2-4 shows that with increasing repair rate β_1 the system availability improves. It can also be noticed that with increasing β_2 the availability improves but to a lesser extent whereas with increasing β_3 only a marginal improvement in [AV_1] could be observrd.

4.3 THE DECOMPOSITION SYSTEM

A schematic diagram of this subsystem is given in fig.4.3:1.

4.3.a SYSTEM DESCRIPTION:

The decomposition system consists of the following four subsystems.

i) the subsystem (E_i), (i=1,2) has two units in series- the reboiler (E_1) and falling film heater(E_2) . Failure of E_1 or E_2 causes complete failure of the system,

ii) the subsystem (E_j), (j=3,4) has two units in series- high pressure absorber (E_3) and low pressure absorber(E_4). Failure of any one of the absorbers causes complete failure of the system,

iii) the subsystem (E_5) called gas separator, has one unit in series with E_3 and E_4. Failure of unit E_5 causes complete failure of the system,

iv) the subsystem (F) called heat exchanger, has one unit under operation and the other one as standby. System failure occurs when both the unit fails.

4.3.b RELIABILITY OF UREA DECOMPOSITION SYSTEM:

Differential equations associated with the various states of the system in transition diagram (fig 4.3:2) are as under:

$$\left(\frac{d}{dt}+\sum_{i=6}^{11}\alpha_i\right)p_0(t)=\sum_{i=6}^{11}\beta_i p_{i-5}(t) \quad ---(4.3.1)$$

$$\left(\frac{d}{dt}+\sum_{i=6}^{11}\alpha_i+\beta_{11}\right)p_6(t)=\sum_{i=6}^{11}\beta_i p_{i+1}(t)+\alpha_{11}p_0(t) \quad --(4.3.2)$$

$$\left(\frac{d}{dt}+\beta_i\right)p_j(t)=\alpha_i p_k(t) \quad --(4.3.3)$$

where the values in equation 4.3.3 are,

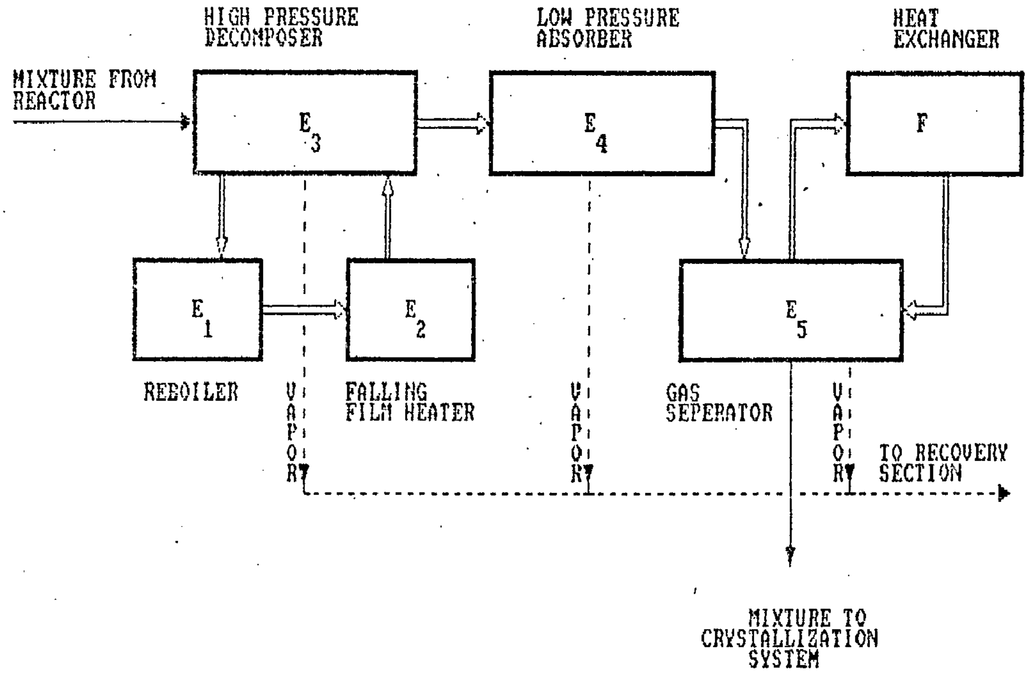


FIG 4.3:1. UREA DECOMPOSITION SYSTEM

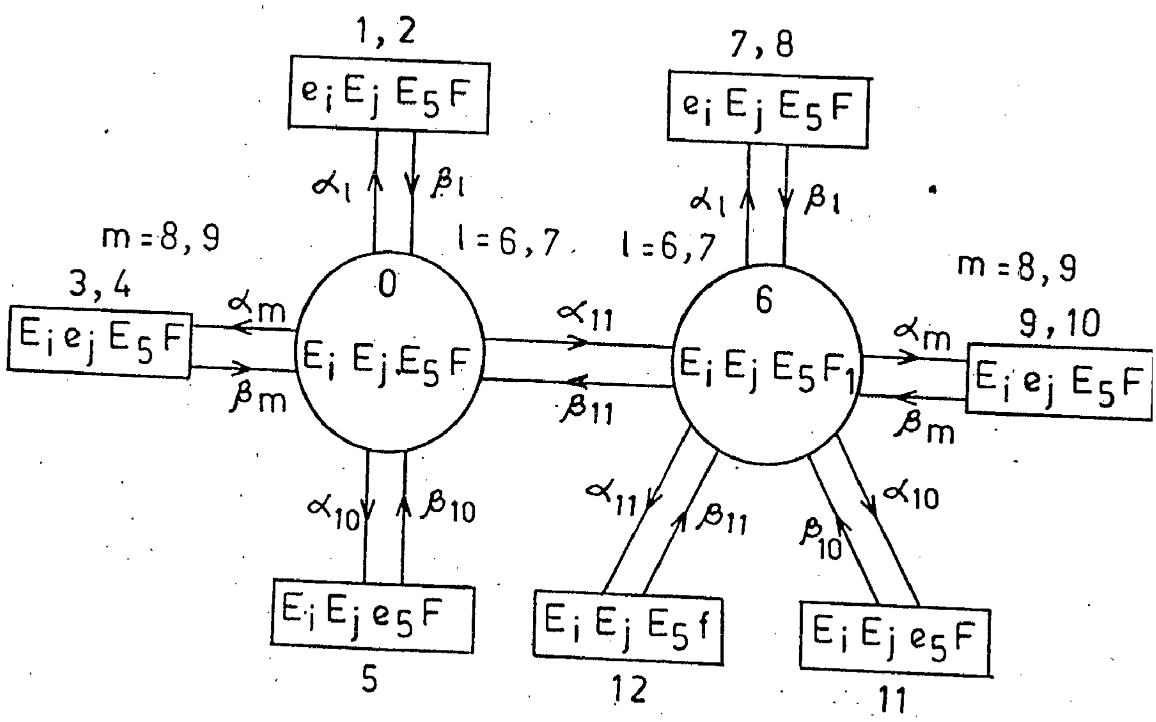


Fig.4.3:2 Urea decomposition system.

$$p_0=[1+\sum_{i=6}^{11}(\alpha_i/\beta_i)\{1+\alpha_{11}/\beta_{11}\}]^{-1}$$

Whereas the steady state availability $[AV_2]$ of the system is as follows:

$[AV_2]=p_0+p_6$

$$=(1+\alpha_{11}/\beta_{11})[1+(1+\alpha_{11}/\beta_{11})\sum_{i=6}^{11}(\alpha_i/\beta_i)]^{-1} \qquad \text{--(4.3.4)}$$

The equation 4.3.4 shows that the performance of the equipment F would be crucial in controlling the system availability $[AV_2]$. Hence its failure rate must be maintained to as small a value as possible by providing better repair facilities.

4.3.d <u>BEHAVIOURAL ANALYSIS</u>:

Table 4.3-1: Effect of failure rate of reboiler, high and low pressure absorber, falling film heater, gas separator and heat exchanger on system availability AV_2 ($\beta_6=\beta_7=0.5$, $\beta_8=\beta_9=0.2$, $\beta_{10}=0.1$, $\beta_{11}=0.25$)

$\alpha_6=\alpha_7$	$\alpha_8=\alpha_9=\alpha_{10}$	Availability$[AV_2]$					
		$\alpha_{11}=0.0$	$\alpha_{11}=.001$	$\alpha_{11}=.002$	$\alpha_{11}=.003$	$\alpha_{11}=.004$	$\alpha_{11}=.005$
.00	.000	1.00000	.99998	.99994	.99985	.99975	.99961
	.005	.90909	.90907	.90903	.90897	.90888	.90876
	.010	.83333	.83332	.83328	.83323	.83158	.83306
.001	.000	.99602	.99600	.99595	.99587	.99576	.99562
	.005	.90826	.90578	.90574	.90568	.90559	.90542
	.010	.83056	.83055	.83052	.83046	.83039	.83029
.005	.000	.98039	.98037	.98033	.98025	.98015	.98001
	.005	.89285	.89284	.89280	.89274	.89265	.89254
	.010	.81967	.81966	.81962	.81957	.81950	.81940

Table 4.3-2: Effect of repair rate of reboiler, high and low pressure absorber, falling film heater, gas separator and heat exchanger on availability AV_2 ($\beta_6=\beta_7, \alpha_6=\alpha_7=.005$, $\alpha_8=\alpha_9=\alpha_{10}=.002$, $\alpha_{11}=.003$).

β_{10}	β_{11}	$\beta_8=\beta_9$	Availability[AV_2]				
			β_6 =0.1	β_6 =0.2	β_6 =0.3	β_6 =0.4	β_6 =0.5
.1	.1	.1	.8614	.9001	.9139	.9209	.9252
	.3		.8620	.9008	.9146	.9216	.9258
.1	.1	.2	.8620	.9008	.9146	.9216	.9258
	.3		.8771	.9173	.9316	.9389	.9433
.3	.1	.1	.8714	.9111	.9252	.9324	.9367
	.3		.8720	.9118	.9259	.9330	.9374
.3	.1	.2	.8720	.9118	.9259	.9330	.9374
	.3		.8875	.9287	.9433	.9508	.9553

Table 4.3-1 shows that failure rate of F is in the range of .001 to .005. The standby unit in F is provided due to its important role in achieving good system availability. Failure rates in F if controlled between once in 1000 hrs to once in 200 hrs would effect the availability by .038% only (within tolerable limit).

Table 4.3-2 on the other hand shows that since failure rate for subsystem F is small therefore decrease in its repair time from once in 10 hrs to once in 2 hrs does not have much effect on system performance. Increasing the repair rates for E_2 and E_4 do not seem to have much effect mainly because their repair times are quite small moreover for this unit complete failures are rare.

The units E_1 and E_3 are insensitive to changes in their repair rates and have only marginal effect on system availability (table 4.3-2).

It should be noted that unit E_3 works due to pressure difference i.e no mechanical operation is involved hence complete failure of the unit at any time does not takes place.However with a faulty unit (E_3) the efficiency of operations is lowered.

The reliability analysis of the system with general repair distribution using Lagrange's method for solution of partial differential equations has also been developed by the author and reported elsewhere (61).

4.4 THE CRYSTALLISATION SYSTEM

A schematic diagram of the crystallisation system is shown in fig. 4.4:1.

4.4.a SYSTEM DESCRIPTION: The crystallisation system consists of the following five subsystems in series-

i) the vacuum generator (G_1), consists of two stage ejector and a barometric condenser, this generates vacuum of 175 mm Hg (abs) and its failure causes complete failure of the system,

ii) the crystallizer (G_2), has two portions- the concentrator (upper part) and the crystallizer (lower part). Failure of any one causes complete failure of the system,

iii) the centrifuge (G_3), consists of five units in series. Failure of any one causes complete failure of the system,

iv) the crystallizer pump (H) has one standby unit. Complete failure occurs when both units fail,

v) the slurry feed pump (Q), has one standby unit. Complete failure occurs when both units fail.

