PULP MILL EFFLUENT TREATMENT USING COMPUTER SIMULATION TECHNIQUES

by

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ABSTRACT

In this study a validated model of the suspended solids and biochemical oxygen demand effluents of a kraft pulp mill was developed by superimposing stochastic chemical spills and normal process discharge.

The effluent generated is input into a validated clarifier aerobic stabilization lagoon waste treatment model. Utilizing cost relationship derived from the literature, capital and operating costs for various system configurations and sizes were determined.

Numerous experiments were run to evaluate the waste treatment system's sensitivity to influent concentration, temperature and hydraulic load. A least cost system configuration was determined for any desired effluent level. The implications of a spill basin and increased spill frequency were evaluated.

It was concluded that the models could be a valuable planning tool to pulp mill management.

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INTRODUCTION

Pulp and paper is a major industry in British Columbia. In 1973 there were 22 pulp mills in the province, 18 of which use the kraft pulping process. Their total production for 1972 was 1,853,000 tons of wood pulp accounting for 37% of the provinces forest exports. In 1969 the forest industry employed 17,500 people and had manufacturing sales of 1.7 billion dollars (Stephenson and Nemetz, 1974).

British Columbia exports its forest products to over 40 countries of which Japan, the United States and Great Britain are the biggest customers, accounting for 43% of the exports. The pulp and paper market has about the same number of customers with the United States being the largest. A majority of the exports is newsprint (approx. 79.8%) while the remainder is primarily bleached pulp.

The pulp and paper process generates a considerable amount of air and water pollution. The severity of the problem was emphasized in a recent study by the Swedish Environment Protection Board. They state that as of 1972 the forest industry was responsible for more than 80% of the total pollution, expressed as BOD (biochemical oxygen demand), from domestic and industrial waste in Sweden, and 80% of the forest industry contribution was from pulp mills (Lekander, 1972). The proportions for Canada are probably very similar since both countries have a similar dependence on the forest industry.

Before 1950 the industry felt that the pulping effluents would be easily absorbed by the environment and little thought was given to waste treatment. As a result tons of toxic chemicals and wood fiber were released into the natural water systems each day. However in the fifties and sixties pulp mill operation costs rose and it became economically advantageous to develop more efficient ways of recycling the process chemicals and the lost fibers.

During this same period the lakes and rivers became increasingly more respected as resources to be protected and maintained. As a consequence of this combined economic and environmental push the pulping industry has become increasingly more concerned with mill wastes and their subsequent treatment.

Over the past decade hundreds of technical and economic studies have been carried out on treatment of pulp mill wastes. Groups such as the National Council of Paper Industry for Air and Stream Improvement Inc. (NCASI), B.C. Research, the Canadian Department of the Environment, and the U.S. Environmental Protection Agency have all been active in this area. However, despite all the new information being generated by these groups, mill management considering waste treatment alternatives can still not be sure how their particular mill situation will be handled by any given waste treatment system. There is great variability in mill effluent quality both between mills and within a single mill from day to day. Over one third of the total chemical and fiber losses are due to accidental spills (Lekander, 1972). Spills are usually due to faulty equipment, incorrect control or the human factor (negligence, etc.).

It is these accidental surges of toxic chemicals and wood fiber which represent a threat to the stability of operation of a waste treatment system. They are also hard to design against. A waste treatment system which can handle such operational transients efficiently may be many times the size of a system needed for normal operating conditions and exponentially more expensive.

Mill management therefore faces a difficult tradeoff problem, namely reliability of the system in meeting required discharge levels versus costs of the waste treatment plant. Management obviously would like to minimize costs but also wants to be sure that the investment is effective in meeting its original purpose.

The problem is to study the systems behaviour in response to typical inputs and determine subsequent costs and efficiencies of operation. There are techniques which facilitate bringing the real world situation into the laboratory. These permit the decision maker to experiment with different policies and investigate their effect over time without worrying about design failures. The techniques referred to are computer simulation and mathematical modelling. They have been applied to many industrial processes with varying amounts of success. Their development and use can greatly increase the understanding of the problem and provide invaluable information on feasibility of proposed solutions.

CHAPTER I

THESIS DEFINED AND LITERATURE REVIEW

This study had two objectives:

1. Develop two computer simulation models. The first of the waterborne effluents generated by a kraft pulp mill and a second of the effluents subsequent modification in a waste treatment plant. Both models function on a one hour time step to give reasonable representation of the systems dynamic behaviour.
2. Use published cost relationships to study cost variability of waste treatment as a function of different system designs, efficiencies and inputs.

In the following three sections the history of the above, as reflected in the literature, is reviewed and it's implications on this study are discussed.

1.1 THE PULP MILL MODEL

Past computer simulation studies in the pulping industry have been primarily concerned with control and process problems of a chemical engineering nature. For example, Sullivan and Schoeffler (1965) presented a technique for simulating stock preparation and fourdrinier dynamics permitting evaluation of different control schemes in response to process modifications and system transients. Tehrar (1967) gave a more general approach to simultion in the pulp and paper industry. He discussed simulation and its potential to the industry and then developed a model of the wet end of a paper machine to study basis weight changes and their control. B.W. Smith (1969) developed a digital simulation of paper making systems. Using both dynamic and steady state models Smith simulated process concentration fluctuations as a consequence of flow surges in storage tanks and connecting pipes. A similar approach was taken by Henrickson and Meinander (1972) to evaluate various process design possibilities.

The published literature reveals very few attempts to model the kraft pulping process and no attempts at the complete mill (pulping and bleaching). In Carroll (1960) the kraft cooking kinetics are measured, the kraft pulping process is modelled and a non-linear technique for optimizing plant operation costs is developed. System balance equations with six independent control variables can be modified in order to maximize the objective function. Boyle and Tobias (1972), developed a new model reportedly correcting some of the deficiencies in Carroll's model.

None of the above models deal with waterborne effluents generated in a pulp mill operation. However there have been numerous data studies made in the past few years which try to establish the main sources of mill effluent and possible operational correlations. Howard and Walden (1971) analyzed over 1000 samples collected over a 40-day period from major process streams of seven B.C. kraft pulp mills. Means and variances for BOD_5 and toxicity were determined although no reliable correlation was found.

In a later study, Walden, Howard and Sheriff (1971) used multiple regression techniques to correlate BOD_5 and toxicity with mill operating data. Some interesting in-plant correlations were obtained, however, correlations for combined mill outfalls were poor.

The Swedish Steam Users Association (1974) made one of the first attempts to look at dynamic aspects of pulp mill losses. They looked at a pulp mill operation on different time scales with intervals ranging from .25 hrs to 1 hour. Their primary state variable was the variation of sodium salts concentration in the effluents. Using this as a measure of accidental discharges in the mill, they found that in many sewers there were temporary discharges (spills) of less than one hour duration over 50% of the time. A more extensive study, Gove (1974), described a control strategy and some analog simulation results of the impact of above normal loadings on a waste treatment plant.

For this study a "black box"[(1)] approach was used to develop the pulp mill effluent model. Regular process losses for various mill areas were generated stochastically, based on empirical data. Superimposed upon this was a sequence of spills generated from a derived distribtuion. The "black box" approach eliminates the need for a detailed model of the process. It does however sacrifice the detail and precision of a more exact model.

[(1)] The "black box" description is a general term applied to an input-output device. The black box represents a functional transform which gives the effect of input changes on output. The contents of the black box are not of interest as long as the transition is achieved in a way that reflects actual system behaviour.

This approach is supported by a statement in the Swedish Steam Users Association (1974) report which states:

> "The total discharge from a pulp or paper mill can be divided into normal process discharges, dependent on the design of the process and the equipment being used, and temporary or accidental discharges caused by disturbances to the process".

1.2 THE WASTE TREATMENT MODEL

With the growing concern for the environment in the last 10 years, waste treatment models have become an increasingly more popular tool for design and management of wastewater treatment systems. They originally were directed towards domestic sewage but in recent years many industrially oriented models have been developed.

Montgomery (1964) developed a model of a sewage treatment system which allowed effluent storage and low-flow augmentation in the receiving stream. The treatment plant was represented as an efficiency of operation relationship, and its influent was an empirical time trace which the model sampled every two hours. The interactions within the model were treated as a system of queues and service facilities. The model determined the dissolved oxygen concentration implications on the receiving stream for different river flow levels.

R. Smith (1969) developed a model for design and evaluation of waste water treatment systems using empirically derived relationships for operational efficiency and costs. The model permitted specification of various component combinations and modelled their steady state operation. However all the inputs and outputs assumed continued steady state and gave no feel for the dynamic implications of the system. Similar approaches to waste treatment design have been developed by Eilers and R. Smith (1973), R. Smith (1968) and Chainbelt Inc. (1972).

In recent years various models have been developed for specific components of waste treatment systems. Many of these models have tried to represent the dynamic behaviour of the component as a consequence of load variations. Takamatsu and Naito (1967) developed a number of mathematical models of hydraulic flow in a sedimentation basin enabling them to simulate efficiency variation as a function of turbulence and changing hydraulic loads. Naito, Takamatsu and Fan (1969) developed a mathematical model of the activated sludge process to facilitate optimizing the system's capital cost. Silveston (1969, 1971) developed residence time distributions of settling basins and used them in a simulation of mean performance of a municipal waste treatment plant. Some reasonable fits to real data were found. In Sakata and Silveston (1974) a first order chemical reaction was assumed to represent settling of a non-flocculating suspension and an exponential relationship for settling velocity was derived and verified.

In Beak-Environment Canada (1973) various mathematical models of residence time distributions for aerated lagoons were derived and verified against three operational lagoons. Other operational characteristics of the lagoon operation are also discussed and a considerable amount of summary data is presented. However, the report does not try to model the systems response to changes in input over time.

Bodenheimer (1967) is a summary paper of the treatment systems available for pulp mill wastes discussing many primary and secondary systems and their costs. A more detailed discussion of the design and operation of secondary waste treatment systems is contained in a report published by the City of Austin, Texas (1971). The principles of secondary waste treatment are summarized and the design of four major biological treatment systems (activated sludge, aerated lagoon, trickling filters and waste stabilization ponds) are discussed in considerable detail.

The need for dynamic models of wastewater treatment processes was recently emphasized in Andrews (1974). On page 263, he states:

> "....dynamic models and control systems do offer many potential benefits, however it should be emphasized that the development of dynamic models for wastewater treatment processes and the use of these models for the improvement of control strategies is a difficult task and is presently in its infancy".

Some benefits of dynamic models cited by Andrews are:

1. Performance - one can study range of plant efficiency levels rather than just average.

2. The development and evaluation of better control systems.
3. One can study start-up behaviour and evaluate alternate start-up procedures.
4. One can evaluate the process stability and study its response to system transients.

For this study a first order model of a wastewater treatment system, common to a number of B.C. pulp mills, was developed. Certain steady state assumptions were made in the model which prevent it from being dynamic in the true sense of the word. The model operated on the same time scale as the pulp mill model and gave a reasonable representation of the system's response to the pulp mill effluent over time.

1.3 WASTEWATER TREATMENT PLANT COSTS

Numerous papers and manuals are available for evaluating the costs of a wastewater treatment plant. Some even complement the costing aspects with a steady state approximation of the systems performance and allow the user to experiment with different component arrangements. [Eilers and R. Smith (1973), R. Smith (1968), Logan et al (1962)]. They are primarily for use with domestic sewage applications.

A comprehensive report on wastewater treatment systems for pulp mills was prepared by the U.S. Department of the Interior (1967). It gives the results of a national study of operational pulp mills with ranges of treatment costs experienced in the industry for different treatment processes versus mill production and age.

Reports published by NCASI have also dealt with the costs of pulp mill treatment facilities [Edde (1968), Gehm and Gove (1968)] as have other papers by Haynes (1968), White (1968), Eckenfelder and Barnard (1971) and Bower (1971).

For the purposes of this study the relationships plotted in Bower (1971) were used. They represent a summary of much of the published data and facilitate the determination of cost as a function of flow and efficiency. Bower's aerated lagoon cost curves were the only ones that could be found in the published literature.

CHAPTER II

SYSTEMS IDENTIFICATION

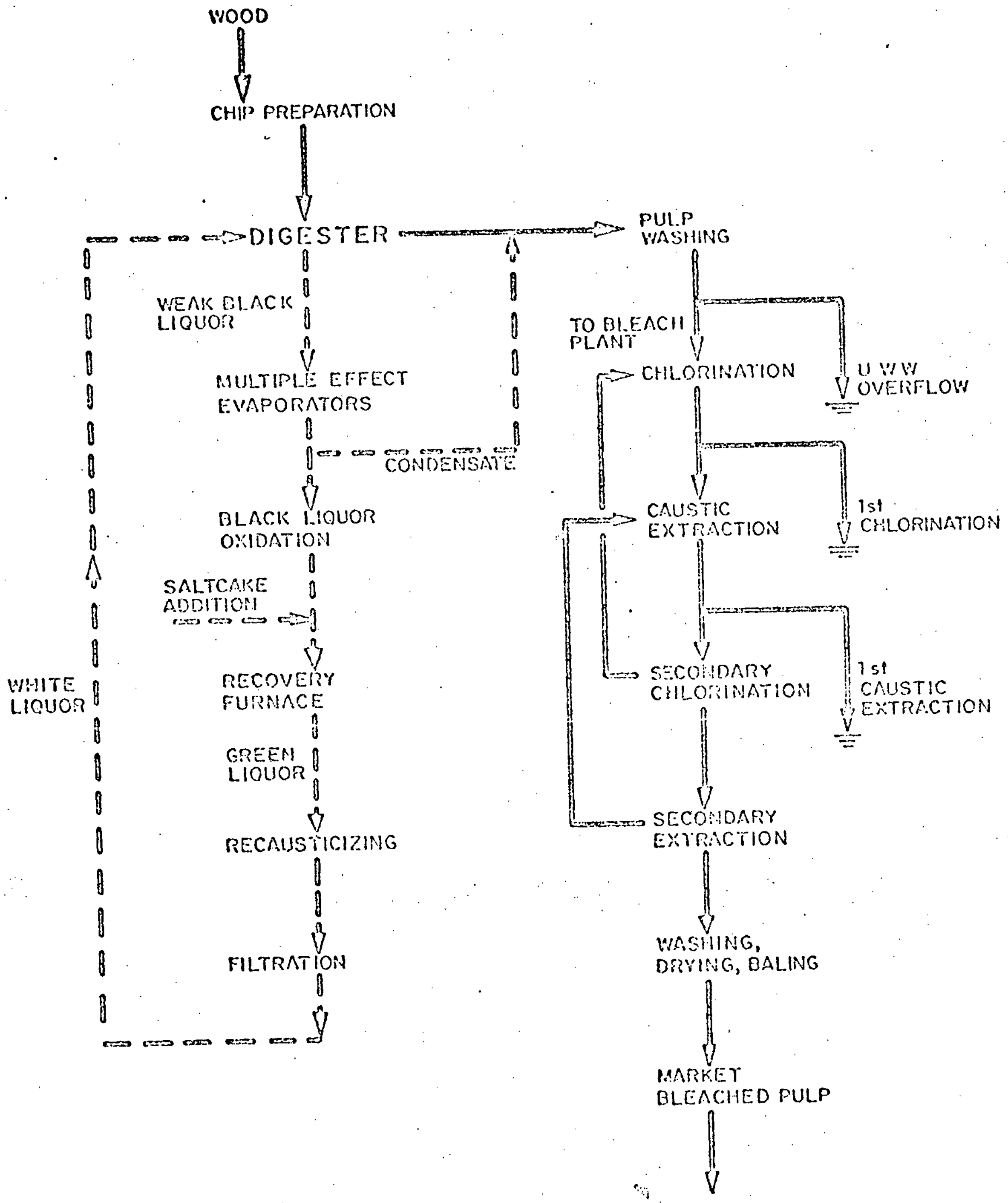
2.1 THE PULP MILL: FUNDAMENTAL PROCESSES AND RESULTING WASTEWATER

Pulping is the process by which wood is reduced to a fibrous mass. In other words it is the means of rupturing the bonds between the fibers of wood. This task can be accomplished mechanically, thermally, or chemically. In this study a mill using the primarily chemical process known as the kraft process is modelled. A flow chart of a bleached kraft mill operation can be found in Figure 2.1.

First introduced by C. S. Dahl in 1879, the kraft process separates the cellulose fibers from the lignin materials by using a digestion mixture consisting of caustic soda and sodium sulphide, together known as white liquor. The wood, which at this point is in the form of small chips, is cooked in a pressure vessel (the digester) with white liquor for approximately two to three hours. The lignin is dissolved forming a black, toxic substance known as black liquor. Black liquor contains approximately 50 percent of the original wood weight in the form of wood extractives and solubilized lignin. The black liquor is then separated from the cellulose fiber by washing the unbleached pulp (brownstock) in a number of counter current wash stages. The black liquor extracted from the pulp during the initial washing stages is returned to the chemical recovery system. Overflow from the last washer is discharged as the main process sewer from the pulping section of the mill, (unbleached white water overflow, i.e. UWW). The combined black liquors are

FIGURE 2.1

SCHEMATIC OUTLINE OF BLEACHED KRAFT MILL OPERATION



concentrated in multiple effect evaporators to produce strong black liquor which is burned in a recovery furnace to retrieve pulping chemicals. The smelt from the recovery furnace is redissolved to give "green liquor". The green liquor is recausticized, adjusted to strength and called "white liquor". The "white liquor" is reused in the digester together with variable proportions of added black liquor. Approximately 95% of the pulping chemicals are recycled and most of the soluble organic material extracted from the wood during digestion is burned in the chemical recovery furnace.

The volume of effluent from the pulping section of a kraft mill (UWW) is normally between 8,000 and 12,000 gal/ADT (ADT = air dry ton of pulp production) with a pH of 7 to 10. Howard and Walden (1971) reported from a survey of seven B. C. bleached kraft mills that the unbleached white water effluent was the most toxic of the different effluent streams.

The dark color and coarse nature of unbleached kraft pulp limit its market usage. Consequently, most mills further process the unbleached fibers to white bleached pulp. The bleaching process involves chlorination of the washed pulp and extraction of the chlorination products in an alkaline extraction stage. Because of the detrimental effect continued exposure of the fibers to chlorine has on the resultant pulp's strength, bleaching is carried out as a multistage process. Basically the system involves chlorination, at about 20°C, of the residual lignin materials remaining after digestion and brownstock washing by contacting the pulp at a consistency of 3 - 3.5% for one half to one hour with chlorine. This is followed by washing and then by caustic extraction (in NaOH) of the pulp at a consistency of 10 - 12 percent for one hour at a temperature of approximately 60°C.

The alkaline extracted pulp is subsequently washed with water and treated with further chlorine, hypochlorite and/or chlorine dioxide stages with intervening washing. Finally the pulp is dried and baled. Bleaching causes further losses of organic material from the pulp which amounts to 5 to 10 percent of the unbleached stock. These losses are discharged from the plant with the effluent.

The first chlorination effluent normally has a volume of 15,000 - 25,000 gal/ADT pulp with a pH of 2 to 3. The first caustic extraction effluent has a flow volume of between 5,000 - 8,000 gal/ADT pulp with a pH of 9 to 11. Both these sewers represent a very high percentage of the mills total pollution load.