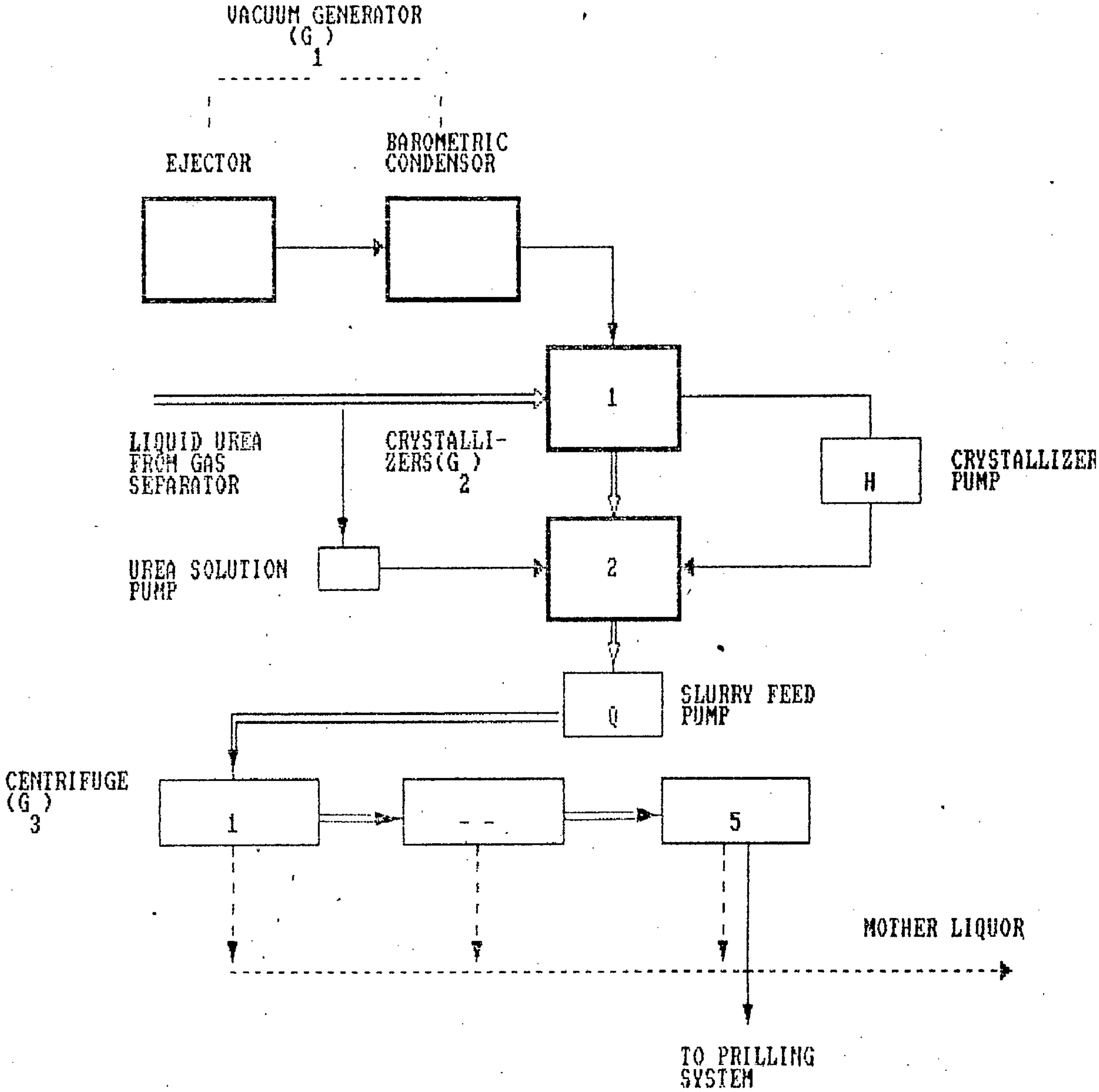


FIG 4.4:1.. UREA CRYSTALLIZATION SYSTEM

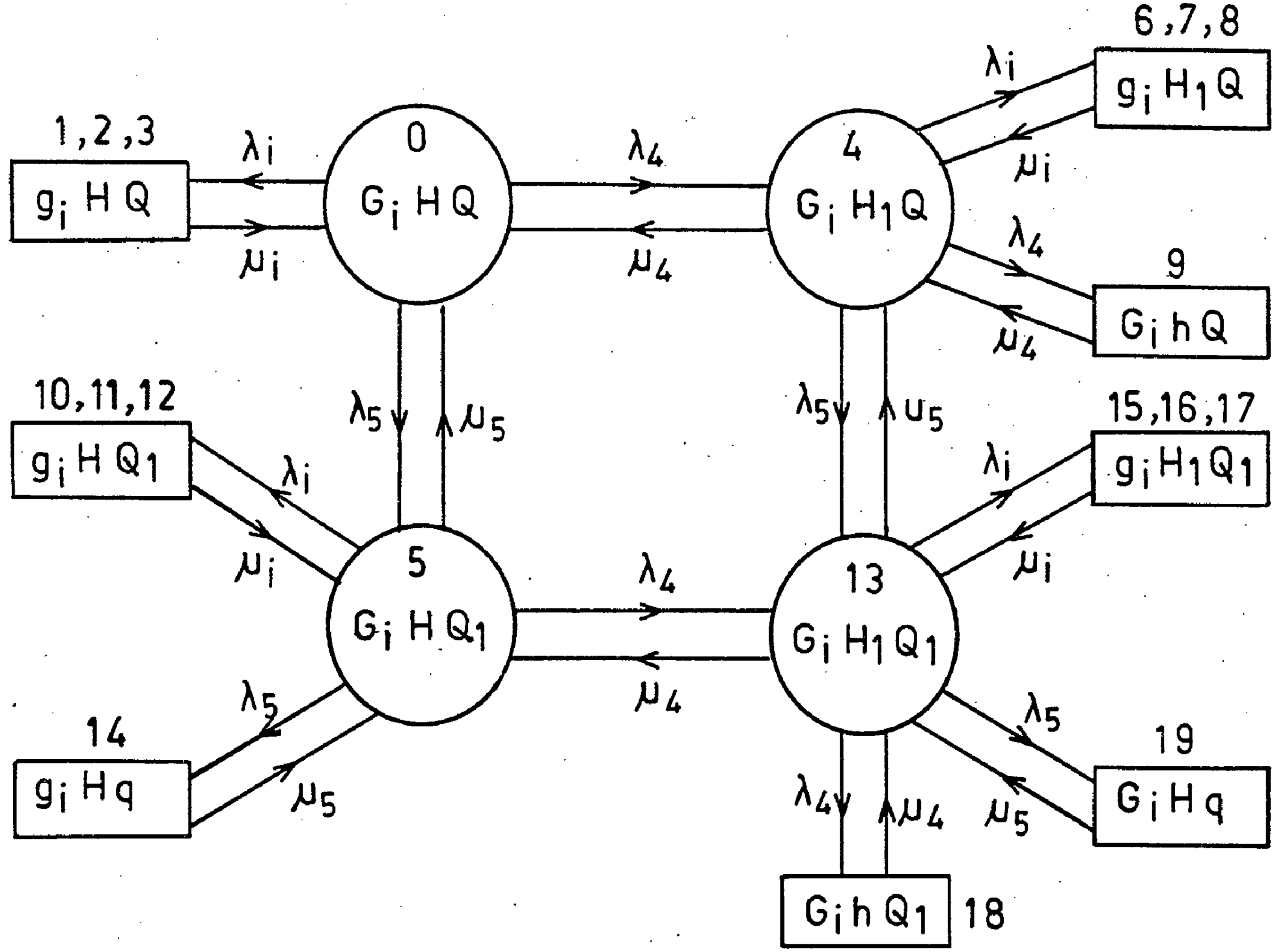


Fig. 4.4:2 Urea crystallization system.

4.4.c STEADY STATE BEHAVIOUR:

This is obtained from the condition, when $t \to \infty$, $(d/dt) \to 0$. Hence putting $(d/dt)=0$ in equations 4.4.1 to 4.4.5 and solving the steady state probabilities for the system are as follows:

$p_j = (T_i/\mu_i)p_k$

where for i=1,2,3; k=0,j=i; k=4,j=i+5; k=5,j=i+9; k=13,j=i+14.

i=4; k=4,j=i+5;k=13,j=i+14

i=5; k=5,j=i+9;k=13,j=i+14

$p_4=(T_4/\mu_4)p_0$; $p_5=(T_5/\mu_5)p_0$; $p_{13}=(T_4T_5/\mu_4\mu_5)p_0$

The probability p_0 is obtained using normalizing condition

i.e $\sum_{i=0}^{19} p_i=1$ and is given by:

$$p_0=\left[\left(1+\sum_{i=1}^{3} T_i/\mu_i\right)(1+T_4/\mu_4)(1+T_5/\mu_5) + (T_5/\mu_5)^2(1+T_4/\mu_4)+(T_4/\mu_4)^2(1+T_5/\mu_5)\right]^{-1}$$

$=[L_2]^{-1}$

The long run availability $[AV_3]$ of the system is given by :

$[AV_3]=p_0+p_4+p_5+p_{13}$

$$=[(1+T_4/\mu_4)(1+T_5/\mu_5)][L_2]^{-1} \qquad ---(4.4.6)$$

The equation 4.4.6 shows that the equipment H and Q having standby units have a controlling influence on system availability.

4.4.d <u>BEHAVIOURAL ANALYSIS</u>:

Table 4.4-1: Effect of failure rate of the subsystem, vacuum generator, crystallizer and centrifuges on AV_3 ($\mu_1=\mu_2=0.05$, $\mu_3=0.1$, $T_4=T_5=0.05$, $\mu_4=\mu_5=0.1$)

T_1	T_2	Availability[AV_3]				
		T_3 =0.0	T_3 =.005	T_3 =.010	T_3 =.015	T_3 .020
.000	.000	.7500	.7229	.6977	.6742	.6522
	.005	.6977	.6742	.6522	.6316	.6122
	.010	.6522	.6358	.6122	.5941	.5769
	.020	.5769	.5606	.5455	.5310	.5172
.005	.000	.6977	.6742	.6522	.6358	.6122
	.005	.6522	.6358	.6122	.5941	.5769
	.010	.6122	.5941	.5769	.5608	.5455
	.020	.5455	.5310	.5172	.5042	.4918
.010	.000	.6522	.6316	.6122	.5941	.5769
	.005	.6122	.5741	.5769	.5608	.5455
	.010	.5769	.5608	.5455	.5310	.5172
	.020	.5172	.5042	.4918	.4800	.4500

Table 4.4-2: Effect of repair rates of vacuum generator, crystallizer and centrifuge on availability AV_3 ($T_1=T_2=T_3=.001$, $T_4=T_5=.05$, $\mu_4=\mu_5=0.1$)

μ_1	μ_2	Availability[AV_3]		
		μ_3 =0.1	μ_3 =0.3	μ_3 =0.5
.10	.10	.7375	.7371	.7378
	.20	.7371	.7407	.7415
	.30	.7378	.7415	.7423
.30	.10	.7371	.7407	.7515
	.20	.7407	.7444	.7452
	.30	.7415	.7452	.7459
.50	.10	.7378	.7415	.7423
	.20	.7415	.7452	.7459
	.30	.7423	.7459	.7466

Table 4.4-3: Effect of crystallizer pump and slurry feed pump failure on Av_3 ($T_1=T_2=T_3=.001$, $\mu_i=0.1$, $i=1,2,3,4,5$)

T_4	Availability[AV_3]				
	T_5 =0.0	T_5 =.025	T_5 =.050	T_5 =.075	T_5 =.10
.00	1.0000	.9259	.8357	.7400	.6536
.025	.9259	.8850	.8021	.7136	.6329
.050	.8357	.8021	.7335	.6587	.5894
.075	.7400	.7136	.6587	.5978	.5401
.100	.6536	.6329	.5894	.5401	.4926

Table 4.4-4: Effect of crystallizer pump and slurry feed pump repair rates on AV_3 ($T_1=T_2=T_3=.001$, $T_4=T_5=.025$, $\mu_1=\mu_2=\mu_3=0.1$)

μ_4	Availability[AV_3]		
	μ_5 =0.1	μ_5 =0.2	μ_5 =0.5
0.1	.8850	.9205	.9239
0.3	.9205	.9589	.9626
0.5	.9239	.9626	.9664

Table 4.4-1 depicts that failure rates of vacuum generator and crystallizer have more or less identical influence upon system availability while failure rate of the centrifuge has comparatively lesser effect. If by proper maintenance planning the failures in vacuum generator and crystallizer are restricted to one failure in about 1000 hrs and the mean repair time is kept at about 10 hrs (table 4.4-1 & 4.4-2), then the availability would be about 73.75% .

Table 4.4-2 shows that increasing the repair rates of the subsystems G_1,G_2, G_3 at very small failure rates (.001), has little effect upon system availability.

Table 4.4-3 shows that the subsystems H and Q have large impact upon system availability i.e slight increase in failure rate (T_4 & T_5) reduces the availability sharply. Therefore in order to attain larger availability, the failure rate be kept as small as possible. This can be made possible by providing standby units. From table 4.4-3 it is observed that for about 88.5% availability, the number of failures in H and Q should not exceed once in 40 hrs.

Table 4.4-4 shows that an increase in repair rate of H and Q increases the availability sharply. Hence for good reliability we must pay larger attention towards the repair of the two subsystems e.g. H and Q.

The reliability analysis of the system with general repair time using Lagrange's method for solution of partial differential equations has also been developed for the system discussed above and reported elsewhere (66).

4.5 UREA PRILLING SYSTEM

A schematic diagram of the prilling system is given in fig.4.5:1.

4.5.a <u>SYSTEM DESCRIPTION</u>: The prilling system consists of the following three subsystems in series.

i) the subsystem (U_j), consists of four units viz- cyclone (U_1), screw conveyor (U_2), melter (U_3) and strainer (U_4). Failure of any one unit causes complete failure of the system,

ii) the subsystem (V), consists of eleven distributors operating simultaneously with one standby. Failure of any one unit does not affect the system availability. Complete failure takes place only when more than one failure occurs (since the flow of molten urea

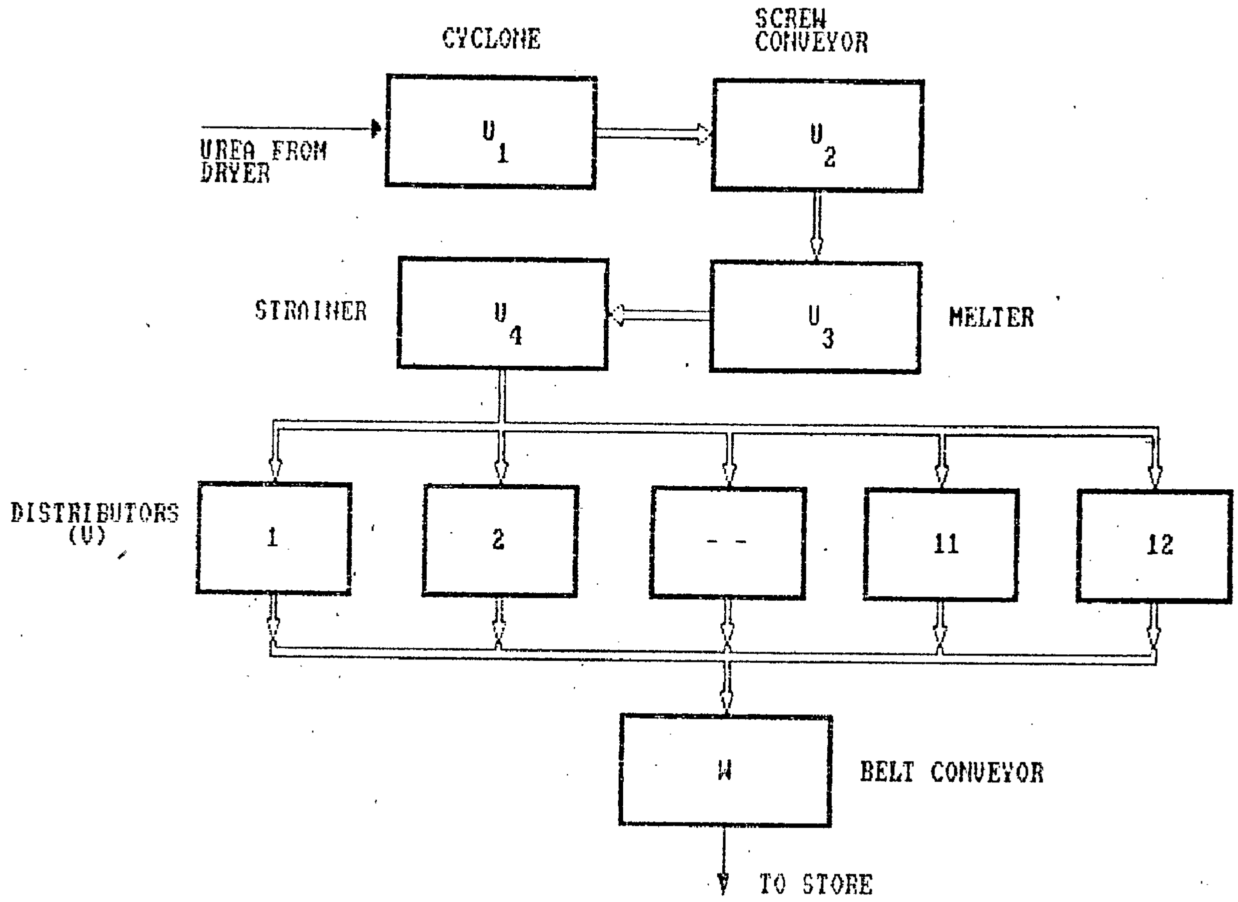


FIG 4.5:1. UREA PRILLING SYSTEM

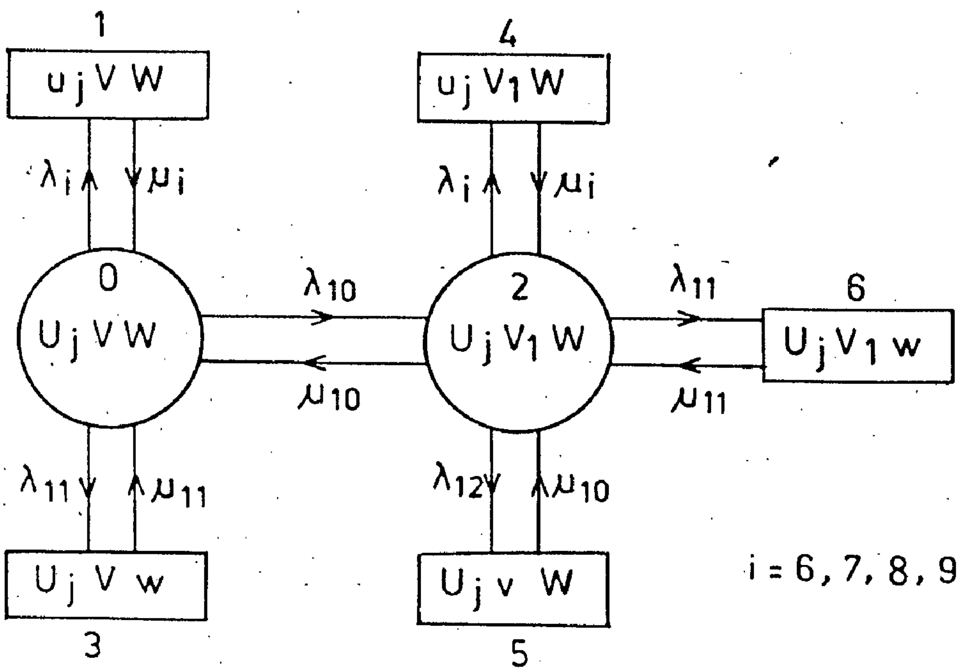


Fig.4.5:2 Urea prilling system.

is continuous converted into uniform pills by eleven distributors but failure in any one causes less inflow of molten urea causing a blockade before distributor hence we call it as failure of the system,

iii)the belt conveyor (W) , consists of one unit and is employed for carrying the product to trommer. Failure of belt conveyor leads to the huge accumulation of urea, blocking the flow path of prilled urea. Hence failure of subsystem W would affect the working of the system.

4.5.b RELIABILITY OF THE PRILLING SYSTEM:

The differential equations associated with the various states of the system in transition diagram (fig 4.5:2) have been derived as:

$$\left(\frac{d}{dt}+\sum_{i=6}^{11} T_i\right)p_o(t)=\sum_{i=6}^{9} \mu_i p_1(t)+\sum_{i=10}^{11} \mu_i p_{i-8}(t) \qquad \text{--(4.5.1)}$$

$$\left(\frac{d}{dt}+\sum_{i=6}^{9} T_i+\mu_{10}+T_{11}+T_{12}\right)p_2(t)$$

$$=T_{10}p_o(t)+\sum_{i=6}^{9} \mu_i p_4(t)+\mu_{10}p_5(t)+\mu_{11}p_6(t) \qquad \text{--(4.5.2)}$$

$$\left(\frac{d}{dt}+\mu_i\right)p_j(t)=T_i p_k(t) \qquad \text{--(4.5.3)}$$

$$\left(\frac{d}{dt}+\mu_{10}\right)p_5(t)=T_{12}p_2(t) \qquad \text{--(4.5.4)}$$

with initial condition $p_o(0)=1$. otherwise=0.

where i, j, k in equations 4.5.3 are:

Taking Laplace transforms of 4.5.1 to 4.5.4 and solving recursively (using initial condition), the Laplace transform $R_4(s)$ of reliability function is obtained as follows:

$$R_4(s)= L\{p_0(t)+p_2(t)\}=p_0(s)+p_2(s)$$

where

$$p_0(s)=[s+x_{12}-y_{12}]^{-1} \quad ; \quad p_2(s)=\{T_{10}/(s+x_{11}-y_{11})\}p_0(s);$$

$$x_{11}=\sum_{i=6}^{9} T_i+\mu_{10}+T_{11}+T_{12} \quad ; \quad x_{12}=\sum_{i=6}^{11} T_i;$$

$$y_{11}=\sum_{i=6}^{9} \frac{T_i\mu_i}{(s+\mu_i)}+\frac{T_{12}\mu_{10}}{(s+\mu_{10})}+\frac{T_{11}\mu_{11}}{(s+\mu_{11})}$$

$$y_{12}=\sum_{i=6}^{9} \frac{T_i\mu_i}{(s+\mu_i)}+\frac{T_{10}\mu_{10}}{(s+x_{11}-y_{11})}+\frac{T_{11}\mu_{11}}{(s+\mu_{11})}$$

and mean time to system failure $[MTTF]_4$ is obtained by taking

Lim $s \to 0$ in $sR_4(s)$

$$[MTTF]_4=\frac{(1+T_{10}/\mu_{10})}{[\{1+\sum_{i=6}^{9}(T_i/\mu_i)\}(1+T_{10}/\mu_{10})+(T_{10}\mu_{10}^{-2})\{T_{12}+T_{10}\}+T_{11}/\mu_{11}]}$$

4.5.c STEADY STATE BEHAVIOUR:

For steady state conditions $t \to \infty$ or $(d/dt) \to 0$. Putting $(d/dt)=0$ in equations 4.2.1 to 4.5.4 and solving recursively the steady state probabilities for the system are obtained as follows:

$$p_1=(T_i/\mu_i)p_0 \quad ; p_2=(T_{10}/\mu_{10})p_0 \quad ; p_3=(T_{11}/\mu_{11})p_0;$$

$$p_4=(T_i/\mu_i)p_2 \quad ; p_5=(T_{12}/\mu_{10})p_2 \quad ; p_6=(T_{11}/\mu_{11})p_2; \quad i=6,7,8,9.$$

The probability p_0 is obtained using normalizing condition

i.e $\sum_{i=0}^{6} p_i=1$. and is given by;

$$p_0=[1+\{\sum_{i=6}^{9}(T_i/\mu_i)+(T_{10}/\mu_{10})\}\{1+T_{10}/\mu_{10}\}+(T_{11}/\mu_{11})+(T_{10}T_{12}/\mu_{10}^{2}]^{-1}$$

Whereas, the steady state availability $[AV_4]$ of the system is given by:

$$[AV_4]=p_0+p_2$$

$$=\frac{(1+T_{10}/\mu_{10})}{[1+\{\sum_{i=6}^{9}(T_i/\mu_i)+(T_{10}/\mu_{10})\}(1+T_{10}/\mu_{10})+(T_{10}T_{12}/\mu_{10}^2)+T_{11}/\mu_{11}]} \quad ---(4.5.5)$$

Equation (4.5.5) shows that the failure of distributor plays an important role in controlling the system availability. Its failure rate should therefore be maintained to as small a value as possible.