Although the process streams mentioned above do not account for the total liquid losses in a kraft pulp mill they do represent the main sources of pollution. Superimposed upon these streams are losses from faulty equipment, process control failures and accidental spills of chemical.

Effluents from a bleached kraft pulp mill are usually discharged through two outfalls. First the alkaline (or general pulping) outfall which includes the alkaline bleaching effluent, the unbleached whitewater and residuals from the pulping and recovery areas. Second the acid outfall containing the chlorination stage bleach plant sewers. Large quantities of foam can be produced when these sewers are combined. Consequently, in mills without treatment facilities the outfalls are either a considerable distance apart or are combined and fed through a foam tank before final discharge.

The recovery process mentioned earlier,which receives the black liquor from the digestor and the brown stock washers,has the potential of being and often is one of the main polluters in the kraft pulp mill. All the chemical liquors used in the kraft process are extremely toxic and have high pollution contributions. Although the recovery process in theory is a nearly closed system the caustic nature of the liquors and other factors precipitate frequent process spills. The basic cyclic stages involved in the recovery system are:

1. Separation of the spent liquor (black liquor) from the pulp.
2. Evaporation of the liquor to a concentration of 50 - 60 percent solids.
3. Combustion of the concentrated liquor in a suitably designed furnace for separating the lignin and other organic compounds from the sodium salts by burning, for reduction of the sulphur-containing salts mostly Na_2SO_4 (salt cake) to sodium sulphide and for utilizing the heat produced to generate steam.
4. Withdrawal from the furnace of the sodium salts in molten condition and their solution in water giving green liquor.

5. Treatment (causticizing) of the green liquor with calcium hydroxide to convert the sodium carbonate in the smelt to sodium hydroxide while at the same time calcium hydroxide is converted to calcium carbonate, which is a precipitate, according to the following reaction:

$$Ca(OH)_2 + Na_2CO_3 \longrightarrow CaCO_3\downarrow + 2NaOH$$

6. Withdrawal of the causticized and clarified solution (white liquor) for use in another cycle.

The calcium carbonate separated in step 5 is usually converted to CaO in a kiln together with make up lime and then is slaked, with the green liquor and is converted by the water to calcium hydroxide and reused in step 5.

The two most widely used measures of pulp mill effluent quality are biochemical oxygen demand and suspended solids. These are now defined since they will be used extensively throughout the remainder of the study.

1. Biochemical Oxygen Demand (BOD)

BOD is a quantitative test, usually done on a 5-day basis, which indicates the rate at which oxygen is used by organic wastes in the effluent. Oxygen is used by bacteria to degrade organic constituents to carbon dioxide, water and other non-organics. For pulp mills the BOD level is proportional to the amount of dissolved wood constituents in the water.

BOD has serious implications to the natural aquatic life in the receiving stream since it too depends on the dissolved oxygen concentration in the water. If a high BOD effluent enters the stream, most of the dissolved oxygen will be used by the bacteria in degrading the organic wastes. As a result the natural aquatic life will not survive. The amount of BOD that a natural system can tolerate depends on the volume of the receiving water and its rate of flow. Its unit of measurement is mg/l or pound of BOD/ADT of pulp.

2. Suspended Solids (SS)

This refers to all material which can be filtered out of a liquid. It is also often called total suspended solids since it includes settleable solids (solids which settle in one hour) and volatile suspended solids (lost on ignition at 575°C). The suspended solids are composed mostly of fiber. They must be removed because being organic they represent a very high total oxygen demand (although not a high BOD). As a consequence they can greatly decrease the efficiency of biological waste treatment systems if allowed to build up. If dumped directly into the receiving stream SS settle and become a major threat to the aquatic life and also greatly affect the aesthetic appeal of the area. Its usual unit of measurement is mg/l or pound of SS/ADT of pulp.

The typical BOD and SS levels experienced at the main kraft mill sewers are summarized in Table 2.1.

TABLE 2.1 TYPICAL BOD AND SS LEVELS FOR KRAFT MILL SEWERS

Sewer	BOD	SS
Pulping (U.W.W.)	12 - 30 lb/ADT	10 - 15 lb/ADT
1st Chlorination	∿25 lb/ADT	1 - 2 lb/ADT
1st Caustic Extraction	∿20 lb/ADT	2 - 4 lb/ADT

The brief description given here does not refelct all the factors affecting a pulp mills BOD and SS levels. The wood species used varies between mills and has widely varying characteristics,in terms of its content of extractable materials,both seasonally and due to the trees location when harvested. Mill procedures are also varied to suit product requirements. Mill design also varies. A combination of these factors, all of which are designed to produce a product of rigid specifications, results in effluent with highly variable characteristics.

2.2 THE WASTE TREATMENT PLANT

2.2.1 Introduction

In this study two processes are modelled, a primary sedimentation tank (or clarifier) and a 5-day aerobic stabilization lagoon. The two quantitative measures of effluent loading and system efficiencies are BOD and SS. The clarifier removes primarily SS while the aerobic stabilization lagoon removes primarily BOD. Since the SS loading can greatly affect lagoon operation the clarifier precedes the lagoon.

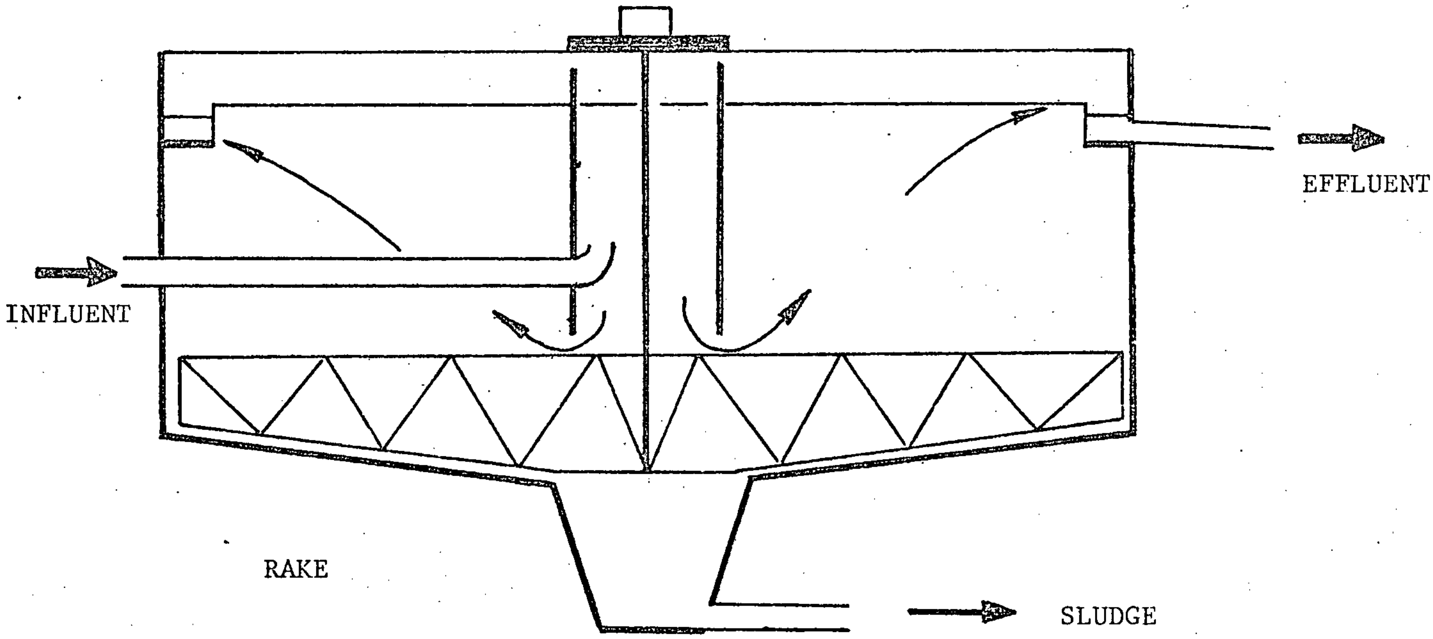


FIGURE 2.2

CIRCULAR CLARIFIER WITH CENTER FEED

The clarifier and aerobic stabilization lagoon were chosen because of their proven reliability and efficiency. With the current emphasis on protection and improvement of the environment and the increased use of effluent limits with respect to BOD and SS in the discharge to public water systems, there has developed a need for reliable, continuous performance, high rate processes. As mentioned earlier, spills are a major factor in the pulping industry and occur at a sufficient frequency to result in costly violations of desired discharge levels. Therefore a reliable system is one which can absorb sudden shocks. The system must also be equipped to efficiently remove both SS and BOD.

The clarifier, possibly followed by a settling pond, is the most efficient and effective way of removing suspended solids. It has found wide acceptance for both municipal and industrial waste. On the average clarifiers in the pulping industry are of centre feed, circular type with an ideal retention time of 3 hours and a depth of no more than 15 ft.

The aerobic stabilization lagoon,which primarily removes BOD,was chosen because of its reliability and capacity to absorb short term spills with little or no reflection in output. As a consequence of this it has found wide acceptance in the pulping industry [see Rand (1972) and Bodenheimer (1967)]. Its main disadvantage is the land area needed to provide an adequate detention time (4 to 10 days). A mill of the type being modelled in this study, with an average water flow of 65 MUSGD, requires a 15' deep lagoon of about 75 acres surface area to provide the needed retention time. Maintenance can also be a problem since biological oxidation generates suspended solids. Often this is solved by following the lagoon with a secondary clarifier or a settling pond. Generally input pH should be kept at 7.0 ± 2.0 in order to ensure bacterial survival. Also water temperature should not drop too low so as to significantly slow the biological reaction. Despite these complications however, with sufficient process control, aerated lagoons function efficiently in many areas of B.C.

2.2.2 The Clarifier

The purpose of a clarifier is to remove suspended solids (SS). Basically clarifier operation involves detaining wastewater in a large basin for a sufficient length of time so that the SS can settle to the bottom of the basin. Settled sludge is continuously removed using a motor driven revolving rake mechanism to collect and concentrate the sludge (see Figure 2.2). The clarifier design common to pulp mills is the circular type in which the waste flow enters in the centre and leaves via an overflow weir running around the circumference of the tank near the upper rim. In this study the efficiency of SS removal was assumed to be a function of the detention time and the settling characteristics of the waste being treated.

Design of a clarifier is based on fiber slowly settling through quiescent water. To be removed, the fiber must settle faster than the rise rate of the water in the clarifier. Large fibers may settle at speeds of 10 to

15 feet per hour. As they become smaller their settling rate decreases. About 92% of the particles will settle faster than 3 1/2 ft per hour (Bodenheimer, 1967).

The capital cost of a clarifier in general is proportional to its surface area (Bower,1971). To ensure an adequate detention time (Detention time = $\frac{\text{volume}}{\text{flow rate}}$) the volume must be kept constant (for an assumed steady state flow rate) implying an inverse relationship between depth and cost for any given volume. In Chapter III, an exponential approximation for the settling rate is developed.

For pulp mill wastes a nominal detention time is from 3 to 4 hours and depth is 12 to 15 ft. For a 3 hour detention time and a 15 ft deep tank with an average flow of 35 M.U.S.G.(1) day, the volume required would be,

$$\text{Vol} = \frac{35 \times 10^6 \ \frac{\text{MUSG}}{\text{day}}}{24 \ \frac{\text{Hrs}}{\text{day}}} \times 3 \text{ hrs} = 4.4 \times 10^6 \text{ US gal}$$

with a depth of 15 ft, the diameter would be,

$$D = 2\text{x} \sqrt{4.4 \times 10^6 \ \text{gal} \times .134 \ \frac{\text{ft}^3}{\text{gal}} \times \frac{1}{15 \text{ ft}} \times \frac{1}{\Pi}} \cong 224 \text{ ft}$$

2.2.3 The Aerated Lagoon

The primary purpose of the lagoon is to remove soluble BOD using biological treatment. Basically the process provides an environment in the lagoon

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(1) M.U.S.G. = million U.S. gallons

which permits bacteria to use the organic material as a substrate for growth and energy. In the aerobic stabilization lagoon dissolved oxygen assimilated by micro-organisms is supplied by mechanical aerators. The biological reactions taking place in the lagoon are summarized in the following equations:

$$\text{org material} + O_2 + NH_3 + P \xrightarrow{\text{bacteria}} \text{New cells } (C_5H_7NO_2)_{10}P + CO_2 + H_2O$$

The degradation of cell material then occurs as follows:

$$(C_5H_7NO_2)_{10}P + O_2 \longrightarrow CO_2 + H_2O + NH_3 + \text{Polysaccharides}$$

Both reactions require oxygen and the 5-day rate at which oxygen is required is the BOD_5 of the waste[(1)].

In the City of Austin, Texas (1971), the biological kinetics active in a lagoon were described. They state that if oxygen and BOD concentration in the aerobic stabilization lagoon are high, the biological reaction rate, K, can be assumed constant. For a sufficiently aerated lagoon this is a reasonable assumption for pulp mill effluent. It is also assumed that the aerator mixing is sufficient to keep all the SS in the lagoon in suspension.

To obtain a reasonable BOD reduction efficiency, the minimum recommended retention time for a lagoon is 5 days, (Bodenheimer, 1967). Lagoons vary from 6 ft to 15 ft in depth. The deeper the lagoon the stronger must be the aerators to function efficiently. However, for a given detention time (and therefore volume) the surface area available will dictate the depth.

[(1)] For the remainder of this study BOD will be written for BOD_5. The five days will be understood.

The SS generated by the oxidation in the aerobic stabilization lagoon is an insoluble material which itself has a 5-day BOD equivalent. For pulp mill wastes, Bower (1971), claims that this biological sludge is produced at a rate of .15 lb for each pound of BOD removed and that it contributes approximately .1 lb of BOD per pound of sludge generated.

Effects of temperature on BOD removal have been documented for many biological waste treatment processes in laboratory studies. The maximum removal rate generally occurs around 37°C which is the optimum temperature for the bacteria (Beak-Environment Canada, 1973). In most systems operating in colder climates the temperature becomes a major factor affecting the system's treatment efficiency. Little has been published on temperature effects in full scale aerobic stabilization lagoons however the liquid temperature within an aerobic stabilization lagoon will depend upon the rate at which heat is lost and the extent of mixing which exists. Beak-Environment Canada (1973) found lagoons with a large length-width ratio to have a roughly linear temperature decrease through the 5-day lagoon. Therefore the mean lagoon temperature can be taken as the arithmetic mean between lagoon influent and effluent temperature.

Nutrients such as nitrogen and phosphorus often must be added to a lagoon to maintain the bacteria life cycle. The dosage required is governed by the concentration of these chemicals already present and by the BOD strength of the wastewater. In this study all necessary nutrients are assumed available.

Another important factor in the operation of a lagoon is influent pH. The pH should ideally be between 6 and 8 for optimum BOD reduction of pulp mill wastes (Beak-Environment Canada 1973). To accomplish this some mills combine the acid and alkali outfalls before entering the lagoon. If this is not sufficient, possibly due to a bleach plant shut down, chemicals may be added as needed. The influent pH can experience sudden shifts as a result of spills in the mill but unless the spill is of major proportions (100,000 gallons of weak black liquor is a major spill) the lagoon can usually absorb these transients. However a continued spill over a number of hours resulting in a substantial pH shock to the system can destroy the bacteria in the lagoon and result in a system failure for a number of days. In Gove (1974), it is recommended that spill basins be constructed and mill outfalls be monitored with conductivity probes. It would then be possible to divert spills to the basin and release them later at a rate which can be handled efficiently by the lagoon. Although spills are considered in this study it was not possible to model the effluent pH.

CHAPTER III

SYSTEMS ANALYSIS

3.1 THE PULP MILL

The pulp mill model generates a typical water borne effluent time trace by sampling each hour empirical BOD and SS distributions for each of the main sewers within the mill and multiplying the results by hourly hydraulic flows. Superimposed upon this normal effluent stream is a sequence of model generated spills.

To establish the above distributions a considerable amount of data were required. Most of the data were supplied by one B. C. pulp mill. The data made available are the following:

1. Six months of conductivity charts at the mill's main outfalls with notes indicating spill locations (not complete).
2. Typical daily mill flow values for main mill sewers.
3. Some BOD and SS sampling results for the same sewers as #2.
4. Twelve months of mill daily operating summaries, six months of of which overlap with #1.
5. BOD and SS readings taken at main outfalls as required by Pollution Control Branch for same four months as #1.

Also, mill supplied samples of the following were analyzed at B. C. Research.

1. Weak black liquor
2. Strong black liquor
3. White liquor

4. Green liquor
5. Acid sewer
6. Alkali sewer
7. Recovery sewer
8. Flyash sewer
9. Recausticizing sewer
10. Machine room sewer

Additional data were also supplied by Dr. T. Howard (personal communication) from previous work at the mill.

3.1.1 SPILL DATA

A spill is an accidental discharge of chemicals frequently caused by human error, faulty control or equipment failure. Spills present a very real problem to mill management since they are next to impossible to predict and represent a financial loss as well as a pollution problem.

To incorporate spills in the model, six months of continuous conductivity charts for the main sewer outfall were analyzed. Each day mill personnel collected the charts, wrote comments as to spill locations and summarized, the past 24 hours total chemical losses expressed as Na_2SO_4 per ton of production equivalent[(1)], tons of fiber lost, and water usage for that day.

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(1) It is common practice in the pulp mills to measure chemical losses in terms of its Na_2SO_4 equivalent. The conductivity reading is proportional to the Na^+, $SO_4^=$ and $S^=$ concentrations and since sodium and sulphur are necessary constituents in the white liquor (NaOH and Na_2S) they must be replaced. Usually Na_2SO_4 (salt cake) is added in the recovery cycle to replace lost sodium and sulphur, thus the term "Na_2SO_4 equivalent".

By establishing a Na_2SO_4 loss per ton of production base level for a clean operating day the Na_2SO_4 equivalent for each spill was determined as the area under each of the spill peaks on the conductivity chart expressed as a fraction of the total area of all spills for each day. These fractions are the proportion of the above base level loss that each individual spill represents. By multiplying each fraction by the total above normal Na_2SO_4 loss for that day, the Na_2SO_4 equivalent for each spill was estimated.

This was done for a total of 178 days. About 70% of the chart indicated spills were identified as to location, although the Na_2SO_4 equivalent of most spills could be determined. Approximately three weeks of mill operation which were not monitored with the conductivity probe were removed from the data.

Mill start-ups which represent a considerable amount of chemical loss were not incorporated in the data base since the conductivity charts did not supply enough information. Their possible implications on the waste treatment system will be considered later. Two items to note are that:

1. Although a spill on the conductivity chart may last over an hour, its effect is recorded as only being felt during the hour in which it was initiated. Very few spills were over an hour in length.
2. The extra hydraulic load created by the spill was assumed negligible since even a large spill of say 100,000 gallons represents less than 3% of the hourly mill flow.

3.1.2 SPILL DATA ANALYSIS

Spill locations were broken down into three major locations with 12 sublocations. (The 12 sublocations belong to one of the three major locations).

Table 3.1 summarizes these.