4.5.d BEHAVIOURAL ANALYSIS:

Table 4.5-1: Effect of failure rates of screw conveyor and strainer upon availability ($T_6=T_8=T_{10}=.001$, $\mu_{10}=0.9$, $\mu_7=\mu_9=0.1$, $T_{12}=.005$, $T_{10}=.01$, $\mu_6=.1$, $\mu_8=\mu_{11}=.2$)

T_7	Availability$[AV_4]$				
	T_9 =0.0	T_9 =.025	T_9 =.050	T_9 =.075	T_9 =.100
.000	.9390	.7605	.6390	.5510	.4843
.025	.7605	.6390	.5510	.4843	.4320
.050	.6390	.5510	.4843	.4320	.3899
.075	.5510	.4843	.4320	.3899	.3552
.100	.4843	.4320	.3899	.3552	.2420

Table 4.5-2: Effect of repair rates of screw conveyor and strainer on AV_4 ($T_7=T_9=.015$, $T_6=T_8=T_{10}=.001$, $T_{11}=.01$, $\mu_6=.1$, $\mu_8=\mu_{11}=.20$, $\mu_{10}=.9$)

μ_7	Availability[AV_4]		
	μ_9 =0.1	μ_9 =0.3	μ_9 =0.5
0.1	.7326	.7905	.8032
0.3	.7905	.8584	.8734
0.5	.8032	.8734	.8889

Table 4.5-3: Effect of failure rate of cyclone, screw conveyor, distributor and belt conveyor on AV_4 ($T_7=0.1$, $T_9=.005$, $\mu_7=0.2$, $\mu_9=0.5$, $T_8=.001$, $\mu_6=.10$, $\mu_8=\mu_{11}=0.2$, $\mu_{10}=0.9$)

T_6	T_{11}	Availability [AV_4]				
		T_{10}=0.00	T_{10}=.0025	T_{10}=.0050	T_{10}=.0075	T_{10}=.010
.000	.00	.93896	.93652	.93409	.93168	.92928
	.01	.93664	.93432	.93203	.92973	.92746
	.05	.89597	.89418	.89242	.89065	.88889
.002	.00	.92166	.91930	.91697	.91463	.91232
	.01	.91940	.91718	.91497	.91276	.91057
	.05	.88019	.87848	.87677	.87506	.87337
.004	.00	.90498	.90271	.90045	.89820	.89598
	.01	.90282	.90066	.89853	.89639	.89428
	.05	.86572	.86405	.86240	.86075	.85911

Table 4.5-4: Effect of failure rate of cyclone, screw conveyor, distributor and belt conveyor on AV_4 (changing the value of T_8 from .001 to .0025)

T_6	T_{11}	Availability[AV_4]				
		T_{10}=.00	T_{10}=.0025	T_{10}=.0050	T_{10}=.0075	T_{10}=.010
.000	.00	.93240	.92999	.92760	.92521	.92285
	.01	.93011	.92782	.92555	.92329	.92105
	.05	.88999	.88823	.88649	.88474	.88301
.002	.00	.91533	.91301	.91071	.90841	.90613
	.01	.91312	.91092	.90873	.90655	.90439
	.05	.87442	.87273	.87104	.86936	.86769
.004	.00	.89888	.89664	.89441	.89219	.88998
	.01	.89674	.89462	.89251	.89041	.88832
	.05	.85939	.85775	.85613	.85449	.85288

Table 4.5-5: Effect of repair rate s of cyclone, melter, distributor and belt conveyor on AV_4 (T_6=.0025, T_7=.01, T_8=.002, T_9=T_{10}=.005, T_{11}=.02, μ_7=.2, μ_9=0.5)

μ_8	μ_{11}	Availability[AV_4]					
		μ_6 =0.1		μ_6 =0.3		μ_6 =0.5	
		μ_{10}=0.5	μ_{10}=0.8	μ_{10}=0.5	μ_{10}=0.8	μ_{10}=0.5	μ_{10}=0.8
0.2	.1	.87848	.88138	.89153	.89452	.89419	.89720
	.5	.90372	.90679	.91754	.92071	.92035	.92272
0.4	.1	.88235	.88528	.89553	.89854	.89820	.90124
	.5	.90782	.91092	.92177	.92499	.92461	.92783

Table 4.5-1 shows that an increase in failure rates of screw conveyor (T_7) and strainer (T_9) affect the availability to a large extent and a high failure rate would mean heavy loss in production. Through planning and controlling the failure in cyclone and strainer to about once in 600 hrs it is possible to achieve an availability of about 70%.

Table 4.5-2 shows that availability of the system can be maintained at sufficiently high value by providing good maintenance facilities.

Table 4.5-3 and 4.5-4 indicate that the failure rates of distributor, belt conveyor and the cyclone have considerable effect upon availability. The effect of distributor failure on AV_4 at low failure rate (T_{10}) is only marginal because of the provision of a standby unit and the higher repair rates. The effect of failure of melter upon availability is also insignificant. Table 4.5-5 shows that generally higher repair rates would lead to reasonable improvement in the system availability but due to factory constraints it may not be possible, to provide high repair rates for all units.

4.6 OVERALL AVAILABILITY OF THE UREA PLANT

Since urea synthesis system, decomposition system, crystallisation system and urea prilling system work in series. The availability of the entire plant [AV] can be given by:

$$[AV]=[AV_1 * AV_2 * AV_3 * AV_4]$$

$$=[\{1+I_5+I_6+I_7+(I_4/M_2)(1+I_2/M_1)+I_1/M_1\}(L_1)^{-1}]_1$$

$$*[(1+\alpha_{11}/\beta_{11})\{1+(1+\alpha_{11}/\beta_{11})\sum_{i=6}^{11}(\alpha_i/\beta_i)\}^{-1}]_2$$

$$*[(1+\sum_{i=1}^{3} T_i/\mu_i)+\{(T_5/\mu_5)^2/(1+T_5/\mu_5)\}+\{(T_4/\mu_4)^2/(1+T_4/\mu_4)\}]_3^{-1}$$

$$*\left[\frac{(1+T_{10}/\mu_{10})}{1+\{\sum_{i=6}^{9}(T_i/\mu_i)+(T_{10}/\mu_{10})(1+T_{10}/\mu_{10})\}+(T_{11}/\mu_{11})+(T_{10}T_{12}/\mu_{10}^2)}\right]_4 \quad \text{---(4.6.1)}$$

Based on the failure and repair data of the plant, the availability (AV) has been computed under the following conditions (table 4.6-1):

i) units, CO_2 booster compressor and CO_2 high pressure compressor do not have standbyes and hence their failures would have a large affect upon system availability. Generally $\alpha_1=\alpha_2=.02$ i.e one failure in 50 hrs , repair rates $\beta_1=\beta_2=.25$ (the mean repair time however may vary depending upon the type of failure).

ii) Ammonia preheater is just like a heat exchanger and there is no mechanical operation and so typical failure rate would be $\alpha_3=.001$ i.e once in 1000 hrs however it takes about 5 hrs to repair mainly on account of replacement of preheater tube after failure [hence $\beta_3=0.2$].

iii) Liquid ammonia feed pump (B) and recycle solution feed pump (D) have units in standby hence their failure rates α_4 & α_5 remains small having very little effect upon system availability. Typical values are $\alpha_4=.002$ i.e once in 500 hrs and $\alpha_5=.004$ i.e once in 250 hrs while the repair rate $\beta_4=\beta_5=.25$ i.e about 4 hrs may very due to mode of failure having very-2 less effect upon system availability.

iv) Equipments viz.,- reboiler, low and high pressure absorber, gas separator and heat exchanger work due to chemical changes, pressure difference or temperature difference only i.e. no mechanical operation is involved in any of the equipments, hence complete failure never occurs. The instruments provided in this system perform chemical analysis, pressure recording at the inlet and outlet and also carry out temperature recording. The failure rate in this case is very small i.e. $\alpha_i=.001$ (once in 1000 hrs). and repair takes about 10 hrs i.e $\beta_i=0.1$ (where i=6,7,8,9,10,11)

v) all the units, in crystallisation system greatly influence the system availability hence their role must be analyzed critically. Failure rate in generator (T_1) may vary from once in 1000 hrs to once in 100 hrs while its repair takes about 20 hrs.

Crystallizer works on temperature difference principle. Since there are no mechanical parts hence its rate of failure is vary small, T_2=.002 i.e. once in 500 hrs while its repair takes about 5 hrs μ_2= 0.2. The failure rate of centrifuge is high and greatly varies from once in 1000 hrs to once in 100 hrs while its repair takes about 5 hrs. Crystallizer pump and slurry feed pump have units in standby hence their failure rates (T_4 & T_5) remain very low T_4=T_5=.02 (once in 50 hrs) while the repair takes about 2 hrs i.e μ_4=μ_5=.5.

vi) Failure rates in cyclone is also small i.e once in 400 hrs T_6=.0025 whereas its repair takes about 5 hrs (μ_6=.2). Failure of screw conveyor may very from once in 200 hrs to once in 100 hrs whereas its repair takes about 2 hrs.Failure rate of melter and strainer is very small T_8=T_9=.005 and their average repair rates are: μ_8=.5, μ_9=.8.

Since distributor has a unit in standby with a unskilled worker, to avoid any chocking of the distributor holes hence its failure rate is very small (T_{10}=.002) and its average repair rate is μ_{10}=.9. Failure of belt conveyor varies from once in 200 hrs to once in 100 hrs whereas at an average repair takes 2 hrs.

Table 4.6-1: Effect of failure rate of vacuum generator, centrifuge, screw conveyor and belt conveyor for repair rate in CO_2 booster & CO_2 high pressure compressor as 0.1. Values based on the plant data are:($\alpha_1=\alpha_2=.02$, $\alpha_3=.001$, $\beta_3=.2$, $\alpha_4=.002$, $\alpha_5=.004$, $\beta_4=\beta_5=.25$, $\alpha_i=.001$, $\beta_i=0.1,(i=6,7,8,9,10,11)$, $T_2=.002,\mu_2=.2$, $T_4=T_5=.02$, $\mu_4=\mu_5=.5$, $T_6=.0025$, $\mu_6=.2$, $T_8=T_9=.005$, $\mu_8=.5$, $\mu_9=.8$, $T_{10}=.002,\mu_{10}=.9$, $\mu_1=.05$, $\mu_3=.2$, $T_{12}=.005$, $\mu_{11}=.5$, $\mu_7=.5$).