TABLE 3.1 MAJOR AND MINOR SPILL LOCATIONS IN PULP MILL MODEL

MAJOR AREA					
RECOVERY-#1		RECAUST-#2		PULPING-#3	
Sub Loc'n	Name &/or Liquor	Sub Loc'n	Name &/or Liquor	Sub Loc'n	Name &/or Liquor
3	Weak black liquor	5	Green liquor	1	Wood Prep'n
4	Precipitators -strong black liq.	6	White liquor	2	Knots-W.B.L.
12	Condensates -strong black liq.	7	White liquor	11	Kamyr Spills-W.B.L.
		8	Slaker-Green liquor	13	B.S. Washers-W.B.L.
				14	Kamyr Condensates

The recovery, recaust and pulping locations represent nearly 100% of the spills recorded in the data. The recovery area alone accounts for nearly 71% of all spills recorded.

Goodness of fit tests were run for the spill amounts[(1)] and the time between successive spill sequences for each of the three major areas.[(2)] The computer

(1) Note: The spill amounts data were expressed in units of 1000 lbs of Na_2SO_4 equivalent. The time data is in hours.

(2) What is meant by a "spill sequence" will become clear in the next few pages. The time differences analyzed here were the time (in hours) between the last spill of a sequence and the next spill in the area which has the potential of initiating a new sequence.

program used was one developed at UBC which uses the Kolmogorov-Smirnov (K-S) and the Chi-square goodness of fit tests for fitting given data to seven theoretical distributions (Kota and Morley, 1973). These include:

1. Normal distribution
2. Poisson distribution
3. Binomial distribution
4. Negative Binomial distribution
5. Gamma distribution
6. Log normal distribution
7. Exponential distribution

The K-S test was used since it is less sensitive to sample size and is generally accepted as a more powerful test (Siegel, 1956). The test determines the greatest distance between the data and the theoretical cumulative distributions and compares it to a table of critical values for a given significance level. If the distance is less than the critical level, then the null hypothesis is accepted, (i.e., we cannot reject the hypothesis that the distributions are the same). For a more complete discussion of the K-S test see Fishmann (1973) or Siegel (1956). The results of the tests are found in Table 3.2 for the spill amounts, and Table 3.3 for the interarrival times.

The K-S routine estimates the distribution parameters from the sample data. If these parameters are ones of scale or location, however, the K-S critical values become distribution dependent (Fishmann, 1973). Lilliefors (1969) gives a table of K-S critical values for the exponential distribution with a sample estimated mean. Comparing these values to a standard K-S table, it

TABLE 3.2 GOODNESS OF FIT RESULTS FOR SPILL AMOUNTS (units of 1000 lb)

Area	# of Observations	Gamma				Negative Binomial				Log Normal				K-S Adjusted
		R	λ	D	KS (.05)	P	K	D	KS (.05)	M	S	D	KS (.05)	
#1 Recovery	100	.414	.024	.074	.136	.109	.364	.087	.136	-	-	-	-	.107
#2 Recaust	30	.515	.045	.064	.245	.189	.444	.072	.245	3.76	2.91	.081	.245	.196
#3 Pulping	19	1.191	.065	.124	.301	.313	1.55	.078	.301	5.47	2.85	.214	.301	.246

TABLE 3.3 GOODNESS OF FIT RESULTS FOR TIME BETWEEN UNRELATED SPILLS (units of hours)

Area	# of Observations	Gamma Distribution				Negative Binomial				Log Normal				K-S Adjusted
		R	λ	D	KS (.05)	P	K	D	KS (.05)	M	S	D	KS (.05)	
#1 Recovery	55	.511	.0024	.089	.183	.1117	.459	.092	.183	10.66	2.75	.034	.183	.144
#2 Recaust	23	.807	.002	.104	.276	.091	.823	.110	.276	12.4	3.16	.103	.276	.223
#3 Pulping	13	1.101	.001	.183	.361	.086	1.25	.197	.361	13.8	2.9	.170	.361	.297

Note: See Table 3.5 for definitions of parameters is seen that the 0.05 significance level critical values for Lilliefors' table are about the same as the critical values for a standard table .20 significance level. This implies that the probability of a type I error (rejecting a true null hypothesis) is decreased when using the standard K-S tables but the probability of a type II error (accepting a false null hypothesis) is increased. In the context of this study, a type II error is more serious. A suitably adjusted K-S critical values table could not be found for the gamma, log-normal or negative binomial distributions, therefore, the K-S standard critical values were also determined for $\alpha = .2$. These are found in the column labeled "K-S Adjusted". Assuming that Lilliefors' result of the similarity of the values for $\alpha = .2$ and $\alpha = .05$ discussed earlier can be generalized to other distributions the results of the tests are not affected and the null hypothesis still cannot be rejected at both the .05 and .20 significance levels.

Often in the spill data, a sequence of up to six spills with only a few hours between each occured in the same sub location implying a possible recurring failure. To handle this situation it was assumed that any sequence of spills occurring in the same sub area, with ten hours or less between each successive spill, were "related" permitting creation of a "related spill distribution". Table 3.4 summarizes the number of related spills for each sub location. The goodness of fit routine results can be found in Table 3.5.

Since not all spills are part of a related sequence it was necessary to establish a related spill decision strategy. Each spill, if not imbedded in an already initiated sequence, is a potential initiator of a related sequence.

TABLE 3.4 RELATED SPILL COUNT FOR 3 MAJOR AREAS

INTERVAL TIME	AREA		
	RECOVERY	RECAUST	PULPING
1 hrs	28	5	0
2 "	11	1	0
3 "	7	1	0
4 "	3	3	0
5 "	5	3	0
6 "	2	0	0
7 "	2	0	0
8 "	1	2	0
9 "	1	1	0
10 "	2	0	0

TABLE 3.5 GOODNESS OF FIT RESULTS FOR TIME BETWEEN RELATED SPILLS (UNITS OF HOURS)

Area	# of Observations	Gamma				Negative Binomial				Log Normal				K-S Adjusted
		R	X	D	KS (.05)	P	K	D	KS (.05)	M	S	D	KS (.05)	
#1 Recovery	67	1.24	.447	.191	.166	.287	.722	.041	.166	1.62	1.77	.268	.166	.123
#2 Recaust	16	2.04	.528	.220	.328	.392	1.86	.136	.328	2.45	1.92	.211		.267
#3 Pulping	NO RELATED SPILLS													

NOTE (FROM KITA AND MORLEY (1977)

1. Gamma Distribution

$$f(x) = \begin{cases} k\, x^{R-1} e^{-x/\beta} & \text{for } x > 0 \\ 0 & \text{for } x \leq 0 \end{cases}$$

where $k = \frac{1}{\beta^R \Gamma(R)}$

$$R = \frac{\bar{x}^2}{\sigma^2}$$

$$\lambda = \frac{1}{\beta} = \frac{\bar{x}}{\sigma^2}$$

2. Negative Binomial Distr.

$$P(x) = \frac{(K+x-1)!}{x!(K-1)!} q^x p^k$$

where
- k = # of successes
- p = prob success in 1 trial
- m = average # of success before k^{th} success

$$k = \frac{m^2}{SD^2 - m^2}$$

$$P = \frac{m}{SD^2}$$

SD = standard dev'n of # of failures before K^{th} success.

3. Log Normal

$$M = \frac{\sum_{i=1}^{n} \log_{10} X_i}{n}$$

$$S = \frac{\sum_{i=1}^{n} (\log_{10} X_i - M)^2}{n-1}$$

Using empirical data it was possible to establish a decision matrix of probablilities that a related spill will occur. An interesting way of thinking of it is as a semi-Markov process.[1] A finite Markov chain can be structured by defining a state as a spills time location in a related sequence, (i.e., the first spill in the sequence puts the system in state 1, a second spill in a sequence puts the system in state 2, etc.). Table 3.6 is a summary of related spill sequences for each of the three major areas. For each state i, the count represents the number of spills that occurred as the i-th spill in a related sequence. For example, in the recovery area, state 3 has a count of 14. This means that of the 52 initializing spills, (the count of state 1), 14 of them resulted in sequences of related spills at least 3 spills long. As indicated in Tables 3.5 and 3.6, the pulping area did not have any "related" spills.

TABLE 3.6 RELATED SPILL COUNT FOR EACH STATE

State	Major Area	
	Recovery-#1	Recaust-#2
1	52	24
2	30	7
3	14	4
4	10	3
5	4	2
6	2	0
7	1	0

(1) A semi-Markov process is a stochastic process which makes transitions from state to state in accordance with a Markov chain but in which the time spent in each state before a transition occurs is random.

Using the data of Table 3.6, it is now possible to construct the related spill decision matrices. For the recovery area, the following matrix results:

TABLE 3.7 RELATED SPILL DECISION MATRIX FOR RECOVERY AREA (#1)

State	1	2	3	4	5	6	7
1	.423	.576	0	0	0	0	0
2	.533	0	.467	0	0	0	0
3	.285	0	0	.714	0	0	0
4	.6	0	0	0	.4	0	0
5	.5	0	0	0	0	.5	0
6	.5	0	0	0	0	0	.5
7	1.	0	0	0	0	0	0

Similarly for the recaust area, the following matrix results:

TABLE 3.8 RELATED SPILL DECISION MATRIX FOR RECAUST AREA (#2)

State	1	2	3	4	5
1	.708	.292	0	0	0
2	.428	0	.571	0	0
3	.25	0	0	.75	0
4	.33	0	0	0	.67
5	1.	0	0	0	0

Notice, given the sequence is in state i, only two jumps are possible, to state i + 1, or back to state 1. This provides sufficient structure for the semi-Markov process. The results summarized in Table 3.5 provide a time distribution between related states (i.e., state i to state i + 1) while the results summarized in Table 3.3 provide a time distribution between the end of a related sequence and the beginning of a new potential sequence (i.e., state i to state 1). Using these results it is possible to determine limiting probabilities of being in any state, mean first passage times and limiting transition probabilities. An analysis of this sort can be found in Appendix I.

To translate a spill amount in terms of its Na_2SO_4 equivalent into an equivalent BOD and SS load, liquor samples from the mill were analyzed and are summarized in Table 3.9

TABLE 3.9 BOD, TS AND SS OF MILL LIQUOR SAMPLES

Liquor	BOD mg/1	TS mg/1	SS mg/1
Weak Black Liquor	36,700	176,148	272
Strong Black Liquor	131,250	624,127	800
White Liquor	0	unreliable	300
Green Liquor	0	"	2021

The Na_2SO_4 equivalent to volume of liquor conversion factors were determined from the literature and the calculations can be found in Appendix II. A summary of the results are:

TABLE 3.10 POUNDS Na_2SO_4 EQUIVALENT TO GALLONS OF LIQUOR CONVERSION FACTORS

	US gal of liquor/lb of Na_2SO_4
Weak black liquor	1.063
Strong black liquor	.270
Green liquor	.325
White liquor	.325

To convert a Na_2SO_4 equivalent to a BOD loading:

$$\text{lbs BOD} = (\text{lbs } Na_2SO_4 \text{ Equiv.}) \times \left(\frac{\text{mg BOD}}{\text{litre of liquor}}\right) \times \left(\frac{\text{gal's of liquor}}{1 \text{ lb of } Na_2SO_4}\right)$$

$$\times\, 10^{-6}\, \frac{\text{kg}}{\text{mg}} \times 2.2\, \frac{\text{lbs}}{\text{kg}} \times \frac{1}{3.785}\, \frac{\text{gal}}{\text{litre}}$$

3.1.3 PRODUCTION AND WATER USAGE

Daily production in air dry tons and water usage in U. S. gallons per day were transcribed from monthly operating sheets and used to establish empirical distributions.

It was originally hoped that there would be a reasonably good correlation between water usage and production; however, this proved not to be the case. The highest correlation for various combinations of complete runs was about .26. The data did indicate, however, that days with lower production tended to use less water. This also fits the intuitive feel of their relationship. Consequently, two empirical distributions for water usage were developed, one for production greater than 1,000 air dry tons per day and one for less. The two distributions are given in Table 3.11 and their cumulative distributions are plotted in Figure 3.1.

TABLE 3.11 TWO EMPIRICAL DISTRIBUTIONS FOR DAILY WATER USAGE DETERMINED BY LEVEL OF PRODUCTION

Production ≤1000 Tons			Production >1000 Tons		
MUSGD	Count	Cumulative Prob.	MUSGD	Count	Cumulative Prob.
51	11	.314	57	2	.023
53	1	.343	59	1	.035
55	1	.371	61	1	.047
57	1	.4	63	3	.081
59	4	.514	65	7	.163
61	3	.6	67	11	.291
63	2	.657	69	28	.616
65	3	.743	71	24	.895
67	4	.857	73	9	1.0
69	1	.886			
71	3	.971			
73	1	1.0			
	Total=35			Total=86	

TABLE 3.12 EMPIRICAL DISTRIBUTION FOR DAILY PRODUCTION IN AIR DRY TONS

Production ADT	Count	Cumulative Prob.
0 - 500	12	.0819
500 - 600	5	.090
600 - 700	9	.114
700 - 800	4	.147
800 - 900	10	.180
900 - 1,000	16	.286
1,000 - 1,100	10	.367
1,100 - 1,200	32	.573
1,200 - 1,300	50	.893
1,300 - 1,400	24	1.000

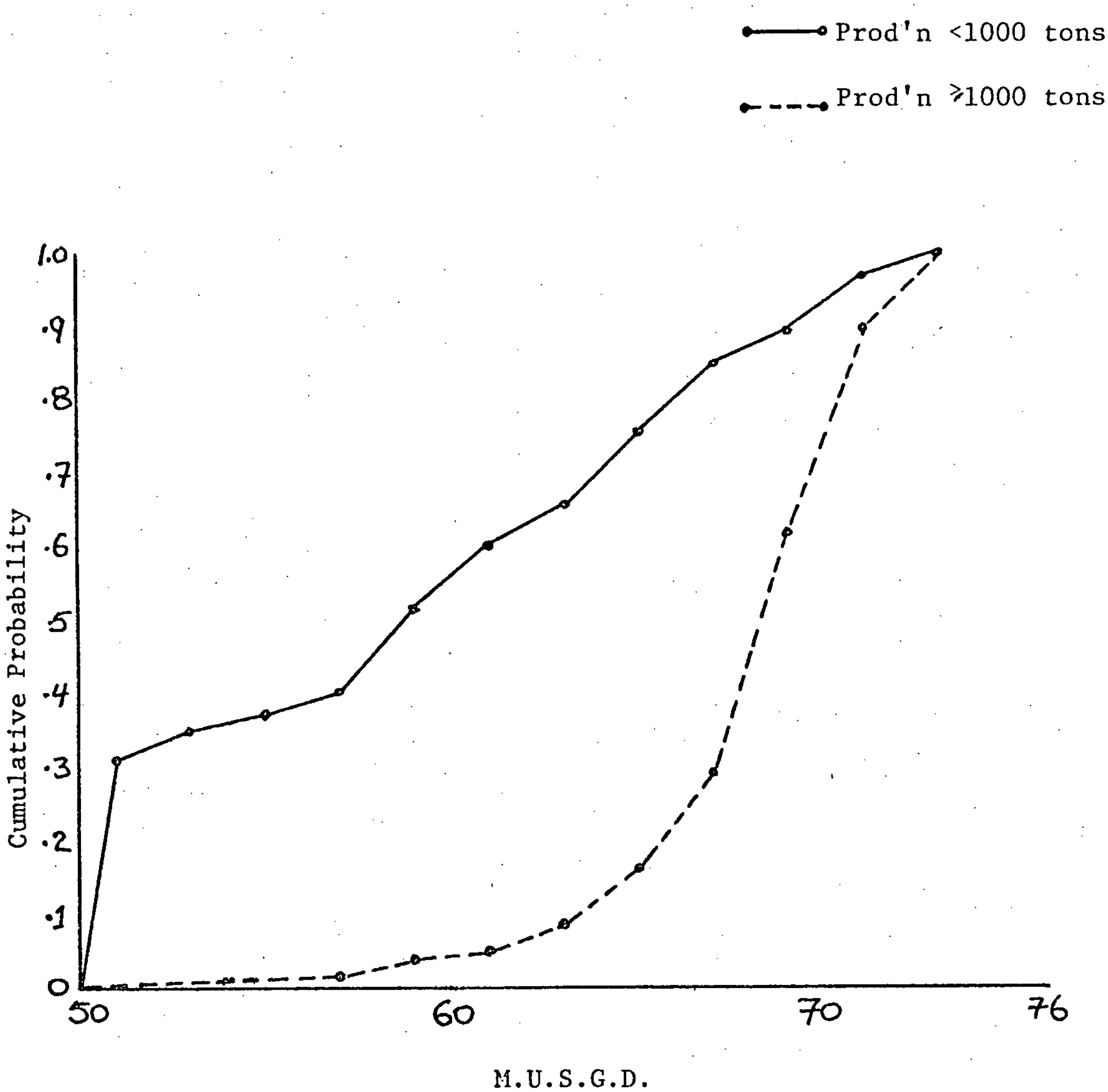


FIGURE 3.1

CUMULATIVE DISTRIBUTIONS FOR PULP MILL DAILY WATER USAGE

An empirical distribution for production was similarly established and is summarized in Table 3.12.

Since the empirical distributions for water and production give a daily figure and the intent is to run the model on an hourly basis, it is assumed that the production and water per hour will be constant for any given day. In other words,

$$\text{Production/hr} = \frac{\text{Day production}}{\text{24 hrs/day}}$$

$$H_2O \text{ Flow/hr} = \frac{\text{Day flow}}{\text{24 hrs day}}$$

3.1.4 REGULAR EFFLUENT

If it were possible to prevent all major spills, the pulping process, by the very nature of its operation, would still generate effluent. Activities such as debarking, dreg and mud washings, brown stock washers, screening and bleaching all result in liquid residuals. This "regular" effluent was grouped according to origin into six areas or streams. These six areas and their resulting effluent streams represent, in several cases, quite a large portion of the mill's operation. However, the breakdown is a fairly standard one (see Bower, 1971). The six streams and what they include are:

1. <u>Acid stream</u> - the bleaching area
2. <u>Alkaline (general) stream</u> - brown stock washers, digestors, blow tanks, screen rooms
3. <u>Recovery</u> - recovery boilers, precipitators, black liquor storage, evaporators, Na_2SO_4 storage.
4. <u>Flyash clarifier</u>

5. Recaust stream - lime kilns, white liquor and green liquor clarifiers, washers and storage
6. Machine room - pulp drying and stacking.

To represent these streams the effluents were assumed to be normally distributed. This is a fairly standard assumption in the industry (Howard & Walden, 1971). The means and standard deviations were determined from a combination of mill data and from Howard and Walden (1971). The results are summarized in Table 3.13.

By sampling from these distributions each hour it is possible to generate hourly "regular" BOD and SS concentrations for each of the streams. Multiplying these concentrations by the water flow in the stream the actual BOD and SS loads for that hour can be determined. The water flow for each stream is a proportion of the hourly mill flow as summarized in Table 3.14.

3.2 WASTE TREATMENT

Most models of waste treatment systems consider only steady state operation. Therefore, given a constant hydraulic load and concentration, it is possible to determine the average performance of a system. This is the common approach used in engineering design. However, in recent years more interest has been shown in the dynamic response of a waste treatment system to hydraulic surges and changes in input concentrations.