T_1	T_3	T_7	Availability[AV]			
			T_{11} =.005	T_{11} =.010	T_{11} =.015	T_{11} =.020
.001	.001	.010	.61276	.60706	.60094	.59597
		.015	.60705	.60145	.59596	.59056
		.020	.60144	.59594	.59055	.58525
	.005	.010	.60118	.59559	.58959	.58471
		.015	.59558	.59009	.58470	.57940
		.020	.59007	.58468	.57939	.57420
	.010	.010	.58730	.58148	.57598	.57121
		.015	.58183	.57647	.57120	.56603
		.020	.57648	.57119	.56602	.58095
.005	.001	.010	.56892	.56382	.55794	.55333
		.015	.56361	.55842	.55332	.54831
		.020	.55840	.55330	.54829	.54338
	.005	.010	.55892	.55372	.54814	.54360
		.015	.55371	.54860	.54359	.53867
		.020	.54489	.54358	.53866	.53383
	.010	.010	.54690	.54182	.54060	.53192
		.015	.54180	.53681	.53191	.52709
		.020	.53680	.53190	.52708	.52235
.010	.001	.010	.52221	.51735	.51214	.50790
		.015	.51734	.51257	.50789	.50329
		.020	.51256	.50788	.50328	.49877
	.005	.010	.51377	.50899	.50387	.49970
		.015	.50898	.50429	.49969	.49516
		.020	.50428	.49968	.49515	.49071
	.010	.010	.50360	.49892	.49389	.48981
		.015	.49891	.49431	.48979	.48536
		.020	.49430	.48979	.48535	.48100

Table 4.6-2: Effect of failure rate of vacuum generator, centrifuge, screw conveyor and belt conveyor on system availability for CO_2 booster and CO_2 high pressure compressor repair rate as 0.2 taking the same value of other parameter as for table 4.6-1

T_1	T_3	T_7	Availability [AV]			
			T_{11} =.005	T_{11} =.010	T_{11} =.015	T_{11} =.020
.001	.001	.010	.71444	.70779	.70066	.69486
		.015	.70777	.70126	.69485	.68856
		.020	.70124	.69484	.68855	.68237
	.005	.010	.70094	.69441	.68742	.68173
		.015	.69440	.68710	.68172	.67555
		.020	.68799	.68170	.67553	.66947
	.010	.010	.68476	.67839	.67155	.66599
		.015	.67837	.67212	.66598	.65995
		.020	.67211	.66597	.65994	.65402
.005	.001	.010	.66332	.65715	.65053	.64515
		.015	.65714	.65108	.64513	.63929
		.020	.65107	.64512	.63928	.63355
	.005	.010	.65166	.64560	.63910	.63381
		.015	.64559	.63964	.63380	.62806
		.020	.63962	.63378	.62805	.62241
	.010	.010	.63766	.63172	.62536	.62019
		.015	.63171	.62589	.62017	.61456
		.020	.62588	.62016	.61454	.60903
.010	.001	.010	.60886	.60320	.59712	.59218
		.015	.60319	.59763	.59217	.58681
		.020	.59762	.59216	.58680	.58153
	.005	.010	.59903	.59346	.58747	.58262
		.015	.59344	.58798	.58261	.57733
		.020	.58796	.58259	.57732	.57214
	.010	.010	.58717	.58171	.57585	.57108
		.015	.57632	.57634	.57107	.56590
		.020	.58717	.58171	.57585	.57108
		.015	.57632	.57634	.57107	.56590
		.020	.57632	.57108	.56589	.56082

Table 4.6-3: Effect of failure of vacuum generator, centrifuge, screw conveyor and belt conveyor upon urea production process for repair rate in CO_2 booster and CO_2 high pressure compressor as 0.3 (values of other parameters are same as in table 4.6-1)

T_1	T_3	T_7	Availability[AV] T_{11} =.005	T_{11} =.010	T_{11} =.015	T_{11} =.020
.001	.001	.010	.75627	.74924	.74168	.73555
		.015	.74922	.74232	.73553	.72888
		.020	.74230	.73552	.72886	.72233
	.005	.010	.74198	.73507	.72766	.72165
		.015	.73510	.72828	.72163	.71510
		.020	.72827	.72162	.71508	.70867
	.010	.010	.72485	.71811	.71087	.70499
		.015	.71809	.71148	.70498	.70630
		.020	.71146	.70496	.69858	.69231
.005	.001	.010	.68982	.68340	.67651	.67092
		.015	.69561	.68921	.68291	.67671
		.020	.68919	.68289	.67671	.67064
	.005	.010	.68982	.68340	.67651	.67092
		.015	.68339	.67709	.67091	.66483
		.020	.67708	.67089	.66482	.65886
	.010	.010	.67499	.66871	.66198	.65650
		.015	.66870	.66244	.65649	.65054
		.020	.66253	.65647	.65053	.64469
.010	.001	.010	.64452	.63852	.63208	.62686
		.015	.63851	.63262	.62684	.62117
		.020	.63261	.62683	.62105	.61558
	.005	.010	.63194	.62606	.61975	.61463
		.015	.62605	.62028	.61461	.60905
		.020	.62027	.61460	.60903	.60357
	.010	.010	.62155	.61577	.60956	.60452
		.015	.61576	.61009	.60451	.59904
		.020	.61007	.60450	.59902	.59365

Table 4.6-2 and 4.6-3 show that increase in repair rates of CO_2 booster and CO_2 high pressure compressor lead to increased availability. For example, reducing the repair time from 10 hrs to 5 hrs increases the availability by 10% and further reduction in repair time to 3.33 hrs increases the availability by 4%. It

has been observed from tables (4.6-1 to 4.6-3) that by employing the available repair facilities in best possible manner i.e. a minimum possible repair time of 4 hrs can be achieved. It is therefore desirable to have units in standby. Through field investigations it has been observed that the units CO_2 booster and high pressure compressor are costly and is not easy to provide them with standbyes. Also tables (4.6-1 to 4.6-3) show that increase in failure of vacuum generator from once in 1000 hrs to once in 200 hrs reduces the availability shaperly while increase in failure rate in any of the centrifuges from .001 to .005 has little effect upon system availability because five centrifuges are working simultaneously in parallel. Increase in failure of screw conveyor from once in 100 hrs to three times in 200 hrs reduces the availability by .667%. Similar effect is is observed for an increase in failure rate of the belt conveyor from .005 to .01.

CHAPTER-5

MAINTENANCE IN PROCESS INDUSTRIES

5.1. INTRODUCTION

To produce profitable products, it is necessary to produce right quality of goods at the right price and delivered at the right time. To achieve this the plant must operate efficiently at the required level of production i.e. there must not be unscheduled stoppages. To ensure maximum availability and reliability, regular maintenance must be carried out. This maintenance schedule be planned carefully in conjunction with production requirements and schedules so that the number of stoppages and loss of production could be minimized. Inadequate maintenance planning can sometimes lead to damages, which may prove to be extremely costly not only on account of repairs but also in the form of lost production. Complexity and sophistication of modern production equipments coupled with high cost and tight production schedules necessitates the use of managerial skill for the organization of maintenance activities.

Due to limited resources e.g. manpower, money etc. available for repair of a failed equipment, it is not possible to handle the repair of broken equipment in a planned manner and minimizing the delay as far as possible. The frequency of breakdowns in general increases with the number of components in the system.

Thus the problem becomes more serious in case of large sized complex plants. Some studies on the availability of process industries were conducted by Cordor (1973) and Priel(1974).

Due to random nature of equipment failure, maintenance managers should have a prior knowledge of the behaviour of equipment, statistical data of their failure, the work plan to execute the repairs etc. Such informations provide guidelines for formatting the future policies.

Based on the availability analysis and general observations an attempt has been made in this chapter to laydown important guidelines for maintenance planning in sugar, paper and fertilizer industries.

5.2. MAINTENANCE IN SUGAR PLANTS

For the purpose of maintenance planning the following subsystems have been considered in detail with a view to formulate general guidlines for preventive maintenance.

(a)**Sugar cane supply & crushing system:**

Routine preventive maintenance must be carried out on the basis of following checks

i) bearings used for rollers.

(ii) Lubrication of cutter & crusher bearings.

(iii) Alignment between cutters & crushers.

(iv) Links and their locks.

The checks in all the above cases be carried out after every 8-10 hours of running to avoid any intermediate failure. This would ensure that the average failure rate in subsystems A_1 & A_2 is one in 50 hours.

(b) **Juice screen:**

To improve its working the following precautions are suggested :

(i) Remove big size cane pieces manually from the flowing juice.

(ii) Control the juice flow rate (as per design).

(iii) A constant watch (by unskilled worker) to check blockade in the juice flow passage.

The above steps have been found to reduce the failure rate of the subsystem to α_3=0.01.

Regular checking of lubrication & other moving parts in the clarifier system as per designer's instruction has been found to ensure its satisfactory performance.

(c) **Sulphonation unit, evaporator & sulphitor:**

Maintenance procedure recommended for this subsystem involves:

(i) Checking the pressure and temperature of the juice.

(ii) Checking the appearance of the surface of the sulphonation unit.

(iii) Controlling the flow rate of SO_2 gas.

(iv) Regular checking of the precipitation rate.

(v) Checking the quantity of SO_2 gas absorbed by the process.

(vi) Checking the readiness of standby feed pump.

The above measures would help in ensuring a failure free run of sulphonation plant i.e. α_7=0.0 & τ_2=0.0

(d) **Juice heaters:**

Following checks on regular basis are recommended:

(i) Monitoring and controlling the temperature of juice at the inlet and outlet.

(ii) Controlling the temperature and pressure of steam at the inlet of each heater.

(iii) Checking the heater valves for leakage.

These measures have been found to reduce the failure rate and through planned maintenance it can often result into α_8=0.0

The maintenance must be planned in advance and carried out in each subsystem during the period of shutdown. Furthermore each equipment has number of parallel units. Hence it is very unlikely that complete failure would take place. The system can however acquire reduced state on account of failures.

(e) **Centrifuges:**

Maintenance of centrifuges involves checking of voltage, speed & lubrication of various moving parts as per instructions. This has been found to limit the failure rate as

τ_1=0.02 , μ_4=0.2

Complete failure of the system however does not occur, since evaporator, cooking pans, crystallizer, centrifuges have more than one units working simultaneously and the maintenance is so planned that at least one unit of each subsystem always remains in working state. Futhermore, as failures in subsystem D_5 do not have any impact on sugar production, hence we can assume that

σ_r=0.0 for r=1,2,3,4,5. The availability of the sugar production process under such a condition is given by equation 5.2.1 (putting the above rates in equation 2.7.1).

$$[AV_p] = \frac{.83333[1+(\tau_1/\mu_4)+\Sigma\tau_m/(\mu_r+\epsilon)]}{[1+(\alpha_5/\beta_5)+(\alpha_6/\beta_6)] * [1+(\tau_1/\mu_4)+(\epsilon/\emptyset)+\Sigma\{\tau_m/(\mu_r+\epsilon)\}\{1+\epsilon/\mu_r\emptyset\}]} \qquad \text{---(5.2.1)}$$

Using equation 5.2.1 the following tables have been tabulated.

Table 5.2-1: Effect of repair rate in juice screen, clarifier, centrifuge & common cause under the conditions α_1=α_2= 0.02, β_1=β_2=0.2, α_5=α_6=0.01, τ_1=0.02, ϵ=0.005, τ_1=0.02, τ_j=0.01, τ_k=.002, μ_1=0.2, μ_2=0.05, μ_3=0.1

β_5	β_6	availability$[AV_p]$		
		$\emptyset$ =0.02	$\emptyset$ =0.03	$\emptyset$ =0.04
0.1	0.05	.36190	.42333	.46261
	0.10	.39204	.45860	.50115
	0.15	.40322	.47170	.51546
0.25	0.05	.37939	.44381	.48499
	0.10	.41267	.48275	.52753
	0.15	.42510	.49728	.54244
0.50	0.05	.38561	.45109	.49294
	0.10	.42004	.49137	.53695
	0.15	.43293	.50644	.55342

From the table 5.2-1 it can be inferred that providing buffer for 5 to 6 hrs (time to maintenance for feeding system) for raw juice processing and buffer for 2 to 3 hrs (repair time refining system) for clear juice processing would give good results. The plant availability of the system, (when repair time for juice screen is four hours and for clarifier 10 hrs) is obtained using equation 5.2.1 as:

$[AV_p]=[(1.15*.8333)*(1.1*.877193)*(.6106156)]$

$=.5646$

which is much higher than previous result given in chapter-2 under the similar conditions.