One concern is that a hydraulic surge effects the effluent detention time. Detention time is an important parameter since the amounts of BOD and SS

TABLE 3.13 BOD, TS AND SS MEANS AND STANDARD DEVIATIONS FOR THE SIX MILL AREAS

AREA	BOD mg/l		TS mg/l		SS mg/l	
	MEAN	ST. DEV.	MEAN	ST. DEV.	MEAN	ST. DEV.
ACID STREAM	79	22	800	100	26	3
ALKALINE "	157	55	1500	200	155	55
RECOVERY "	86	36	900	150	33	17
FLYASH CLAR.	10	2	200	40	48	5
RECAUST STREAM	12	3	220	40	118	41
MACH. ROOM	9	2	58	15	26	5

TABLE 3.14 PROPORTIONS OF TOTAL HYDRAULIC FLOW FROM THE SIX MILL AREAS

AREA	FLOW GAL/MIN	PROPORTION OF TOTAL
ACID STREAM	22,400	.477
ALKALINE "	18,750	.400
RECOVERY "	2,900	.063
FLYASH CLAR.	900	.019
RECAUST STREAM	700	.014
MACH. ROOM "	1,250	.027
TOTAL	46,900	1.00

reduction are a function of the length of time a given unit of polluted water is in residence. The waste treatment model in this study enables a pulp mill manager to study some of the dynamic effects of pulp mill operation on the clarifier-lagoon treatment facility.

3.2.1 THE CLARIFIER

The clarifier model treats the clarifier as a first order chemical reactor where the degree of settling is directly proportional to the concentration of suspended solids in the clarifier at any time t. This results in an exponential relationship for the weight fraction of SS removed in the basin by time t. Sakata and Silveston (1974) developed a first order reaction assumption for settling. For the first order reaction assumption, they state:

$$X(t) = 1 - \exp(-kt) \qquad \underline{\text{eqn 3.1}}$$

where $X(t)$ = weight fraction of SS removed in the basin by time t

k = apparent sediments removal coefficient (rate of reaction) sec^{-1}

t = time (sec)

If we let $t = \frac{h}{\nu_o}$

where h = depth of clarifier in cm

ν_o = threshold settling velocity cm/sec[1]

---

(1) Threshold velocity ν_o is a lower bound on the settling velocity. Any particles with settling velocity $\nu \geqslant \nu_o$ will settle in the time $= \frac{h}{\nu_o}$. If we let $\frac{h}{\nu_o}$= detention time, then ν_o is the minimum velocity any particle starting at a distance h from the bottom of the clarifier must have to ensure settling.

we get $X(t) = 1 - \exp\left(\frac{-hk}{\nu_o}\right)$

Note: $\nu_o = \frac{Q}{A}$

where Q = fluid flow rate into clarifier in cm^3/sec

A = surface area of clarifier cm^2

Sakata and Silveston then showed that a differential weight distribution of the settling velocity ν could be expressed as:

$$p(\nu) = \exp\left(\frac{-a}{\nu}\right) + \frac{a}{\nu}\exp\left(\frac{-a}{\nu}\right) \qquad \underline{\text{eqn. 3.2}}$$

where

$a = hk$

$p(\nu)$ = differential weight distribution of ν

This implies for any suspended matter, if the settling velocity curve is fitted by equation 3.2, the fractional removal can be expressed as a first order exponential equation, namely equation 3.1.

In Silveston (1969) a graph of the settling velocity for pulp mill wastes in a 6 ft column is presented. (This is reproduced as Figure 3.2). By fitting equation 3.2 to this graph the parameter "a" for pulp mill wastes was estimated (i.e., equation 3.2 was evaluated at 3 points on the graph iteratively, until a reasonable fit was found). A value of $a = .104 \frac{cm}{sec}$ fit the plot quite well. Therefore, for any given depth of clarifier it was possible to determine the parameter k for pulp mill wastes. Namely:

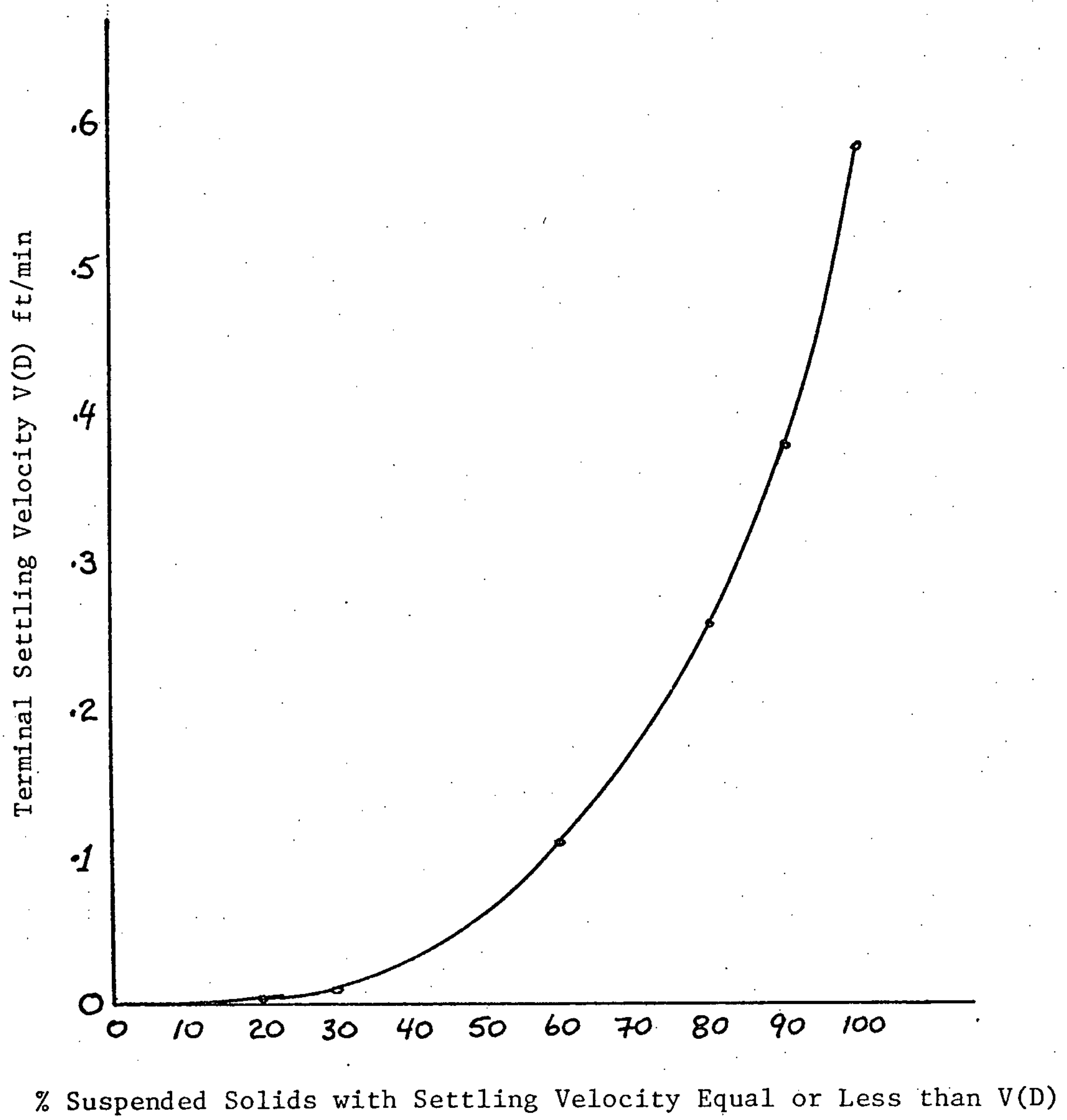


FIGURE 3.2

DISTRIBUTION OF TERMINAL SETTLING VELOCITIES FOR PULP MILL WASTES

$$k = \frac{a}{h} = \frac{.104 \frac{cm}{sec}}{h\ cm} = \frac{.104}{h} sec^{-1}$$

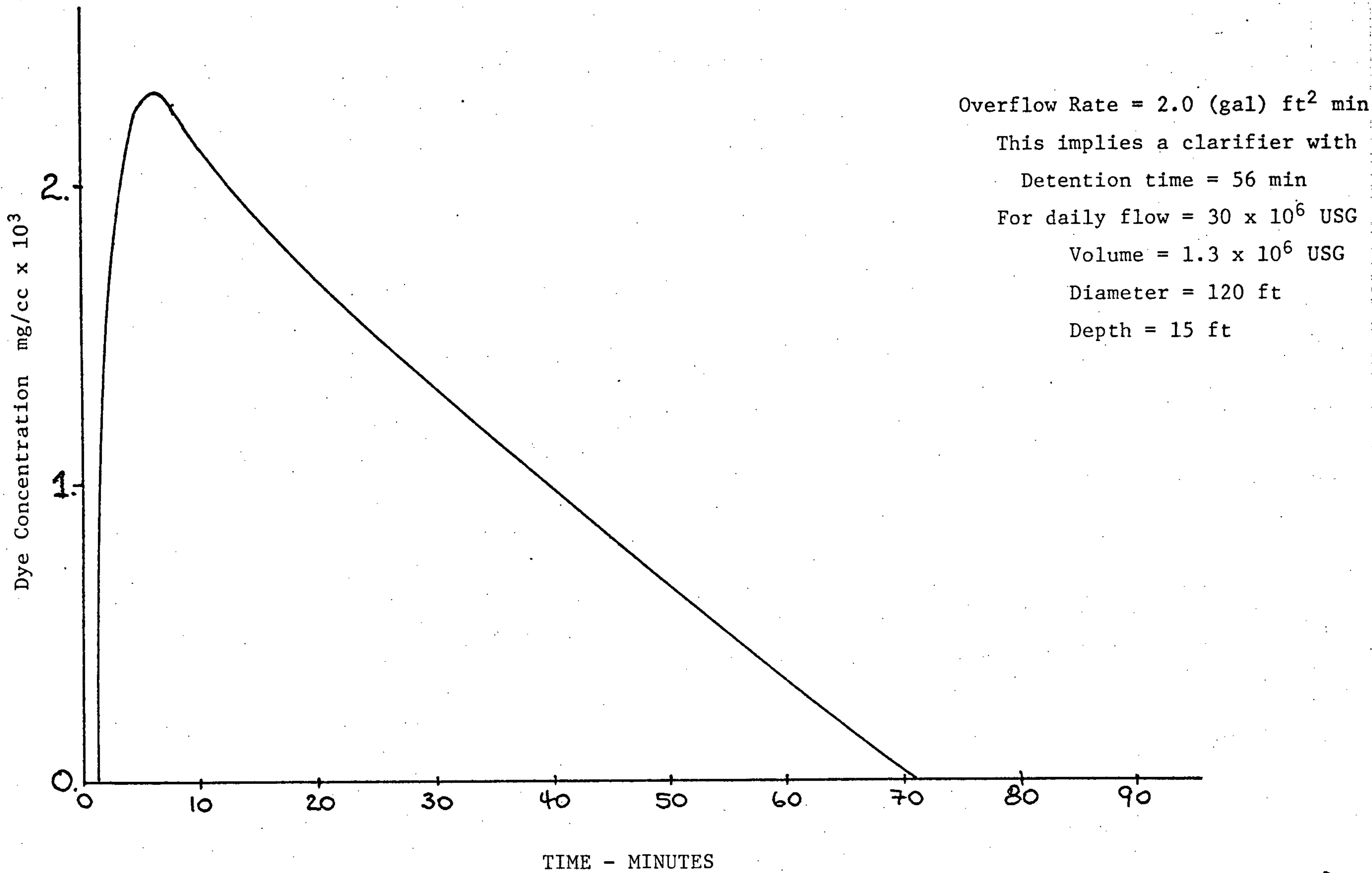
In Figure 3.3 is seen a copy of a typical residence time plot for a center-feed clarifier (Chainbelt Inc. 1972). The output has a quick response to the change in inflow concentration. To mathematically model this kind of behaviour a technique popular in the field of chemical reaction engineering was used.

Basically, the problem is to model the clarifier's mixing behaviour so as to adequately represent its response to changes in influent concentration. Levenspiel (1972), in his book, "Chemical Reaction Engineering", goes into considerable depth on this problem. Tank mixing models are bounded by two extremes, the backmix (completely mixed) flow model and the plug flow model. The backmix model assumes any incoming reactant is mixed immediately upon entering the tank, implying that the tank has a uniform concentration at any time t. The plug flow model assumes no mixing and the plug moves in the direction of flow as a separate element. The plots in Figure 3.4 should help in understanding these concepts.

By linking a number of tanks in series it is possible to approximate a partially mixed system. The greater the degree of mixing the less the number of tanks in series (Note: an infinite number of tanks in series is equivalent to plug flow). The mathematical modelling technique involves solving a system of differential equations representing the mass balance of two completely mixed tanks in series, where the total volume of the tanks equals the clarifier volume.

FIGURE 3.3

DISPERSION CURVE FOR CENTER FEED CLARIFIER



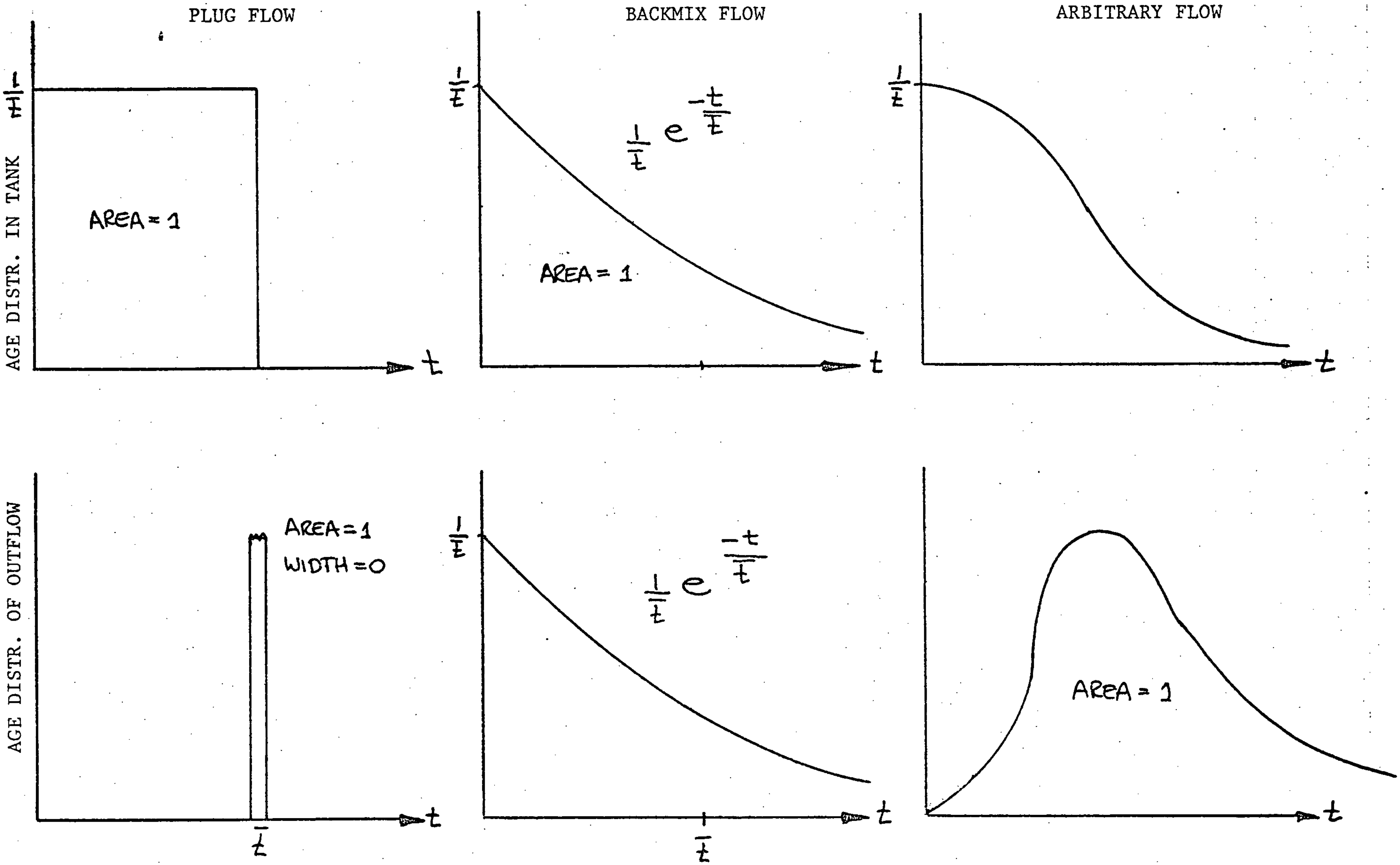
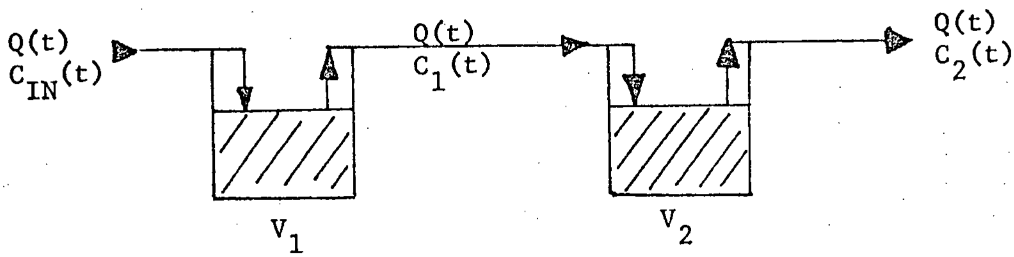


FIGURE 3.4

PROPERTIES OF AGE DISTRIBUTIONS IN TANK AND OF OUTFLOWS FOR VARIOUS FLOWS

Therefore, take the following system:



where

$Q(t)$ = hydraulic flow at time t.

$C_i(t)$ = concentration of SS in tank i at time t

V_i = volume of tank i.

(Note: V_1 and V_2 are assumed to be equal and $V_1 + V_2$ = volume of clarifier. Also the volume of liquid retained in each tank remains constant independent of Q(t)).

First perform a mass balance on tank 1 at time t over a time span of Δt

(a) Change in mass from time t to time $t + \Delta t = M(t + \Delta t) - M(t)$

$$= \underbrace{Q(t)C_{IN}(t)\Delta t}_{\text{inflow mass of SS}} - \underbrace{Q(t)C_1(t)\Delta t}_{\text{outflow mass of SS}} - \underbrace{V_1C_1(t)k_c\Delta t}_{\text{mass of SS which settles in time }\Delta t}$$

k_c = sediments removal coefficient ($\sec^{-1}$)

= first order "reaction" rate

$= \frac{.104}{h}$

(b) Now dividing by Δt we get

$$\frac{M(t+\Delta t)-M(t)}{\Delta t} = Q(t)\ C_{IN}(t) - Q(t)\ C_1(t) - V_1 C_1(t) k_c$$

Using $\frac{\text{Mass}}{\text{Volume}}$ = concentration

(c) we can express (b) as

$$\frac{\Delta M(t)}{\Delta t} = V_1 \frac{\Delta C_1(t)}{\Delta t} = Q(t)\ C_{IN}(t) - Q(t)\ C_1(t) - V_1 C_1(t) k_c$$

Defining $\frac{V}{Q(t)}$ = detention time = $T(t)$

dividing (c) by V_1 and taking the limit as $\Delta t \rightarrow 0$

We get

$$\frac{dC_1(t)}{dt} = \frac{C_{IN}(t)}{T(t)} - \frac{C_1(t)}{T(t)} - k_c C_1(t)$$

rearranging

$$\frac{dC_1(t)}{dt} + C_1(t)\left[\frac{1 + k_c T(t)}{T(t)}\right] = \frac{C_{IN}(t)}{T(t)} \qquad \text{eqn. 3.3}$$

Equation 3.3 is a linear differential equation of the general form,

$$\frac{dy}{dx} + P(x)y = Q(x)$$

which has a solution

$$Y = e^{-\int P(x)dx} \int Q(x) e^{\int P(x)dx}\, dx + Ce^{-\int P(x)dx} \qquad \text{(Wilcox and Curtis (1966))}$$

Applying this to equation 3.3 we get

$$C_1(t) = e^{-\int_0^t \frac{1+k_c T(t)}{T(t)} dt} \int_0^t \frac{C_{IN}(t)}{T(t)}\, e^{\int_0^t \frac{1+k_c T(t)}{T(t)} dt}\, dt + \gamma_1 e^{-\int_0^t \frac{1+k_c T(t)}{T(t)} dt}$$

eqn. 3.4

where γ_1 = integration constant for end conditions.

Feeding the clarifier is the pulp mill model which has a constant hydraulic flow over a 24-hour period and a constant effluent concentration $C_i(t)$ each hour. Making these assumptions in equation 3.4 greatly simplifies the solution. Since the pulp mill model cycles on an hourly basis, little resolution should be lost as a consequence.

Therefore assuming

$T(t) = T_c$ = constant for each 24-hour period

$Q(t) = Q$ = " " " " " "

$C_{IN}(t) = C_{IN}$ = " " " 1 " "

and solving eqn. 3.4, we get

$$C_{1S}(t) = \frac{C_{IN}}{1+k_cT_c}\left[1 - e^{-(1+k_cT_c)\frac{t}{T_c}}\right] + C_1(0)e^{-(1+k_cT_c)\frac{t}{T_c}} \qquad \text{eqn. 3.5}$$

where

C_{IN} = inflow concentration of SS for any given hour (mg/1)

T_c = detention time (for each tank) for current 24-hour period (secs)

i.e., $T = \frac{\text{Vol of tank}}{Q}$

$C_1(0)$ = concentration of SS in tank 1 at t = 0 (mg/1)

For the two-tank situation, a differential equation similar to equation 3.3 was derived, only in this case the feed concentration from tank 1 to tank 2 is changing with time as described by equation 3.5. The assumption that Q,T and the feed concentration C_{IN} into tank 1 are constant is retained.

The differential equation for the outflow concentration of tank 2 was then

$$\frac{dC_2(t)}{dt} + C_2(t)\left(\frac{1+k_cT_c}{T_c}\right) = \frac{C_{1S}(t)}{T_c} \qquad \underline{\text{eqn. } 3.6}$$

Applying the general solution indicated earlier

$$C_{2S}(t) = e^{-\int_0^t (1+k_cT_c)\frac{dt}{T_c}} \int_0^t \frac{C_1(t)}{T_c} \quad e^{\int_0^t (1+k_cT_c)\frac{dt}{T_c}} + \gamma_2 e^{-\int_0^t (1+k_cT_c)\frac{dt}{T_c}}$$

substituting equation 3.5 for $C_1(t)$ and solving

$$C_{2S}(t) = \frac{C_{IN}}{(1+k_cT_c)^2}\left[1-e^{-(1+k_cT_c)\frac{t}{T_c}}\right] + e^{-(1+k_cT_c)\frac{t}{T_c}}\left[C_2(0)+C_1(0)\frac{t}{T_c} - \frac{C_{IN}(t)}{T_c(1+k_cT_c)}\right]$$

$\underline{\text{eqn. } 3.7}$

Looking at equation 3.7 notice that:

at $t = 0$, we get $C_2(t) = C_2(0)$ as expected. Now as t increases the term $e^{-(1+k_cT_c)\frac{t}{T_c}}$ decreases implying that the second term in 3.7 has less effect on $C_2(t)$ as t increases. As t approaches infinity, 3.7 becomes

$$\frac{C_2(t)}{C_{1n}} = \frac{1}{(1+k_cT_c)^2}$$

implying that with a constant input concentration and no changes in T, the output concentration $C_2(t)$ approaches a constant and the system has therefore a limiting efficiency.

For an instantaneous shock load $C_{1n} = 0$ and $C_1(0) = \frac{\text{mass of shock load}}{\text{vol. of tank 1}}$

and $C_2(0) = 0$, we get the theoretical response curve of the clarifier model.

$$C_{S2}(t) = C_1(0)\frac{t}{T_c}\, e^{-(1+k_c T_c)\frac{t}{T_c}}$$

which has a shape similar to that of Figure 3.3.

3.2.2 THE LAGOON

In Chapter II, the biological oxidation process occurring in an aerated lagoon was described. The removal rate K_L for oxidation is treated here as a constant, implying that the amount of BOD removal at any time t is directly proportional to BOD concentration at time t. To model the temperature dependence of K_L, an empirical relation expressing K_L as a function of temperature was used (Beak - Environment Canada (1973)).

The function is: $K_L^* = .256\ (1.032)^{T-20}$

Where T = temperature, ^oC

K_L^* = lagoon removal rate, day^{-1}

(Since the model is run on an hourly basis the resultant K_L^* must be divided by 24).

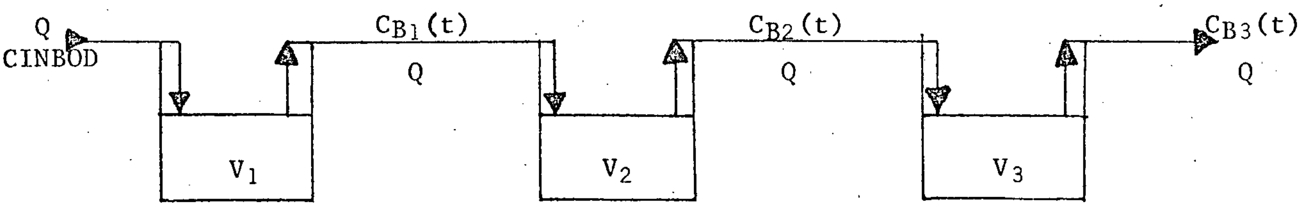
In Beak-Environment Canada (1973) and in City of Austin, Texas (1971), the tanks in series model was found to give reasonable representation of a lagoon's response time curve. As far as BOD reduction was concerned however, they only looked at the long term steady state operation and did not try to model lagoon performance variations as a function of changing hydraulic loads and input concentrations. In other words, for steady state, they claimed:

$$\frac{\text{BOD conc. out}}{\text{BOD conc. in}} = \frac{1}{(1+K_L*T_L)^3} \quad \text{where:} \quad \begin{array}{l} K_L = \text{lagoon removal rate } (hr^{-1}) \\ T_L = \text{detention time of each of the tanks} \end{array}$$

for three equal volume tanks in series.

For the purposes of this study, a three-tanks-in-series model of the lagoon's behaviour over time was developed.

Schematically the model is:



Note: $V_1 = V_2 = V_3$, $V_1 + V_2 + V_3$ = volume of lagoon

Q = hydraulic flow, assumed constant for each 24-hour period (1/sec)

CINBOD = concentration of influent BOD constant for any given hour ($^{mg}/1$)

Setting up mass balance relationship for each tank, relationships identical to eqns. 3.3 and 3.6, except with different constants, result. Using the results of section 3.2.1, it was only necessary to carry the solution one more step and solve for the output from tank 3 in terms of the solution already developed in the clarifier model for tank 2 (eqn. 3.7).

Applying a mass balance to tank 3 results in the following linear differential eqn.

$$\frac{dC_{B3}(t)}{dt} + C_{B3}(t)\left[\frac{1 + K_L T_L}{T_L}\right] = \frac{C_{B2}(t)}{T_L}$$

Using the general solution and substituting equation 3.7 for $C_{B2}(t)$ (with the necessary parameter changes)

$$C_{B3}(t) = \frac{CINBOD}{\alpha^3}\left[1-e^{\frac{-\alpha t}{T_L}}\right] + e^{\frac{-\alpha t}{T_L}}\left[C_{B1}(0)\frac{t^2}{2T_L^2}+C_{B2}(0)\frac{t}{T_L} + C_{B3}(0)- \frac{CINBOD}{2\alpha}\frac{t^2}{T_L^2} - \frac{CINBOD}{\alpha^2}\frac{t}{T_L}\right]$$

Eqn. 3.8

where $\alpha = (1 + K_L T_L)$

(subscript L indicates lagoon parameters)

$C_{B1}(0)$ = concentration of BOD (mg/l) in tank 1 at t = 0

$C_{B2}(0)$ = concentration of BOD (mg/l) in tank 2 at t = 0

$C_{B3}(0)$ = concentration of BOD (mg/l) in tank 3 at t = 0

K_L = BOD removal rate constant (hr^{-1})

T_L = detention time for each tank for any given 24 hour period

$= \frac{\text{Volume of tank gal}}{\text{gal/hr inflow}}$ (hrs)

t = time in hours

For steady state operation as t approaches infinity equation 3.8 reduces to

$$\frac{C_{B3}(t)}{CINBOD} = \frac{1}{\alpha^3} = \frac{1}{(1 + K_L T_L)^3}$$

which is in complete agreement with Beak-Environment Canada (1973) report.

To model the suspended solids generated as a byproduct of the biological oxidation process an approximation developed in City of Austin, Texas (1971) was used. If the complete lagoon is treated as a completely mixed basin and the sludge age is assumed equal to the detention time;

$$X = \frac{a*(S_0 + X_0)}{1 + b *t}$$

where

X = effluent SS concentration mg/l

X_o = influent SS concentration mg/l

a = lbs of SS generated per lb of BOD removed

b = rate of endogenous respiration of active solids (lb/lb - day)

Values for the constants were obtained from two separate papers

a = .15 lb SS/lb BOD removed   Bower (1971)

b = .2 day^{-1} Kormanik (1972)

This relation has no direct time dependence and differs with the BOD lagoon model in its mixing structure and therefore was used only as an SS indicator on a daily basis.

The SS generated also contributes BOD to the lagoon. For each pound of SS generated .1 pounds of BOD is created (Bower, 1971). This was incorporated in a change of the reaction rate constant as follows

The sludge generation rate = $k_L^* = .15K_L$

$$\begin{pmatrix}\text{amount of sludge generated} \\ \text{in each tank over time } \Delta t\end{pmatrix} = k_L^* \text{ x volume x concentration (t) x } \Delta t$$

Rewriting the mass balance equation for tank i

$$\Delta M(t) = QC_{IN}(t)\Delta t - QC_i\ (t) - K_L V_i\ C_i\ (t)\Delta t + .1\ k_L{*}V_i\ C_i\ (t)\Delta t$$

giving

$$\frac{\Delta M(t)}{\Delta t} = QC_{IN}(t) - QC_i\ (t) - K_L V_i\ C_i\ (t) + .1k_L^*\ V_i\ C_i\ (t)$$

and dividing through by Vi

$$\Delta C_i\ (t) = \frac{C_{IN}(t)}{T_L} - \frac{C_i\ (t)}{T_L} - (K_L - .1k_L^*)\ C_i\ (t)$$

$$= \frac{C_{IN}(t)}{T_L} - \frac{C_i\ (t)}{T} - k_L^{**}\ C_i\ (t)$$

where

$$k_L^{**} = K_L - .1k_L^* = .985\ K_L$$

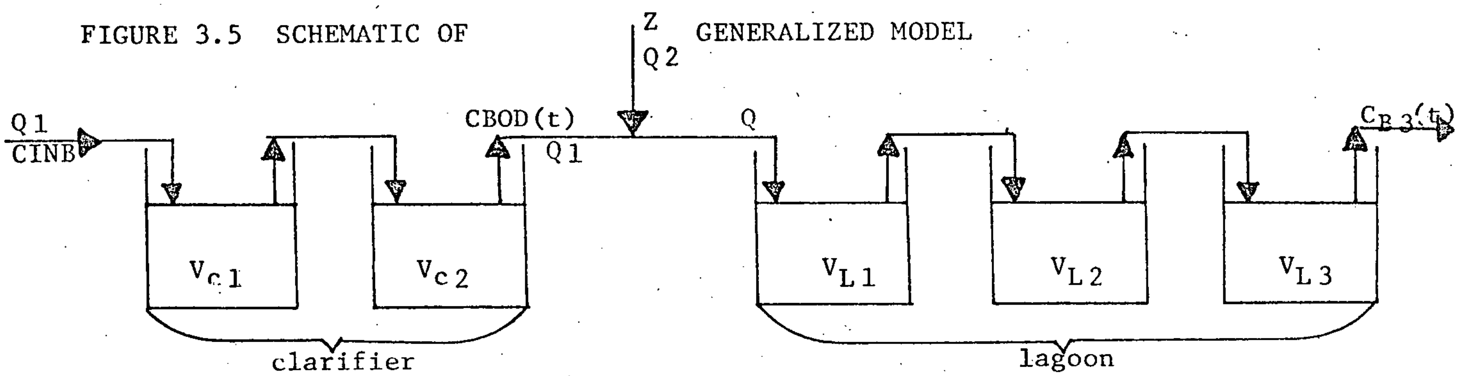
Therefore, with the appropriate change in K_L, equation 3.9 is still valid.

3.2.3 Waste Treatment Generalization

In most mills, as with the one modelled in this study, the acid and alkaline (or general) effluent sewers were kept separate and were not linked until just before the waste treatment plant. When finally linked they were mixed in a controlled manner so as to ensure a neutral (pH ≃ 7 ± 2) influent into the lagoon. In some cases only the general sewer was fed to the clarifier and the two sewers were mixed just before the lagoon. This resulted in the BOD in the general sewer feed to the lagoon being buffered by the clarifier as a result of it's 2 or 3 hour detention time. In other words a chemical spill in the alkaline sewer will have its impact on the lagoon buffered and somewhat dispersed by the clarifier.

To facilitate various combinations of influent into the lagoon a more generalized model was developed. Schematically this model looks like

FIGURE 3.5 SCHEMATIC OF GENERALIZED MODEL



The two main changes were first the lagoon influent BOD concentration was made a function of time and second the mill hydraulic load was split between the clarifier and lagoon feeds (ie., Q1 and Q2).

To solve for $C_{B3}(t)$ in terms of the knowns (ie., Q1, V_{C1}, V_{C2}, V_{L1}, V_{L2}, CNIB, V_{L3}, Z, Q2) five differential equations one for each of the tanks were developed in the same manner as in the last two sections, remembering that the BOD in the clarifier is only mixing and not taking part in the first order settling "reaction", [it is assumed that 10% of the BOD travelling through the clarifier settles out (private communication - T. Howard)] then starting with the first tank in the sequence, the equations are solved successively, the solution for each tank in turn being substituted into the differential equation for the next tank.

The final solution for $C_{B3}(t)$ in terms of the known parameters is

$$C_{B3}(t) = \frac{[CINB*Q1 + Z*Q2]}{\alpha^3 Q}\left[1-e^{\frac{-\alpha t}{T_L}}\right] + e^{\frac{-\alpha t}{T_L}}\left[J - Lt + \frac{It^2}{2*(T_L)^2}\right] + \frac{e^{-\frac{t}{T_L}}}{T_L}\left[\left(\frac{F}{\beta} + \frac{G}{\beta^2}\right) + \frac{Gt}{\beta}\right]$$

Eqn. 3.10

where

$$J = C_{B3}(0) + \frac{1}{\beta T_L}\left[F + \frac{G}{\beta}\right]$$

$$L = \frac{1}{T_L}\left[\frac{CBINCL*Q1}{\alpha^2 * Q} + \frac{Z}{\alpha^2}\frac{Q2}{Q} - H\right]$$

$$I = \left[D - \frac{CBINCL}{\alpha}\frac{Q1}{Q}\right]$$

$$H = C_{B2}(0) - \frac{Q1}{Q}\frac{1}{(T_L)^2}\frac{1}{\beta}\left[A + \frac{B}{\beta}\right]$$

$$G = \frac{Q1}{Q}\frac{1}{(T_L)^2}\frac{B}{\beta}$$

$$F = \frac{Q1}{Q}\frac{1}{(T_L)^2}\left[\frac{A}{\beta} + \frac{B}{\beta^2}\right]$$

$$D = \left[\frac{-Q1}{QT_L}\left[\frac{C_2*(0)}{\beta} + \frac{C_1*(0)}{T_c\beta^2} - \frac{CBINCL}{\beta} - \frac{CBINCL}{\beta^2}\right] - \frac{ZQ2}{\alpha Q} + C_{B1}(0)\right]$$

$$B = \left[\frac{C_1*(0)}{T_c\beta} - \frac{CBINCL}{T_c\beta}\right]$$

$$A = \left[\frac{C_2*(0)}{\beta} + \frac{C_1*(0)}{T_c\beta^2} - \frac{CBINCL}{\beta} - \frac{CBINCL}{T\beta^2}\right]$$

and

$$\alpha = (1 + kT_c)$$

$$\beta = \left(\frac{\alpha}{T_L} - \frac{1}{T_c}\right)$$

Q = total flow into lagoon (l/sec)

$Q1$ = flow into clarifier (l/sec)

$Q2 = Q - Q1$ = flow which bypasses clarifier

CBINCL = concentration of BOD into clarifier (mg/l)

Z = concentration of BOD in Q2 (mg/l)

T_c = detention time for each tank in clarifier model (secs)

T_L = detention time for each tank in lagoon model (hrs)

$C_i*(0)$ = initial concentration of BOD in tank i of clarifier at $t = 0$ (mg/l), $i = 1, 2$

$C_{Bj}(0)$ = initial concentration of BOD in tank j of lagoon at $t = 0$; (mg/l) $j = 1,2,3,$

If it is assumed that the clarifier is completely bypassed by all the sewers, implying

$$C_i*(0) = 0, \quad i = 1,2$$

$$Q = Q2 \quad (\text{ie. } Q1 = 0)$$

$$\alpha = 1$$

$$\beta = \frac{1}{T_L}$$

$$CBINCL = 0$$

$$Z = \text{total BOD concentration from mill}$$

$$T_c = 0$$

then equation 3.10 reduces to equation 3.8.

3.2.4 Discussion

In the last three sections a mathematical model was developed for a clarifier and aerobic stabilization lagoon waste treatment system. The dynamics of the system to which this study was directed should be reflected in the one hour resolution the model operates under. It should be stressed that the final model is not dynamic in the true sense of the word. The model in fact functions in a kind of quasi-steady state. Each hour the various parameters assumed to be constant are set and the clock starting at t = 0, runs the model in steady state for one hour. At the end of the hour the final state of each tank becomes it's initial state for the next hour. The parameters are changed accordingly and the model is run again for one hour. The changes in concentration each hour, and in hydraulic load each 24 hours, although not smooth transitions, should reflect overall system behaviour.

3.3 CAPITAL AND OPERATING COSTS OF WASTE TREATMENT

Two of the major factors in any management decision are the capital cost of that decision and the future costs it may create. Waste treatment systems are no exception. The two processes modelled here, a clarifier and aerobic stabilization lagoon,represent a very large investment in space, time and money. To cost a structure as large as a lagoon accurately an intensive engineering feasibility study would almost surely have to be completed first. However in using this model as a management aid, figures of this accuracy are not essential. What is more crucial is to get a feel of the magnitude of cost changes as a result of changes in the basic design of the system.