Total reliability of the system can further be increased by providing standby units at the critical failure points.

5.3 MAINTENANCE IN PAPER MILL

In paper mill the system performance can be improved by providing adequate maintenance for various subsystems as described below:

a) **Digester:**

The common precautions to be observed in its operation are Checking the digester walls, steam valves and blow up valves. Periodic checks lead to reduced intermediate failures (checking should normally be scheduled during shutdowns).

b) **Decker:**

The following regular checks are recommended :

(i) lubrication in bearings

(ii) oil level in every gear box

(iii) level of vibration. Vibrations may arise due to worn-out bearing, shafts, gears, missalignments etc. In case such faults are detected, the gear box should be replaced.

(iv) An unskilled worker be employed to keep a watch on the vacuum maintained at surface. Improper rolling of pulp on decker cylinder be reported and immediate repairs be undertaken.

Through the above measures, it is possible to achieve a failure rate in the range of 0.025 and 0.02

c) **Screen:**

Maintenance procedure as adopted for decker if applied to screen would help to maintain the failure rate (α_{10}) between once in 500 hrs to 100 hrs whereas its repair time has been found to vary between 2.5 and 5 hrs.

d) **Vacuum pumps:**

Providing two vacuum pumps as standby and immediate start of the repairs in case of their failure would help in achieving a low failure rate (σ_{8}). However it is normally observed that the effect of vacuum pump failure on the system performance is negligible.

e) **Opener:**

Providing a screen before the opener to remove any foreign material, iron etc. in addition to the precautions given in the instruction manual could lead to very low rates of failure (α_{14}) in the opener system.This may be of the order of once in 100 hrs whereas, the repair can be done quickly by a skilled worker in about 2.5 hrs.

Taking the following failure and repair rates, availability values for various systems have been calculated as below. The effect of failure & repairs of the decker (α_7, β_7) and screen

(α_{10}, β_{10}) on system availability is tabulated in tables 5.3-1 to 5.3-4 for α_6=0.0, α_7=.001 to .01, β_7=0.2 to 0.4, α_8=α_9=0.01, β_8=β_9=0.2, α_{10}=.002 to .006, β_{10}=0.2 to 0.4, α_{12}=.005, β_{12}=0.2 α_{11}=.006, β_{11}=0.5, σ_8=0.0, α_{14}=0.01, β_{14}=0.2.

Special case:

a) Availability of the process for white paper production [WAV] (putting the values of above failure and repair rates in equation 3.9.1) is given by equation (5.3.1):

$$[WAV]=\frac{.859696451}{[(1.118775+1.1025\alpha_7/\beta_7)(1.0376742+1.02\alpha_{10}/\beta_{10}]} \quad\text{--(5.3.1)}$$

Table 5.3-1: Effect of failure and repair rate of decker, failure rate of screen (β_{10}=0.2).

α_7	α_{10}	Availability[WAV] β_7 =0.2	β_7 =0.3	β_7 =0.4
.001	.002	.72998	.73092	.73152
	.004	.72294	.72387	.72447
	.006	.71604	.71696	.71755
.005	.002	.71569	.72147	.72440
	.004	.70879	.71452	.71741
	.006	.70202	.70769	.71056
.010	.002	.69888	.71000	.71569
	.004	.69214	.70314	.70879
	.006	.68554	.69644	.70202

Table 5.3-2: Effect of failure and repair rate in decker, failure rate of screen (β_{10}=0.4)

α_7	α_{10}	Availability[WAV]		
		β_7 =0.2	β_7 =0.3	β_7 =0.4
.001	.002	.73355	.73449	.73510
	.004	.72998	.73092	.73152
	.006	.72644	.72738	.72797
.005	.002	.71919	.72500	.72794
	.004	.71569	.72147	.72440
	.006	.71222	.71776	.72089
.010	.002	.70789	.71347	.71919
	.004	.69884	.71000	.71569
	.006	.70101	.70656	.71222

b) For the production of brown paper the availability of the process [BAV] is given (by putting the values of failure and repair rates and bypassing the bleaching system in equation 3.9.1) by equation (5.3.2):

$$[BAV]=\frac{.919875635}{[(1.118775+1.1025\alpha_7/\beta_7)(1.0376742+1.02\alpha_{10}/\beta_{10})]} \quad \text{--(5.3.2)}$$

Table 5.3-3: Effect of failure and repair rate in decker, failure rate of screen with β_{10}=0.2

α_7	α_{10}	Availability[BAV]		
		β_7 =0.2	β_7 =0.3	β_7 =0.4
.001	.002	.78107	.78208	.78272
	.004	.77354	.77454	.77518
	.006	.76616	.76715	.76778
.005	.002	.76579	.77197	.77510
	.004	.75840	.76453	.77339
	.006	.75116	.75723	.76030
.010	.002	.74781	.75970	.76579
	.004	.74060	.75237	.75840
	.006	.73353	.74519	.75210

Table 5.3-4: Effect of failure & repair rate in decker, failure rate in screen with β_{10}=0.4

α_7	α_{10}	Availability[BAV]		
		β_7 =0.2	β_7 =0.3	β_7 =0.4
.001	.002	.78489	.78597	.79074
	.004	.78107	.78208	.78272
	.006	.77729	.77829	.77893
.005	.002	.76953	.77575	.77890
	.004	.76579	.77197	.77510
	.006	.76208	.76823	.77135
.010	.002	.75146	.76341	.76953
	.004	.74781	.75970	.76579
	.006	.74418	.75602	.76208

Comparing the values given in table 3.9-1 with those in tables 5.3-1 & 5.3-2 it can be observed that through planned maintenance & close watch of the system functioning, the failure in the decker of pulping system & screen in washing system can be reduced which improve the availability of the total process. Typical values of failures that can be achieved are once in 1000 hrs for decker in pulping system & once in 500 hrs for screen, the repair time for both the units is 2.5 hrs.

Similarly comparing the values given in table 3.9-3 with those in tables 5.3-3 & 5.3-4, it can be observed that through maintenance planning the availability of the brown paper production process with the same failure & repair rate in decker and screen can be improved and would be of the order of 79 percent. Loss in production could also be reduced by providing buffers of sufficient capacity after pulping system, washing system, bleaching system and screening system so that any succeeding part of the system can be made operative for some defined period even the preceeding system has stopped due to unscheduled failure.

5.4 MAINTENANCE IN FERTILIZER PLANT

Maintenance plan for various units of the urea fertilizer plant has been discussed under the following heads:

a) **Ammonia preheater:**

The following maintenance procedure is recommended.

i) checking of all the tubes thoroughly during scheduled maintenance. This is planned after every 1000 hrs of plant running. This step would ensure very small failure rate (α_3=0.0)

b) **Liquid Ammonia feed pump & recycle solution feed pump:**

The following should be closely monitored in these subsystems:

i) lubrication of the bearings and their temperature,

ii) auto start of oil pump, oil level, oil temperature, pressure difference across filter, differential pressure of sealing water,

iii) immediate attention for the repair of the pump be given irrespective of its standby unit

These measures have been found to reduce the failure rate once in 600 hrs in liquid ammonia feed pump and once in 400 hrs in recycle solution feed pump.

c) **Reboiler, low and high pressure absorber, gas separator and heat exchanger:**

The maintenance must be planned in advance and thorough checking of each part be carried out during the period of shut down which is organized after every 1000 hrs of plant operation. This would ensure failure free running of the plant i.e. $\alpha_i=0.0$ for i=6,7,8,9,10,11.

d) **Screw conveyor and distributor:**

Failure in these units occur mainly due to chocking of excess material, Providing an unskilled worker who can keep a regular watch and report any malfunctioning immediately would reduce the failure time in screw conveyor from 200 hrs to 400 hrs and no failure in the distributor T_{10} =0.0

e) **Vacuum generator:**

Effort must be made to achieve low failure rate for this unit and in no case it should exceed once in 200 hours. i.e. if the failure exceeds this limit then the equipment is to be replaced by new one . The repair in the failed unit be started immediately by a skilled worker and the instruction be issued for its thorough checking.

Accounting the above maintenance programme in various units and putting the assumed values of failure and repair rates in equation 4.6.1 the availability of the urea fertilizer production process with reduced failure rate and reduced repair time is given as:

$$[AV_p]=\frac{.901317895}{[(1.095734+21.632T_1+5.408T_3)\{1.02875+2(T_7+T_{11})\}]} \quad \text{--(5.4.1)}$$

Table 5.3-1: Effect of failure rate of vacuum generator, centrifuge, screw conveyor and belt conveyor

T_1	T_3	T_7	Availability[AV]			
			T_{11}=.005	T_{11}=.010	T_{11}=.015	T_{11}=.020
.001	.001	.010	.75821	.75111	.74415	.73732
		.015	.75749	.74415	.73734	.73061
		.020	.74415	.73732	.73061	.72402
	.005	.010	.74388	.73692	.73008	.72338
		.015	.74317	.73009	.72338	.71679
		.020	.73008	.72338	.71679	.71033
	.010	.010	.72671	.71991	.71323	.70668
		.015	.72602	.71323	.70668	.70025
		.020	.71323	.70668	.70025	.69393
.005	.010	.010	.70402	.69743	.69097	.68462
		.015	.70335	.69091	.68462	.67839
		.020	.69091	.68462	.67839	.67227
	.005	.010	.69159	.68511	.67876	.67253
		.015	.69093	.67876	.67253	.66641
		.020	.67876	.67253	.66641	.66040
	.01	.010	.67672	.67039	.66417	.65807
		.015	.67608	.66417	.65807	.65208
		.020	.66417	.65807	.65208	.64620

Comparing the table 5.3-1 with 4.6-2 we observe that through proper maintenance planning the availability of the system can be increased by 5%. Further improvement in the system availability is achieved providing standby units in the CO_2 booster and CO_2 high pressure compressor i.e reducing the failure rate to T_1=T_3=0.0, which would yield AV_3=.98709, thus improving the availability of total system by about 2%.

Kumar-et-al (1989) have suggested some measures to be adopted by the manager/ section incharge of the plant to reduce unwanted failures in the system through the following steps:

i) reduce the delay in information to the section incharge,

ii) provide instruction manuals and supporting software,

iii) minimizing the delay in starting the repairs,

iv) trained workers who can undertake repairs of the failed equipment efficiently. Their knowledge and skill be updated periodically through education/training,

v) use of scientific approach for maintenance/repairs,

vi) study the cause of increased failure rate of units.

CHAPTER-6

RESOURCE ALLOCATION IN PROCESS INDUSTRIES

6.1 INTRODUCTION:

Achieveing economic and reliable performance of the types of systems, discussed earlier, is important for their survival in commercial world . Several steps that can be taken to achieve this are the use of large safety factors, reducing the system complexity , increasing use of reliable constituent components, planning the maintenance and repair schedule etc.

For an existing system , planned maintenance and repair schedule are effective means of ensuring high system reliability. In this chapter the process industry has been modelled as a k stage system in series and the effort needed for its maintenance (or the benefit derived there from) has been expressed as a function of input variables e.g. cost and manpower with a view to optimize the objective function (maintenance effort).

6.2 THE MODEL:

A process industry normally consists of k stages in series operating under constraints such as , availability of maintenance resources , manpower etc . Such a problem can be treated as a multistage decision problem. At stage j, decision must be made regarding the amount of resource to be allocated to activity j (i.e. c_j). The decision for the kth stage of the problem can be made on the basis of allocations made at the previous k-1 stages. The optimum allocation (c_j, $j=1,2,\ldots,k$) would also depend on the total quantity of resource ϵ available for allocation to k stages. If the stage j comprises of x_j number of components with reliability p_j, then the resource allocated at jth stage will be $x_j = (c_j/F_1)$ or $c_j = F_1 x_j$.

Whereas, F_1 is known as coefficient for components cost.

Reliability of successful operation of stage 'j' $R_j(c_j)$ when resource allocated to that stage is (c_j) [Bellman and Dreyfus E.(1962), Barlow, R.E.(1965), Misra K.B (1971)] is given by.

$$R_j(c_j)=[1.-\{1.-p_j\}^{(c_j/F_1)}]$$

Since all the k stages are in series,the overall reliability of the system is given by:

$$R_s=R_1*R_2*.....*R_j=\prod_{j=1}^{k} R_j(c_j)=\prod_{j=1}^{k}[1.-\{1.-p_j\}^{(c_j/F_1)}]$$

Taking log of both sides we get :

$$\ln R_s=\ln R_1+\ln R_2+......+\ln R_j=\sum_{j=1}^{k} \emptyset_j(c_j)=Z \text{ (say)}$$

where

$$\emptyset_j(c_j)=\ln R_j(c_j)=\ln[1.-\{1.-p_j\}^{(c_j/F_1)}].$$

Now the problem before the management is:

$$\text{Maximize } Z = \sum_{j=1}^{k} \emptyset_j(c_j) \quad ,c_j>0,\ j=1,2,....,k \qquad ---(6.2.1)$$

subject to constraints

$$\sum_{j=1}^{k} c_j x_j \le c_1, \text{ (maintenance resource constraints)}$$

$$\sum_{j=1}^{k} m_j \bar{c}_j \le c_2 \quad \text{(maintenance manpower budget constraints) and } c_1>c_2$$

c_1=total maintenance resource available(excluding manpower)

c_2=total available manpower budget for maintenance

Where x_j and m_j are the number of components and manpower respectively at the jth stage and are known beforehand. Since manpower required for maintenance depends on the number of units/components at the stage j hence manpower cost c_j can be taken proportional to c_j i.e. $c_j=F_2c_j$ (i.e. for more number of components cost will be more hence manpower cost will also be more (in general). Where F_2 is known as coefficient of manpower cost and lies $0<F_2<1$.

Introducing Lagrange's multiplier the problem becomes:

$$\text{Maximize } Z_1=\sum_{j=1}^{k} \emptyset_j(c_j)-\lambda\sum_{j=1}^{k} m_jc_jF_2 \quad (c_j>0) \qquad \ldots(6.2.2)$$

subject to

$$\sum_{j=1}^{k} c_jx_j\le c$$

The recursive equation for 'n' stage problem is as follows:

$$f_n(\epsilon)=\underset{c_n}{\text{Max}}[\ln \{1-\{1-p_j\}^{(c_j/F_1)} -\lambda m_nc_nF_2 + f_{n-1}(\epsilon - c_nx_n)] \quad ..(6.2.3)$$

Raw cost data for the operation of three plants have been obtained from their respective accounts books. For the missing data use has been made of the experience and judgement of the experts.

Based on the information thus gathered estimates were made regarding allocation of optimum capital to each stage so as to achieve maximum availability.

For different industries the following values for component cost coefficients (F_1) have been suggested by the concerned plant personnel:

Sugar F_1=5.0 ; Paper F_1=10.0 ; Fertilizer F_1=6.0. whereas F_2 for each case has been taken as 0.8. The values of best possible steady state availabilities have been taken for respective stages from the analysis given in chapters 2,3 & 4 for sugar, paper and fertilizer industries respectively. The data for sugar, paper and fertilizer industries are tabulated below in table 6.2-1.

Table 6.2-1: Data table

Stages	1	2	3	4	5	6
Sugar industry						
system availability	.85	.80	.62			
no.of component	4	4	5			
no. of personnel	7	4	9			
permitted range of maintenance cost	80.0 to 110.0					
permitted range of manpower cost	120.0 to 155.0					
Paper industry						
system availability	.92	.75	.90	.70	.72	.70
no. of component	5	3	3	2	4	4
no. of personnel	8	5	4	3	6	10
permitted range of maintenance cost	300.0 to 400.0					
permitted range of manpower cost	500.0 to 700.0					
Fertilizer industry:						
system reliability	.80	.95	.85	.90		
no. of component	5	4	5	3		
no. of personnel	8	3	6	5		
permitted range of maintenance cost	90.0 to 115					
permitted range of manpower cost	120.0 to 165.0					

Starting with the first stage for each industry, a table 6.2-2 n be prepared for each stage for the given values of the state nctions ϵ and using the recursive relationship . The value of location for which state function is maximum found out for each lue of λ. These are checked against the available resources. en a new value of λ is chosen and the allocation is repeated. e process is continued till the given constraints are tisfied. Table 6.2-3 gives the values of allocated money with fferent value of Lagrange multiplier λ.

ble 6.2-2: Process of computation for sugar industry

currence formula used is

$$(\epsilon)= \text{Max}\,[\ln\{1-(1-p_j)^{(c_j/5)}\}-.8\lambda m_n c_n + f_{n-1}(\epsilon - c_n x_n)$$

d $x_j c_j \le \epsilon$

λ	.002		|		.0025		|		.0015	
stage	f(ε)	c(ε)|	ε	stage	f(ε)	c(ε)|	ε	stage	f(ε)	c(ε
1				1				1		
	-2.41364846	1	5		-1.043742364	5	10		-0.57387141	10
	-1.029742364	5	10		-0.62987714	10	20		-0.330518929	20
	-0.601877141	10	15		-0.485791085	15	24		-0.309896281	24
	-0.443791085	15	20		-0.442518929	20	25		-0.307998732	25
	-0.386518929	20	21		-0.440675205	21	26		-0.307124268	26
	-0.377342192	23	22		-0.440480059	22	27		-0.30716300	26
	-0.377096281	24	23		-0.441742193	22	28		-0.308018921	26
	-0.377998732	24	24		-0.444296281	22				
	-0.379924268	24								
2				2				2		
	-2.9433097	1	10		-1.113263655	10	10		-0.947907868	10
	-1.51394895	5	20		-0.82362361	20	20		-0.626267819	20
	-1.03387982	10	25		-0.784059549	25	30		-0.544822738	30
	-0.828443187	15	28		-0.775479903	28	32		-0.539925667	32
	-0.728239832	20	29		-0.774443988	29	34		-0.53734722	34
	-0.680675771	25	30		-0.774178529	30	35		-0.536801767	35
	-0.662794751	30	31		-0.774612276	30	36		-0.536694836	36
	-0.661628498	31	32		-0.775681458	30	37		-0.536988567	36
	-0.66109768	32								
	-0.661145077	32								
	-0.661719233	32								

3			3			3	
-3.946615781	1	10	-2.090705389	10	10	-1.781221696	1(
-1.94162454	10	20	-1.75246635	20	20	-1.370982657	2(
-1.56738501	20	28	-1.691187022	28	30	-1.236321485	3(
-1.468724329	30	29	-1.689959887	29	36	-1.210845624	3
-1.463155676	33	30	-1.689805178	30	38	-1.208145656	3
-1.462985303	34	31	-1.690645354	30	39	-1.20768489	3
-1.463565635	34	32	-1.692410323	30	40	-1.20777000	3

ble 6.2-3: Cost allocation with different values of λ

λ	.0005	.00075	.001	.0015	.002	.0025	.(
gar industry:							
location				26,36,39	24,32,34	22,30,30	
intenance st				101	90	82	
npower cost				151.5	135.2	122.5	
timum liability				.677348	.60666	.54782	
st of sales				470.82	436.619	409.84	
per industry:							
location	56,67,51, 65,84,71	48,61,46, 59,72,60	43,55,42, 54,64,60		32,41,33, 43,46,41		
intenance st	394	346	318		236		
npower cost	670.3	586.3	543.5		399.533		
timum liability	.70849	.59178	.550681		.31589		
st of sales	1354.03	1151.71	1074.39		800.758		
rtilizer dustry:							
location			42,31, 42,27		31,26, 32,22	--	25, 27,
intenance st			142		111		94
npower cost			185.85		161.8		121
timum liability			.78896		.635444		.5
st of sales			558.66		473.3		411

Table 6.2-3 clearly shows that decrease in value of λ increases the availability, which leads to the requirement of more money both for maintenance and manpower. Hence subject to the available resources an appropriate value of λ is taken so as to allocate the money to each stage for achieving optimum system reliability i.e for maximum profit with available factory conditions. Also for a given value of λ a relation giving optimum reliability with minimum allocated resources can be achieved by differentiating the equation 6.2.3 with respect to cost c_j and equating to zero; this yields

$$\lambda = \frac{-[\{1-p_j\}^{(c_j/F_1)}]^{-F_1} \ln(1-p_j)}{F_m\, m_n[1-\{1-p_j\}^{(c_j/F_1)}]} \quad ....(6.2.4)$$

Since $[d^m f_n(\epsilon)/dc_j]$ is negative for $c_j>0$ hence the relation given by (6.2.3)is the condition for maximum reliability for a given value of money.

6.3 ECONOMIC PRODUCTION CHART:

The data in table 6.2-3 will guide the process engineer to chose an appropriate level of maintenance according to his factory requirements. However a certain minimum level must be maintained so as to achieve the minimum required profit. Analysis shows that the system availability increases with the increase of maintenance and manpower cost. Profit increases with the increase of availability and profit fluctuates with the increase of variable cost (i.e. maintenance cost + manpower cost).

Considering that sales are proportional to system availability (assuming that the fixed cost is about 30 % of the total cost), the relation for cost of sales C_s is given as:

C_s= Maximum Av* [maintenance cost + manpower cost] + Fixed cost

Sales cost for sugar and urea product is taken as 10 units per ton of production. Sales cost for paper product is taken as 20 units per ton of production.

Fig 6:1 which is based on the information given in table 6.2-3 shows that break even point (B E P) for sugar production would be at 36 % availability. The gross profit increases linearly beyond 36% system availability. Profit at 40% availability is 30 units while at 50% it is 105 units. Hence more facility we provide to improve system availability more profit we achieve irrespective of all expenditures.

Similarly B E P for paper industry is found at 50.5% . The fig. 6:2 shows that increase in availability from 50.5% to 60% yields a profit of 40 units only whereas for 70% availability the profit is equal to 65 units.

From fig 6:3 it can be noticed that for urea plant B E P is low i.e. 34% and increase in profit is also large at high system availability.

The analysis presented herein would help the process engineers to consider the application of optimization techniques in making a decision regarding resource allocation. It is hoped that the technique for the problem modelling and controlling the process through optimization will motivate the personnel to undertake creative investigations so that the tendency of accepting the past practice without proper scrutiny is minimized.