In Figures 3.6, 3.7, 3.8 and 3.9 can be seen graphs of the capital and operating costs for a center feed clarifier and an aerobic stabilization lagoon (Bower, 1971). Using the plots it is possible to develop explicit cost relations for use in the model. These will now be developed.

a) Lagoon Capital Costs

In Figure 3.6 lagoon capital costs are a function of lagoon efficiency and flow in MUSG/day. Since each of the 8 plots for the different efficiencies are linear on a log-log plot, the cost relationship will have the following form:

$$CC = A*(FLOW)^B$$

where A = cost intercept for flow = 1. mgd

B = slope of log-log curves

Since the plots are linear and parallel, the B coefficient will be identical for all efficiency levels. The A intercepts however will be different.

To determine B, take the 40% curve

$$B = \frac{\ln 8.1 \times 10^5 - \ln 3.1 \times 10^4}{\ln 100 - \ln 1.0} = \frac{2.092 + 11.51 - (1.131 + 9.21)}{4.61 - 0}$$

$$= .708$$

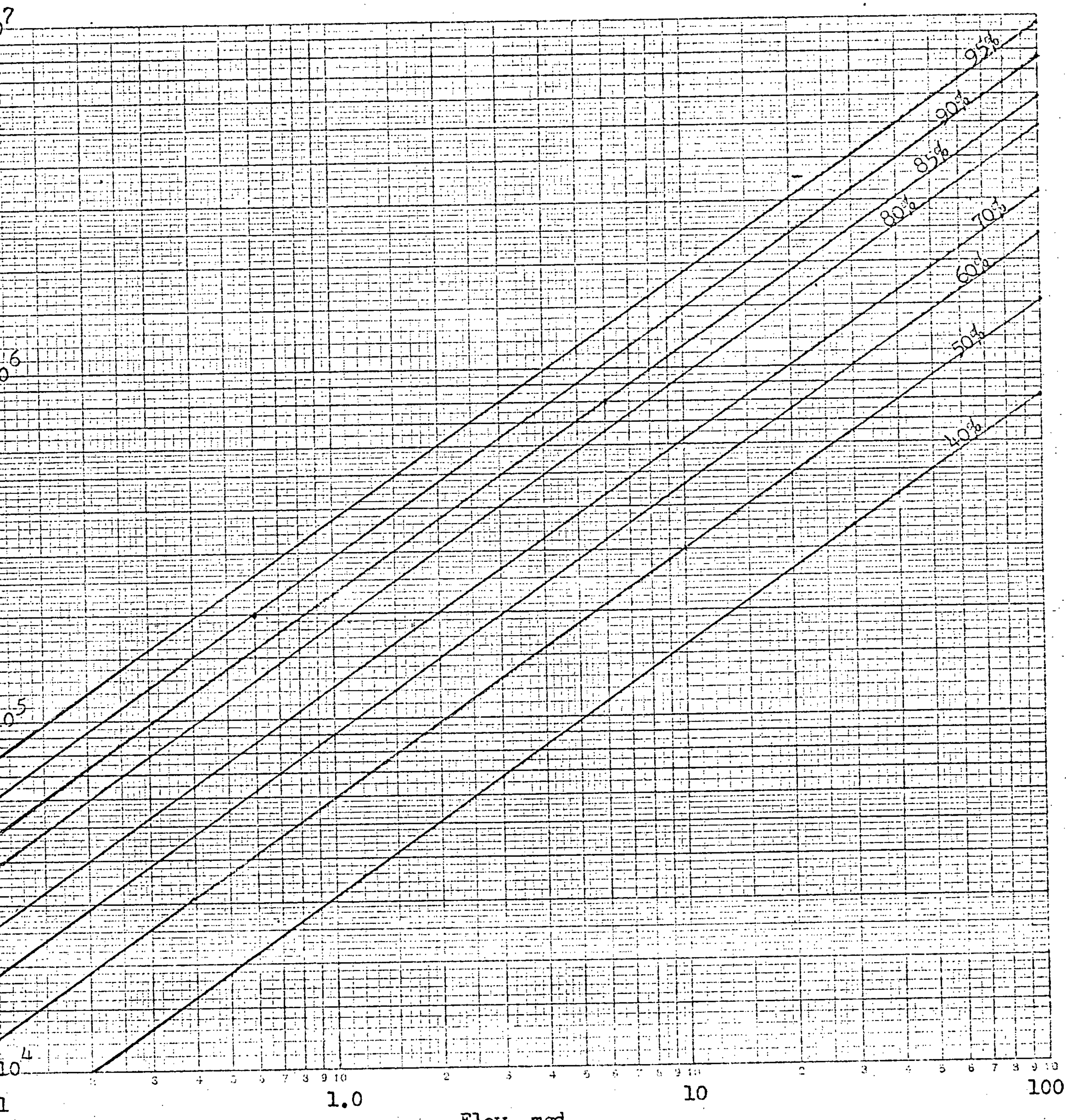
The A intercepts (The CC value for Flow = 1 mgd) are

efficiency	intercept
.40	$\$3. \times 10^4$
.5	6×10^4
.6	9×10^4
.7	12×10^4
.8	18.8×10^4

FIGURE 3.6

CAPITAL COST VS. FLOWRATE AT VARIOUS % REMOVAL OF BOD : AERATED LAGOON

CURVE NEW H



(At any removal below 40% , use the 40% line)

efficiency	intercept
.85	23.0×10^4
.9	29.0×10^4
.95	37.0×10^4

For efficiencies below .4, the intercept for the .4 curve is used. For lagoon efficiencies between any 2 consecutive data points the A intercept is determined by linear interpolation. For example if the efficiency (EFF) is between .8 and .85, then the A intercept is calculated as follows:

$$GA = \log(18.8 \times 10^4) + [(EFF - .8)/(.85 - .8)]*[\log(23 \times 10^4) - \log(18.8 \times 10$$

then

$$A = EXP(GA)$$

The capital cost of the lagoon is then evaluated as

$$CC_L = A*(FLOW)^{.708}$$

Note: EFF = lagoon efficiency, determined at the completion of the experiment

$$EFF = \frac{\text{total BOD into lagoon} - \text{total BOD out of lagoon}}{\text{total BOD into lagoon}}$$

where totals are taken for the complete experiment.

b) Lagoon Operating Costs

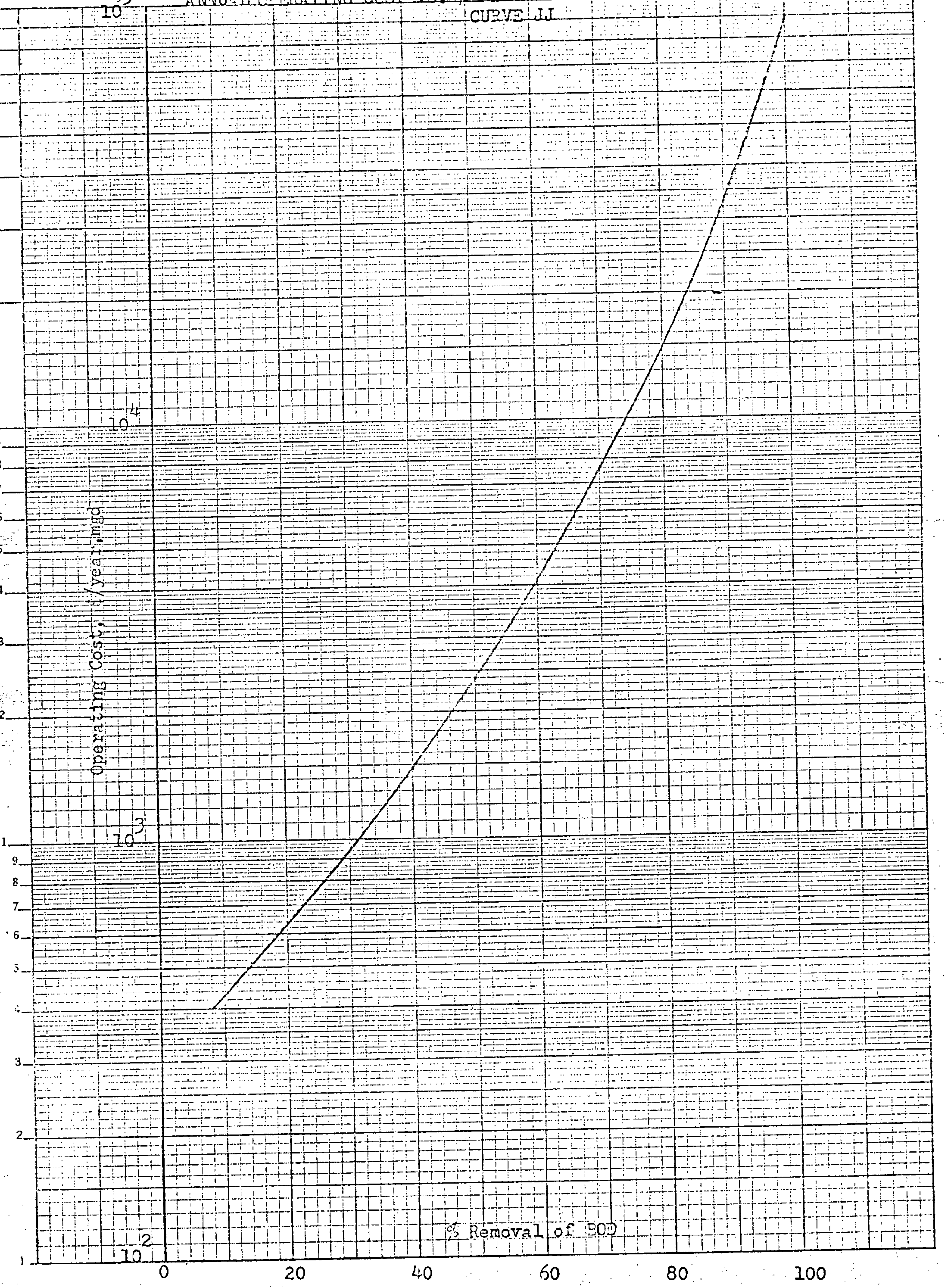
Figure 3.7 is a semi-log plot of lagoon operating costs (per(MUSG/day) flow) versus lagoon efficiency. For any given efficiency operating costs are a linear function of lagoon flow.

Namely Operating Costs = OC = C*FLOW where C = constant dependent on efficiency.

FIGURE 3.7

ANNUAL OPERATING COST VS. % REMOVAL OF BOD : AERATED LAGOON

CURVE JJ



The constants C were determined for the same efficiency levels used for capital costs. The data points taken from Figure 3.7 are:

efficiency	.4	.5	.6	.7	.8	.85	.9	.95
C	1480	2400	4100	7600	14700	21500	33000	53000

If lagoon efficiency falls between any 2 consecutive data points C is determined using linear interpolation. For example, for an efficiency between .8 and .85

$$GC = \log (14700) + [(EFF-.80)/(.85-.8)]*[\log (21500) - \log (14700)]$$

then $C = EXP(GC)$

The operating costs are then

$$OC_L = C*FLOW \text{ dollars.}$$

c) Clarifier Capital Costs

Figure 3.8 is a log-log plot of clarifier capital costs versus clarifier surface area. The relationship will have the following form:

$$\text{Capital Costs} = CC_{cL} = D*(AREA)^E$$

where D = Cost intercept at Area = 1. ft^2

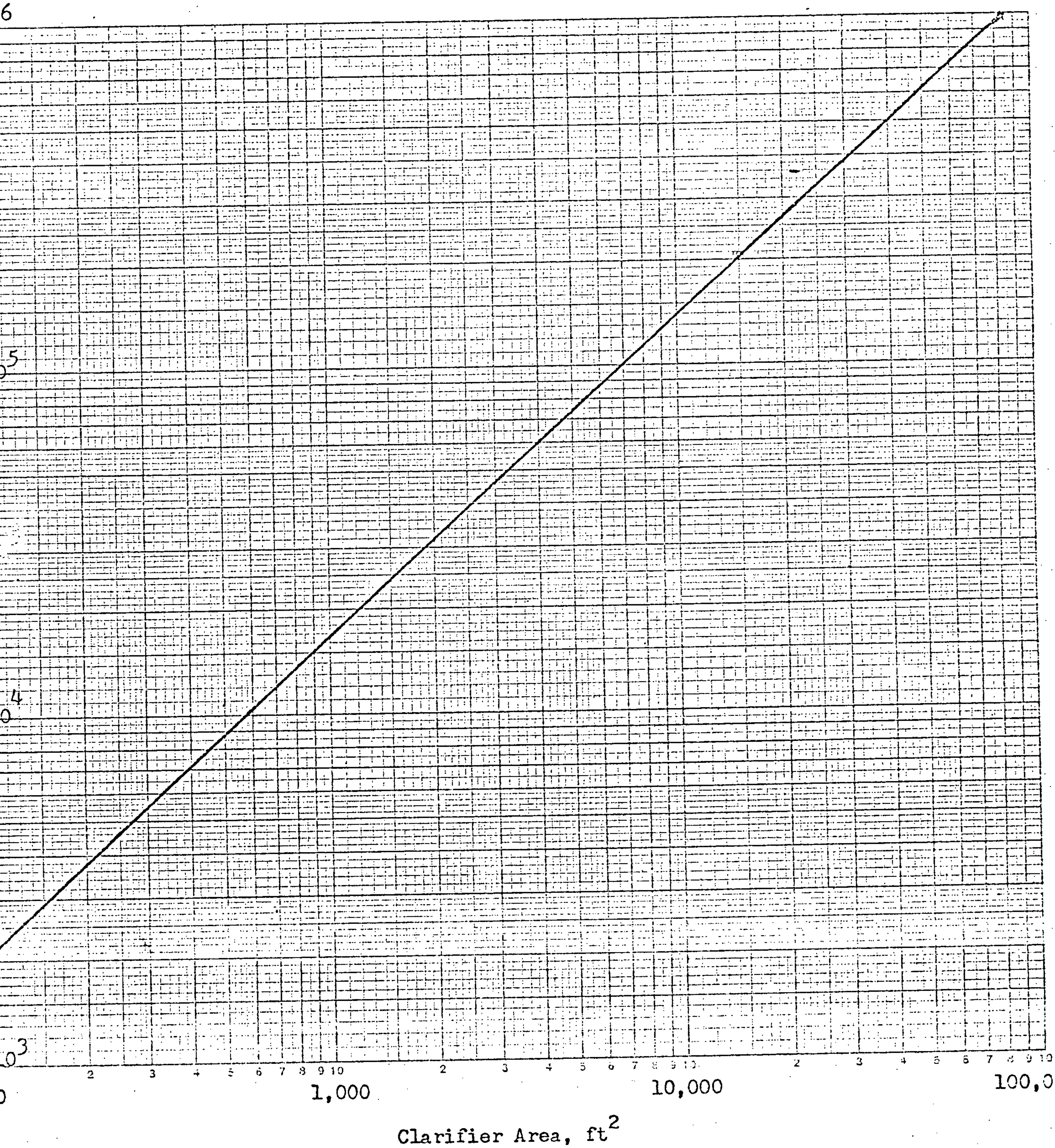
E = slope of log-log curve

To evaluate D it is necessary to extrapolate the curve beyond that shown on the plot, giving D = \$29.5

FIGURE 3.8

CAPITAL COST VS. CLARIFIER AREA : PRIMARY & SECONDARY CLARIFIER

CURVE C



To evaluate E

$$E = \text{slope} = \frac{\ln\ (2 \times 10^5)\ -\ \ln\ (2 \times 10^3)}{\ln\ (1.5 \times 10^4)\ -\ \ln\ (10^2)}$$

$$= \frac{4.6}{5} = .92$$

therefore

clarifier capital costs = $CC_{cL} = 29.5*(\text{Area in ft}^2)^{.92}$

Knowing the depth of the clarifier daily flow and theoretical detention time, the surface area can be determined.

$$\text{Surface Area} = \frac{\dfrac{\text{Daily flow } \frac{ft^3}{day}}{24\ \frac{hrs}{day}} \times \text{detention time (hrs)}}{\text{depth (ft)}}$$

d) Clarifier Operating Costs

Figure 3.9 shows a log-log plot of clarifier operating costs versus clarifier daily flow. Due to its linear nature in the area of interest in the model (10 MUSGD/day to 100 MUSGD/day) the plot was linearized (dashed line). The mathematical form for the clarifier operating costs is

$OC_{cL} = F*(FLOW)^G$

where

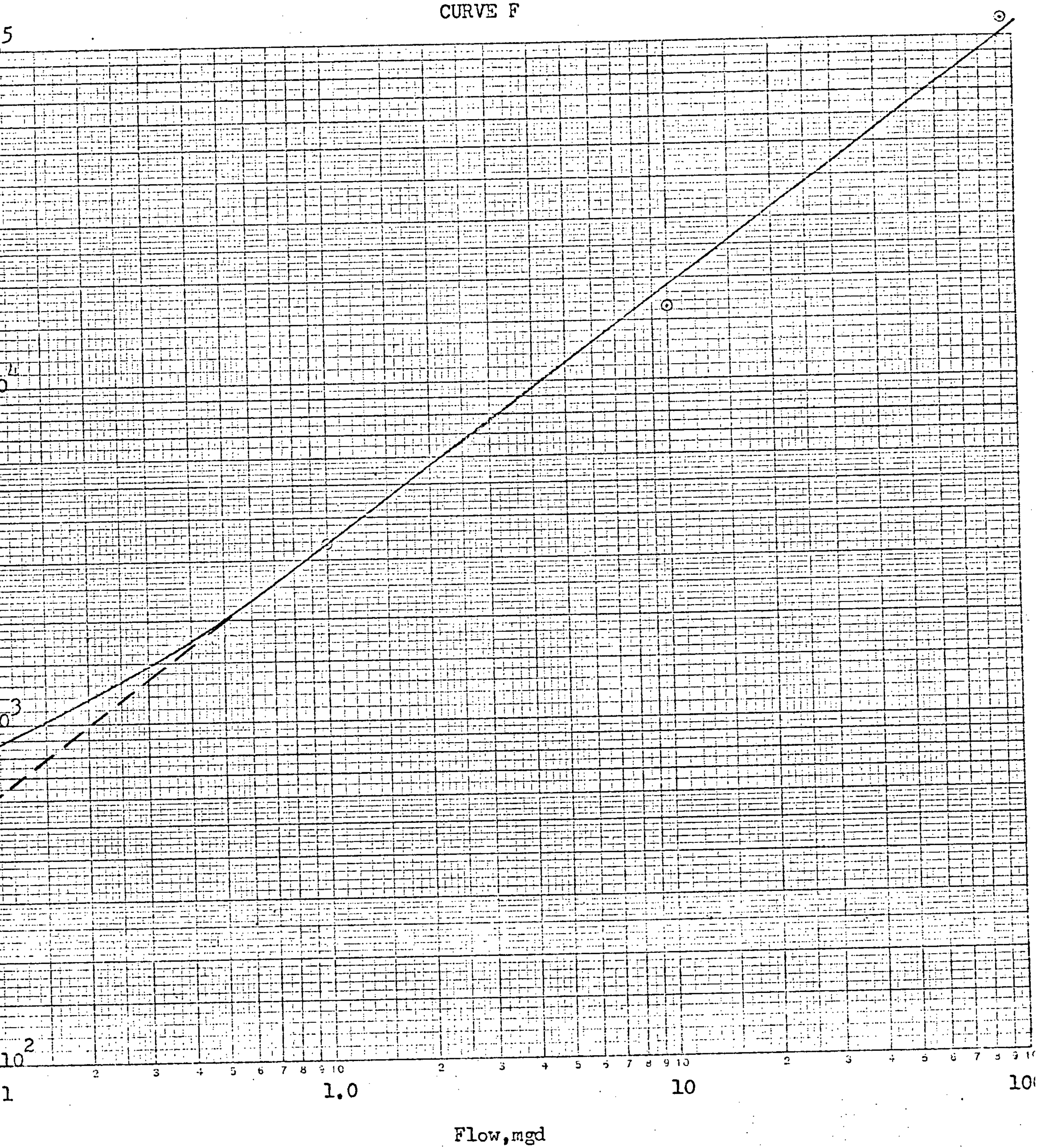
F = cost intercept for flow = 1. mgd

G = slope of log-log plot

FIGURE 3.9

ANNUAL OPERATING COST VS. FLOW : PRIMARY & SECONDARY CLARIFIER

CURVE F



The constants were evaluated as F = \$3600

$$G = \text{slope} = \frac{\ln(3.2 \times 10^4) - \ln(3.6 \times 10^2)}{\ln(20) - \ln(1)}$$

$$= .726$$

Therefore

clarifier operating costs = $3600*(\text{FLOW})^{.726}$ dollars where FLOW is in MUSG/day.