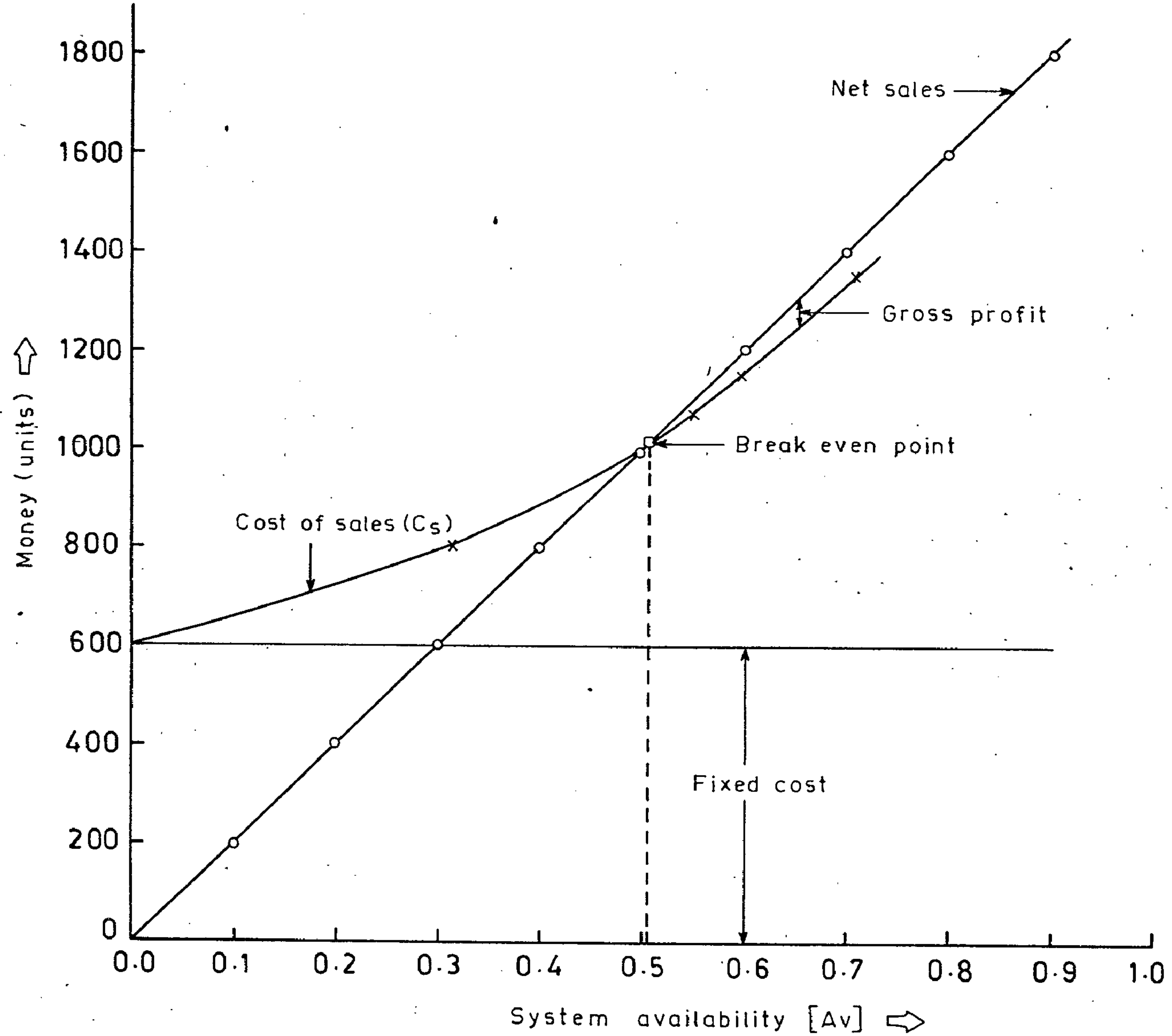


Fig. 6:2 Economic chart for paper industry.

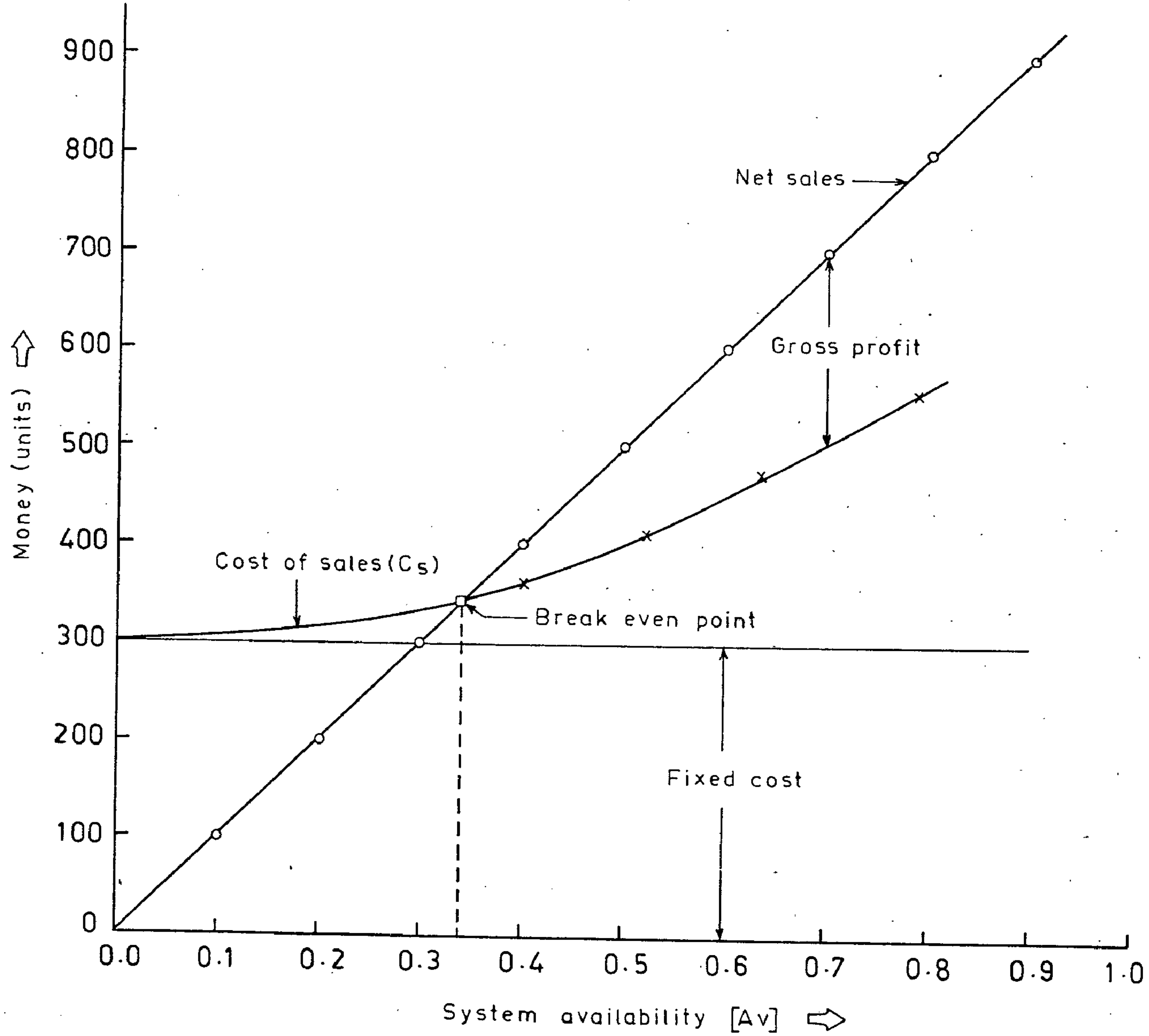


Fig. 6:3 Economic chart for urea fertilizer industry.

CHAPTER -7

CONCLUSIONS AND SCOPE FOR FUTURE WORK

7.1 CONCLUSION

The literature survey indicates that a small work has been done in the area of reliability of process industries. In this thesis important aspects like reliability, availability, MTTF and operational behaviour have been discussed in detail for sugar, paper and fertilizer industries. Based on the work presented in previous chapters the following conclusions can be derived.

7.1.a SUGAR PLANT:

a)feeding system :

i) failure rate in this system be controlled in the following order of preference- crushing, sugar cane supply, boiler and bagasse carrying unit.

ii) for achieving about 70 % availability the repair rate must be high so that repair for any type of failure would not take more than 3 hrs.

b) refining system:

iii) for achieving 77% availability of the refining system, the failure rate should be controlled as follows:

for juice screen once in 200 hrs,

for clarifier once in 40 hrs,

for heating plant once in 100 hrs

and if time to failure in sulphonation plant is kept above 50 hrs then system availability can be better than 77.5%.

iv) if the repair rate in the three units is kept as follows: juice screen once in 2 hrs, clarifier once in 5 hrs, heating plant once in 10 hrs, then it is possible to achieve an availability of 70 %.

v) repair facilities may be allocated in the following order of preference.

clarifier, Juice screen, heating plant and sulphonation system.

c) **crystallisation system:**

vi) For reliable operation of the system, means should be provided to limit the common cause failure in evaporator, cooking pans and crystallizer.

vii) The failure rate for the system must be controlled in following order of preference through proper maintenance.

cooking pans, centrifuges, crystallizer, evaporator and sugar carrying system (D5)

viii) Repair priorities should also be provided in the same order as in (vii) to maintain high system availability.

ix) In order to achieve a reasonable value of plant availability, when considered as a whole, the juice flow must be through juice storage tank having excess juice for 5 to 6 hrs of operation in case of failure of feeding system. During that period the maintenance of feeding system must be completed.

x) Similarly a tank is also must for clean juice to supply the juice to crystallisation system for atleast 2 to 3 hrs of operation in case of failure of refining system and the maintenance of the failed system must be completed in that period.

7.1.b. PAPER MILL

a) Feeding system:

i) Special care must be taken for the maintenance of the blower so that failures may be avoided or minimized (i.e. a skilled worker be provided at the blower and efforts be made to achieve its prompt repairs in case of failures).

ii) repair priorities in the feeding system can be fixed in the following order of preference - blower, chain conveyor, belt conveyor, bucket elevator and standby unit.

b) Pulping system:

iii) failure rate in this case must be controlled in the following order of preference using appropriate maintenance procedures.

decker, opener, knotter and digester.

c) Washing system:

iv) failure through maintenance be controlled and repair priority be given in the following order- screen, decker and cleaner.

vi) For screen the repair time limit be fixed at 5 hrs.

c) Bleaching system:

vii) Attention must be given in the following order to control the failure and reduce the repair time- filter, opener.

viii) repair time limit must be fixed at 4 hrs for both the units.

d) **Screening system:**

ix) failure and repair times should be controlled in the following order of preference- decker, filter and screen.

e) **Paper production system:**

x) The special failure (failure due to steam supply) rate must be kept low. Since its repair takes long time. So the time to failure be kept at once in 100 hrs and its repair must be done on priority basis within 10 hrs.

xi) Failures and repairs must be done in the following order of preference- wiremesh, synthetic belt, vacuum pumps and rollers.

x) The plant shutdown must take place after every 40 days to replace wiremesh & synthetic belt.

7.1.c. **FERTILIZER PLANT**

a) **Urea synthesis system:**

i) Failure & repair times must be controlled in the following order of preference- CO_2 high pressure compressor, CO_2 compressor and Ammonia preheater.

Attention should be given to liquid ammonia feed pump and recycle solution feed pump so as to achieve early repairs.

b) **Decomposition system:**

The analysis shows that since there is no mechanical operation in any part of the system hence failure of the system is analysed only through quality level and the quantity of urea production. If quality or quantity goes down beyond a limit then a shutdown must be declared to perform the overall maintenance.

c) Crystallisation system:

Failure and repair times must be controlled in the following order of preference through maintenance.

crystallizer pump, slurry feed pump, vacuum generator, crystallizer and centrifuges.

d) Urea Prilling system:

Attention should be given to controll the failure rate in screw conveyor and strainer.

The failure and repair times must be controlled in the following order of preference- screw conveyor, strainer, cyclone, melter and distributor.

Advanced planning for equipment repair should be undertaken during shutdown and preventive maintenance should be arranged for critical equipments.

For the conditions assumed the following values of break even system availability have been evaluated. Sugar and fertilizer plants- 35%; paper industry 50.5%.

However the operating availability level for sugar and fertilizer should be maintained at about 70%, while for paper industry it should be about 80% (approx).

7.2. SCOPE FOR FUTURE WORK

The method of analysis for evaluation of reliability can further be extended in the following directions:

i) a data-bank can be developed containing history cards of failure and repairs of each component,

ii) analysis which account for repair priorities can be developed for each system ,

iii) similar studies can be extended to evaluate system behaviour in petroleum ,food processing and chemical industries ,

iv) advance estimates for repair planning can be developed,

v) methodology for requirements of manpower, material, inventory and budget allocation can be developed based on the analysis presented here,

vi) the work also be extended to arbitrary repairs and failure time distributions.

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1. Reliability analysis of the feeding system in the paper industry, Micro. & reliab., 28(2), 1988.
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16. Availability Analysis of the crystallization system in the sugar industry under common cause failure ~~(IEEE trans. on reliability, revised)~~ IEEE, Trans on Reliab. Vol 41,(1) 1992 pp. 85-91. ~~revision~~).

17. Operational behaviour and profit function for bleaching and screening system in paper industry (microelectro. & reliab. U.K)