All the cost relationships are in 1970 dollars. To determine the operating costs the following relation was used by Bower;

Total Annual Operating Costs = 1.25 (Capital Cost) + operation and maintenance costs based on 350 days operation per year.

The elements Bower included in the costs are:

1. Clarifier
   a. Capital Costs - concrete structure, sludge pumps, rakes
   b. Operating Costs - power, administration, maintenance, sludge removal.
2. Aerated Lagoons
   a. Capital Costs - floating aerators, PVC lining, power supply (the land was assumed to be already available)
   b. Operating Costs - power, operating labour, maintenance, nutrients, administration.

The following assumptions were made by Bower in the development of the cost data:

1. All facilities operate for 350 days per year.
2. Primary clarifier is of the circular type with center upflow feed. Clarifier diameter depends on flow rate, settling velocity of suspended matter and detention time.
3. Clarifier sludge is assumed to have 5% solids.
4. Chemical additives were assumed not required in the clarifier.
5. The aerated lagoon is assumed to be water tight.
6. Aerators are of the floating type and have sufficient horse power to maintain all solids in suspension.
7. The lagoon feed is assumed to be neutralized. This can usually be accomplished by combining the general and acidic sewers. However, often chemical additives such as ammonia or lime must be used. The costs of the mixing station and these chemicals are not included in the model. Bower does indicate however that the capital costs for the holding tanks and chemical feeders are around $10,000. The operating cost is nominally around $65/ton of ammonia required.
8. Sludge disposal is not included.

CHAPTER IV

MODEL DEVELOPMENT

4.1 PULP MILL MODEL DESCRIPTION

The model described herein is concerned with the waterborne effluent characteristics of a kraft pulp mill. It is primarily a stochastic model sampling from empirically derived distributions each hour. The computer program is written in FORTRAN (a listing can be found in Appendix III). The model was not designed to be used as a pulp mill design aid. It's purpose is to generate a typical pulp mill effluent time trace to be used as input into the waste treatment model. It is possible to change the distribtuion parameters in the model and thereby create a better or worse than normal time trace.

Figure 4.1 provides a general flow chart of the pulp mill as visualized in the model. Notice that each of the six effluent streams have a regular effluent contribution while only three streams have a spill contribution. The streams combine and exit from the mill modelled as indicated. These three effluent outfalls from the mill are maintained in the model and alternate combinations of them are available as influent to the waste treatment plant.

Figure 4.2 is an overall schematic of the model's structure giving the generation sequence and the model decision points. In the following pages the model will be discussed in detail with a discussion of the results of chapter III.

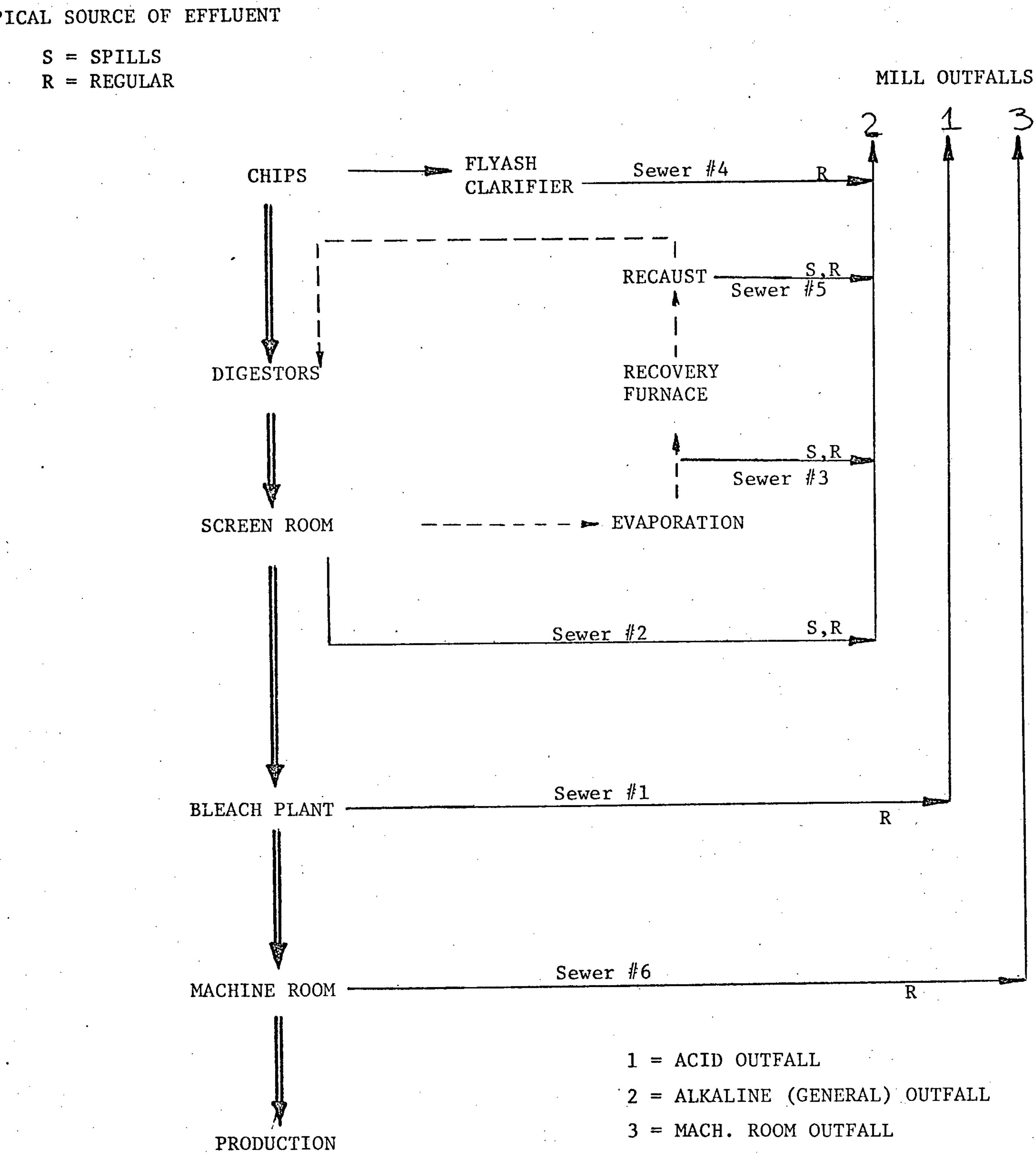
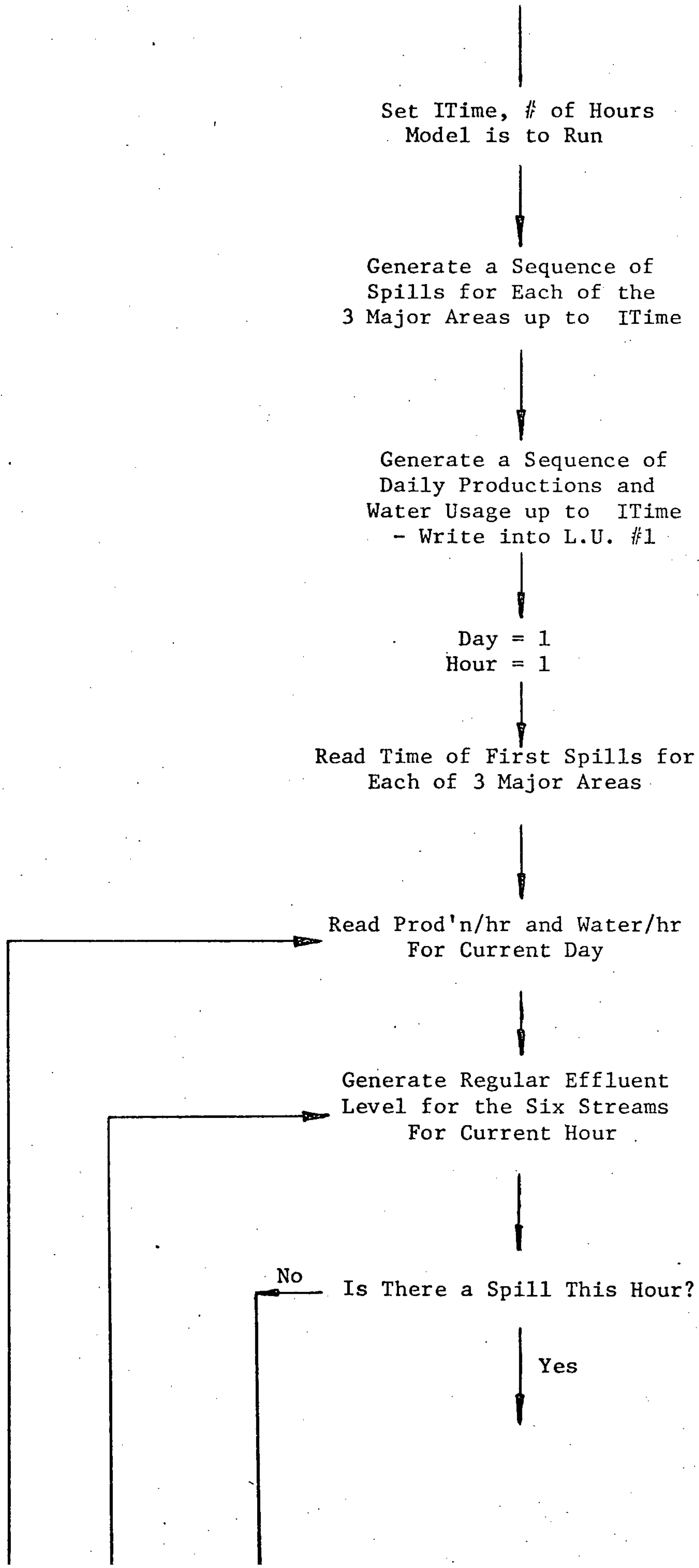


FIGURE 4.1

DIAGRAM OF WATERBORNE EFFLUENT STREAMS INCLUDED IN MODEL INDICATING SPILL AND REGULAR EFFLUENT LOCATIONS

FIGURE 4.2 FLOW DIAGRAM OF PULP MILL MODEL



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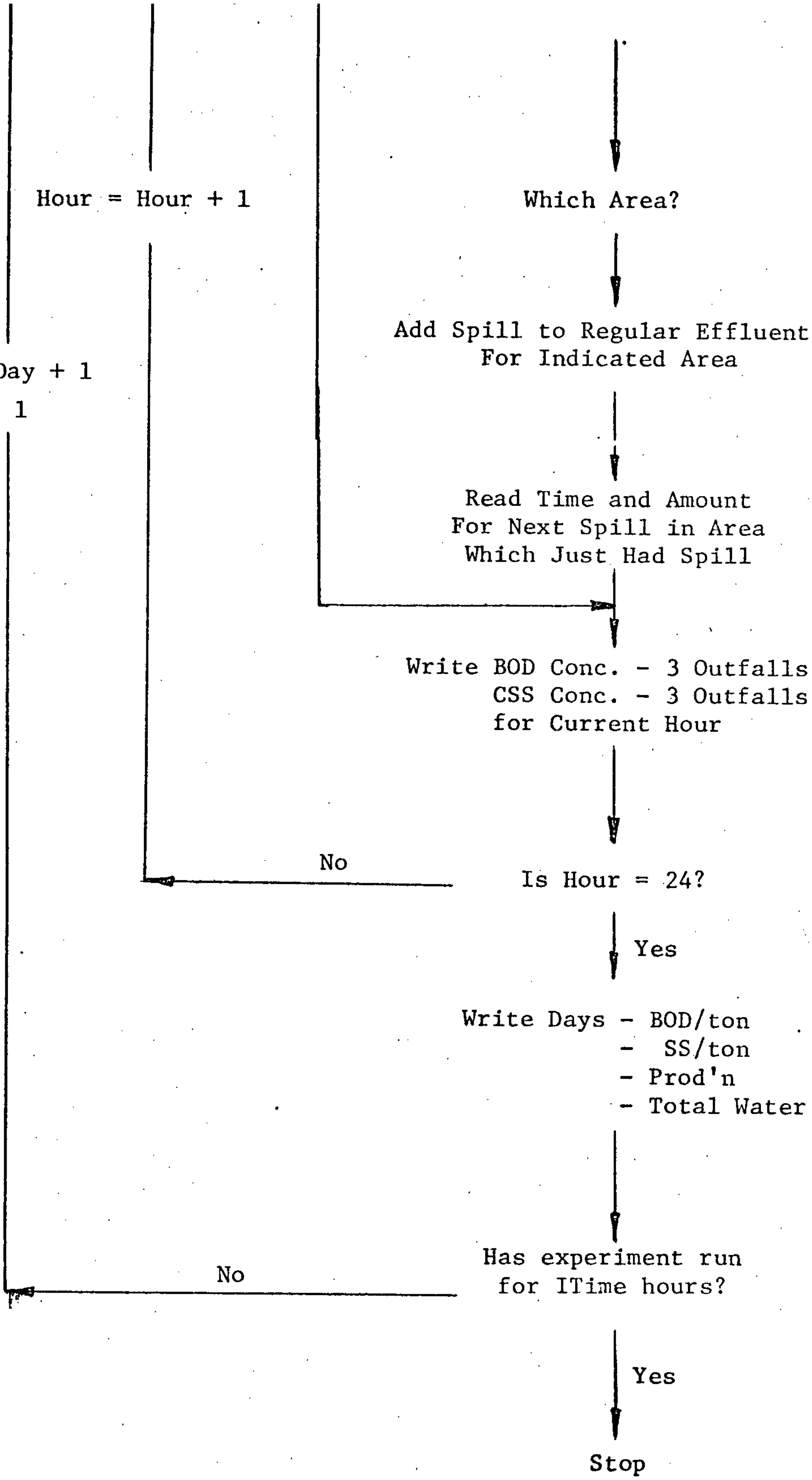


Note: L.U. = System Logical Unit

4.1.1 GENERATING CHEMICAL SPILLS

In chapter III the spill data acquired from a B.C. mill was presented in a summarized form. Using the results shown there, it was possible to generate both related and unrelated spills in the model.

Looking at Tables 3.2 and 3.3 the null hypothesis for the gamma, negative binomial and log-normal distributions cannot be rejected for both the spill amounts and times between unrelated spills. The Kolmogorov-Smirnov D statistic for both the spill amounts and the times between unrelated spills was the smallest or second smallest for the gamma distribution. Consequently it was used in the model to generate those random variables. The distribution parameters were supplied by the goodness of fit program. (Note for the spill amounts the variates units are in terms of 1000 lbs of Na_2SO_4).

The gamma distribution has the following density function:

$$f(x) = \begin{cases} \frac{1}{\Gamma(\alpha)\beta^{\alpha}} x^{\alpha-1} e^{-x/\beta} & \infty \geq x \geq 0, \ \alpha \text{ and } \beta \text{ are constants.} \\ 0 & \text{elsewhere} \end{cases}$$

where $\Gamma(\alpha)$ = gamma function = $\int_0^{\infty} y^{\alpha-1} e^{-y} dy$

and α = shape parameter

β = a scale parameter (the mean rate)

Note when $\alpha = 1$, f(x) becomes the density function for the exponential decay distribution. As α increases beyond 1, the distribution approaches the normal distribution more quickly as the number of sample points increases.

By calculating the sample mean, $\bar{x}$, and sample variance S^2, the parameters α and β can be estimated since

$$E(x) = \alpha\beta$$

$$\mathrm{var}(x) = \alpha\beta^2$$

Therefore solving for α and β

$$\alpha = \frac{\bar{x}^2}{S^2} \quad \beta = \frac{S^2}{x}$$ [ref. Phillips and Beightler (1972)]

Phillips and Beightler (1972) presented a new algorithm for generating gamma variates with integer or non-integer parameters, called "Phillips technique". It appeared to have more statistical reliability for gamma distributions with $\alpha<1$ and equal reliability for $\alpha>1$ when compared to other techniques for generating gamma variates.

Phillips technique employs a numerical approximation to generate the gamma variate over valid ranges of α and β. Using stepwise regression, functional relationships for different ranges of α were determined. These permit generation of gamma variates for $0 \leq \alpha \leq \infty$. The method has a great computational advantage over other methods in that it requires the generation of only one random variable each time the algorithm is used. Also for any given α and β parameter set, the functional relationships need only be determined once and the results then stored for any future calls for the same parameter set.

This algorithm was programmed for the model and can be found in the program listing in Appendix III as subroutine GAMMA.

As listed in the appendix it is only valid for $0 \le \alpha \le 2$. If a higher range is needed, the required functional expressions can be found in Phillips and Beightler (1972).

For times between related spills table 3.5 indicates these were best fitted by the negative binomial distribution. The negative binomial distribution is based on the number of independent Bernoulli trials (K + x) which occur before a given number of successes K are observed (It is x that has the negative binomial distribution).

The probability mass function is:

$$f(X=x) = \frac{\Gamma(K + x)}{\Gamma(x + 1)\Gamma(K)} \; p^k (1-p)^x \qquad x = 0, 1, 2, \ldots \infty$$

Therefore the probability that x failures are encountered prior to the K success is:

$$p(x) = \binom{k + x-1}{x} p^k (1-p)^x = \frac{(k + x-1)!}{(x!)(k-1)!} \; p^k (1-p)^x$$

where p = probability of success in one trial

k = number of successes

x = number of failures

Using the moments method the goodness of fit routine discussed in Chapter III determined the distribution parameters listed in Table 3.5.

Note, when K = 1, the negative binomial reduces to the geometric distribution. In the model situation K was not an integer and therefore the concept of the k^{th} success becomes somewhat meaningless. However by making use of a relationship between the negative binomial, Poisson and gamma distributions a negative binomial distributed x was generated for a non-integer K as follows.

Suppose X is from a Poisson distribution with parameter Y, where Y is a random variable generated from a gamma distribution with parameters $\alpha = K$ and $\beta = \frac{1-p}{p}$, where K and p are as previously defined, then X is a negative binomially distributed variate.

In other words

$$f(X=x/Y) = \frac{e^{-Y}Y^{x}}{x!} \qquad x = 0,1,\ldots.$$

and

$$f_Y(y) = \frac{\lambda^K y^{K-1} e^{-\lambda y}}{\Gamma(K)} \qquad 0 \le y \le \infty$$

where $\lambda = \frac{p}{1-p}$

then

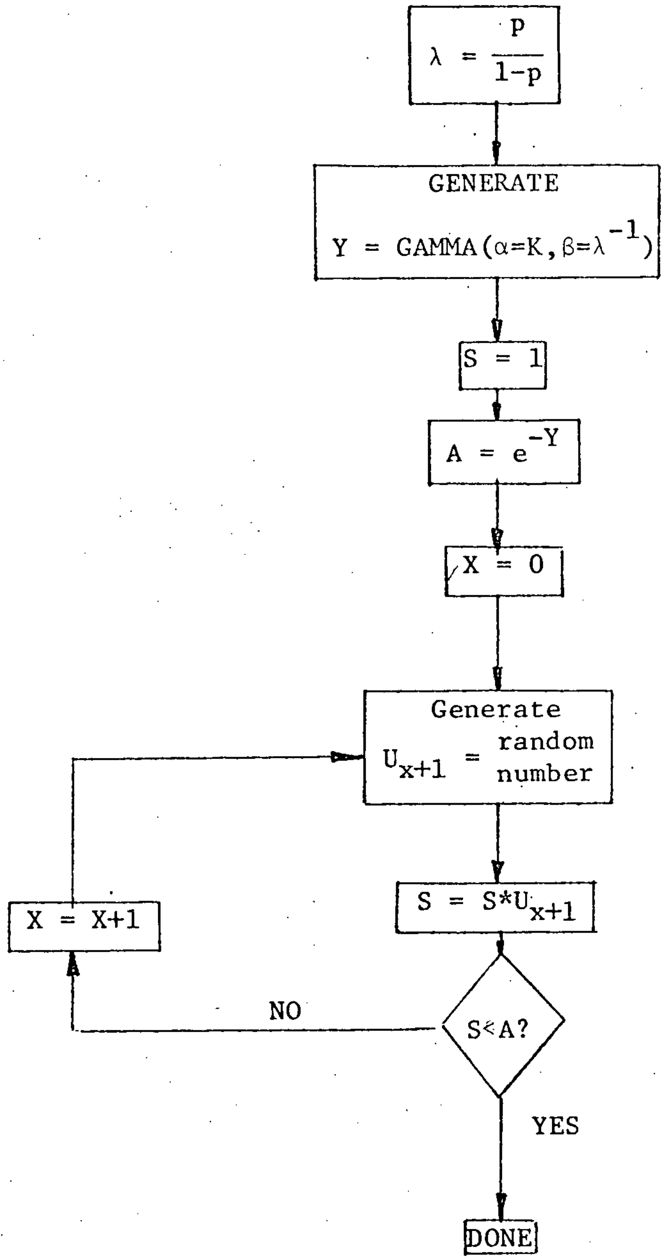
$$f(X=x) = \int_0^\infty f(X=x/Y)\; f_Y(y)\,dy$$

$$= \frac{\Gamma(x+K)}{\Gamma(x+1)\Gamma(K)} \left(\frac{\lambda}{1+\lambda}\right)^K \left(\frac{1}{1+\lambda}\right)^x$$

$$= \frac{\Gamma(x+K)}{\Gamma(x+1)\Gamma(K)}\, p^K (1-p)^x$$

which is the density function for the binomial distribution [Fishman (1973)].

The subroutine NEGBIN then looks like:



Note p and k are given parameters to the routine. The listing for subroutine NEGBIN can be found in appendix III.

The two distributions, gamma and negative binomial, were used in subroutine SPILL to generate three typical mill chemical spill time traces, one for each the 3 major areas. The subroutine SPILL is only called once by the main program. In that one call it generates the spill sequences for the number of hours previously defined in the main program.

In determining the spill time traces, the following procedure is followed for each of the major areas (recovery, recaust, pulping) in turn.

1. Determine time interval (in hours) and amount (in #Na_2SO_4 equiv.) of next unrelated spill using Gamma dist.
2. Determine spills sublocation within current major area
3. Convert spill amount into gallons of spill for chemical typical of sublocation determined in 2.
4. Convert gallons of spill into BOD, TS and SS equivalents (kgs)
5. Record location, time interval, amount (in gals) and BOD, TS and SS equivalents of spill.
6. If current clock time is equal to specified number of hours for current experiment go to 10, otherwise continue
7. Determine if current spill is to be followed by a related spill. If No, then return to 1. If YES, continue.
8. Determine time interval (subroutine NEGBIN) and amount (subroutine GAMMA) of related spill.

9. Return to 3

10. Repeat 1 to 9 for next major area, returning clock to 0.

A copy of a model generated spill sequence for the recovery area can be found in Table 4.1. In Figure 4.3 is a flow chart of subroutine SPILL showing more explicity how the various distributions and decision matices are used in the model.

4.1.2 PRODUCTION AND WATER

Production serves two functions in the model. First as a pointer to decide which water distribution to use and second as a factor to determine the pounds of effluent per ton of production.

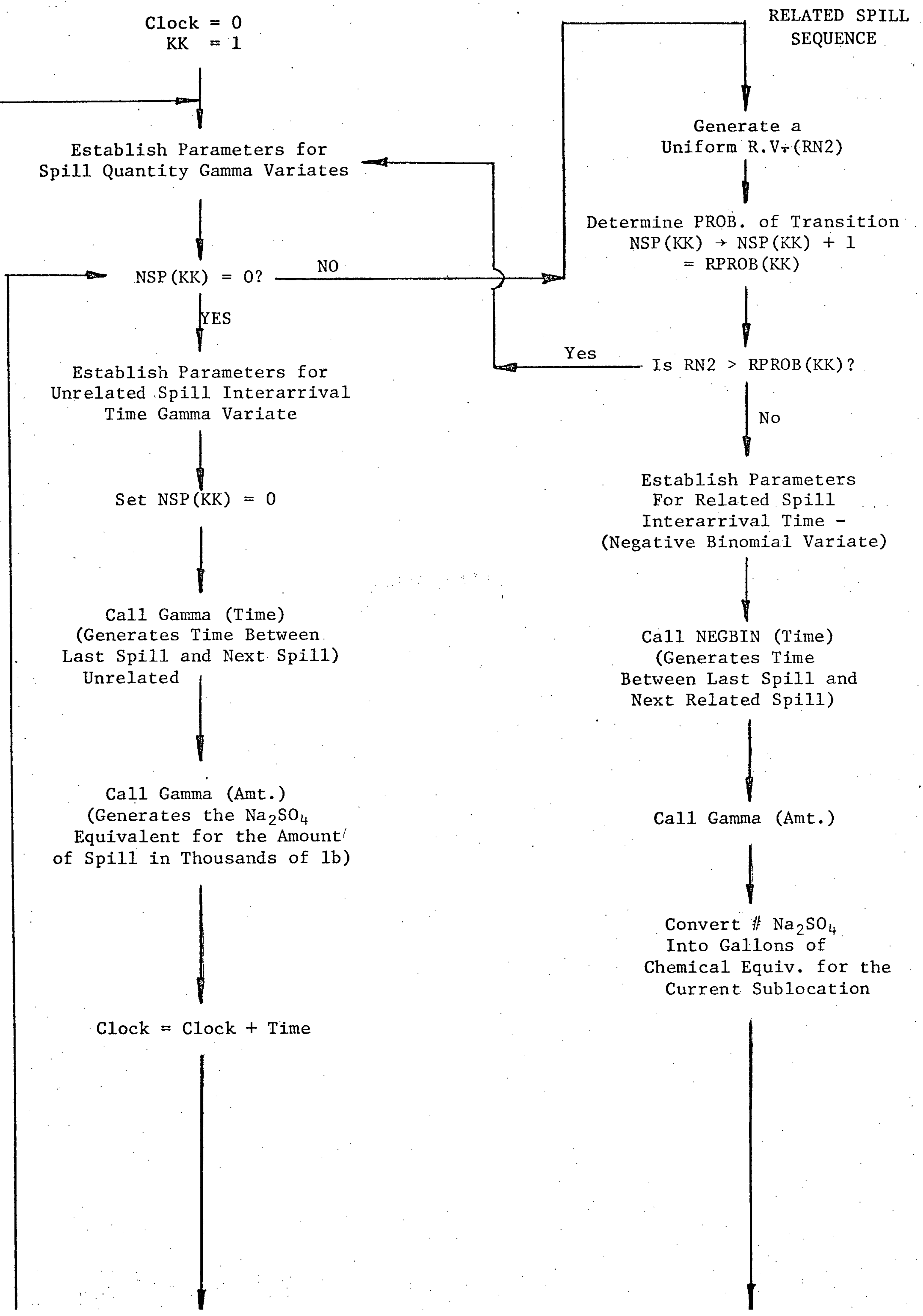
The production data described in Chapter III was used to establish an empirical distribution for production. The cumulative distribution is read into the model as 11 data points (see Table 3.12). To determine a day's production, a uniformly distributed random variable is generated and located in an interval of the cumulative distribution. The production is then determined by interpolation. This is accomplished in subroutine PRODN which returns the daily and hourly production in air dry tons.

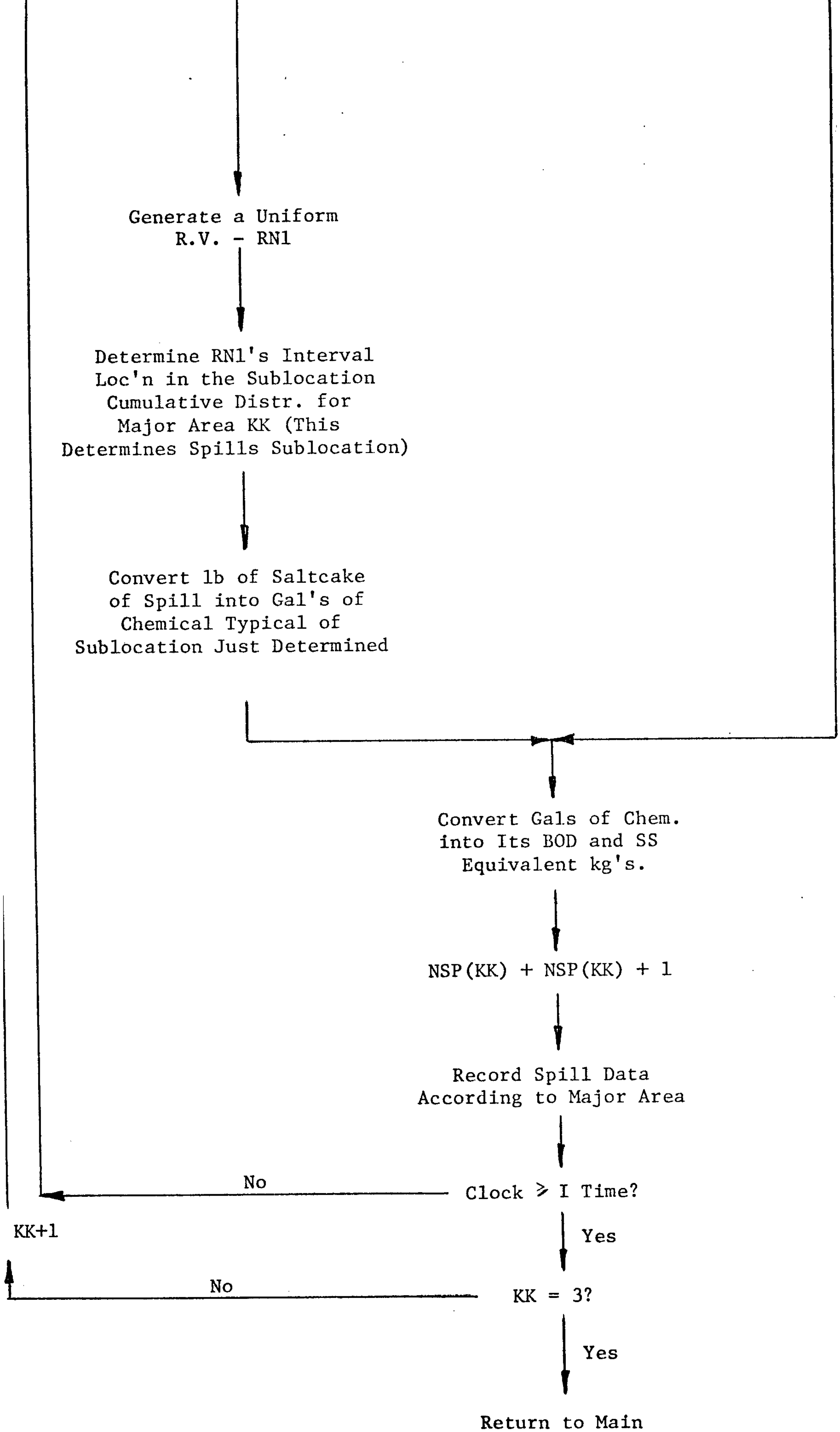
In the model the two cumulative distributions for the water usage are read in as empirical data points (see Table 3.11). The correct water distribution corresponding to production is determined and a uniformly

TABLE 4.1 A SEQUENCE OF SPILLS GENERATED BY THE PULP MILL MODEL FOR THE RECOVERY AREA.

ub ation	Time (hr) Interval	Gal of Liquor	BOD Equiv in KGS	TS Equiv in KGS	SS Equiv in KGS
12	17	242.6849	120.6144	573.2217	0.7231
12	2	23704.7578	11781.2617	55990.6484	71.1143
12	1	95.3940	47.4108	225.3207	0.2862
4	11	767.6257	381.5098	1813.1323	2.3029
4	2	3241.4980	1611.0244	7656.4180	9.7245
3	615	4856.2422	660.4467	3234.2573	4.8562
3	8	22301.9375	3033.0630	14853.0898	22.3019
4	11	1954.2971	976.2556	4639.6680	5.8929
4	3	6323.2930	3142.6763	14935.6172	18.9699
4	2	466.7375	231.9686	1102.4341	1.4002
3	95	4652.9336	632.7986	3098.8538	4.6529
3	5	9.2318	1.2555	6.1484	0.0092
4	25	227.6367	113.1355	537.6780	0.6829
4	1	842.4756	418.7102	1989.9275	2.5274
4	134	1971.1541	979.6633	4655.8633	5.9135
3	108	9707.7695	1320.2563	6465.3711	9.7078
3	7	22600.6914	3073.6934	15052.0586	22.6007
3	1	6695.9023	910.6423	4459.4688	6.6959
3	5	686.5461	93.3703	457.2395	0.6865
3	1	6210.2383	844.5920	4136.0156	6.2102
3	2	40255.9102	5474.9375	26811.1016	40.2569
3	4	1004.3867	136.5986	668.9214	1.0044
4	188	3733.5679	1855.5830	8818.6875	11.2007
3	110	8122.2852	1104.6304	5409.4414	8.1223
3	2	30605.3438	4162.3242	20383.1563	30.6053
3	110	6842.8867	930.6323	4557.3594	6.8429
3	1004	1199.9780	163.1970	799.1853	1.2000
3	5	4448.3008	604.9688	2962.5681	4.4483
3	1	16499.0234	2243.8667	10988.3477	16.4990
3	2	2926.1909	397.9617	1948.8430	2.9262
4	15	4452.5664	2212.9253	10516.9609	13.3577
4	142	12016.1680	5972.0352	28382.1914	36.0485
4	2	7635.3555	3794.7715	18034.7109	22.9061
4	5	427.8833	212.6580	1010.6604	1.2836
4	5	25.4332	12.6403	60.0731	0.0763
4	21	3713.6399	1848.1638	8783.4258	11.1559
4	4	975.9705	485.0571	2305.2427	2.9279
4	161	7555.1367	3754.9026	17845.2344	22.6654
3	234	18635.1602	2534.3813	12411.0156	18.6351
3	2	4495.1289	611.3374	2993.7559	4.4951
3	95	812.3699	110.4823	541.0383	0.8124
3	1140	20453.2227	2781.6377	13621.8438	20.4532
4	12	2062.6860	1025.1548	4872.0625	6.1881
4	2	1513.4216	752.1704	3574.7024	4.5403
4	3	106.2987	52.8304	251.0776	0.3189
4	3	90.4520	44.9546	213.6476	0.2714
4	93	651.2300	323.6611	1538.2053	1.9537
4	5	3793.2065	1885.2234	8959.5547	11.3796
4	3	12821.8594	6372.4609	30285.2344	38.4656
4	327	340.3679	169.1628	803.9490	1.0211
4	54	1280.6885	636.5020	3024.9866	3.8421
4	398	1533.7502	762.2737	3622.7186	4.6013

FIGURE 4.3 FLOW CHART OF SUBROUTINE SPILL




Generate a Uniform
R.V. - RN1
Determine RN1's Interval
Loc'n in the Sublocation
Cumulative Distr. for
Major Area KK (This
Determines Spills Sublocation)
Convert lb of Saltcake
of Spill into Gal's of
Chemical Typical of
Sublocation Just Determined
Convert Gals of Chem.
into Its BOD and SS
Equivalent kg's.
NSP(KK) + NSP(KK) + 1
Record Spill Data
According to Major Area
No
Clock ⩾ I Time?
Yes
KK+1
No
KK = 3?
Yes
Return to Main

distributed random number is located within a distribution interval. The water usage is then determined by interpolation between the interval end points.

In subroutine WATER, the daily and hourly $\frac{(daily)}{24}$ water usage levels are determined. Also the hourly flows for the six mill streams are calculated using the proportions presented in Table 3.14.

The results of calling the two subroutines PRODN and WATER for each simulated day are recorded for the number of days specified at the start of the experiment. $(\frac{\#\text{ of hours of experiment}}{24} + 1)$. A copy of this data as computed by the model is in Table 4.2. A complete record of this data for the specified number of days is created by the model before the actual experiment is run.

4.1.3 BRINGING IT ALL TOGETHER

Having created the spill production and water usage data for the specified number of days the model uses this information, combined with hourly data generated by subroutine REGUL, to generate the mill effluent time trace.

Subroutine REGUL is called by the main program each hour of simulated time. It creates a regular effluent stream to account for chemical and fiber losses not classified as spills since by the very nature of the pulping process, a certain amount of effluent is generated no matter how adequate

Production		Fiber Losses (Tons/Hr)			Water Flows ($x10^6$ Gal/Hr)					
Day	Ton/Hr	1	2	3	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
1	50.02	0.29	0.08	0.04	1.34	1.10	0.17	0.05	0.04	0.07
2	37.91	0.83	0.03	0.04	1.18	0.97	0.15	0.05	0.04	0.07
3	15.40	0.67	0.04	0.04	1.32	1.09	0.17	0.05	0.04	0.07
4	56.74	0.54	0.03	0.04	1.40	1.15	0.18	0.06	0.04	0.08
5	47.80	0.38	0.08	0.04	1.41	1.16	0.18	0.06	0.04	0.08
6	54.92	0.54	0.03	0.04	1.44	1.18	0.19	0.06	0.04	0.08
7	41.31	0.17	0.04	0.04	1.03	0.85	0.13	0.04	0.03	0.06
8	18.63	0.25	0.04	0.04	1.02	0.84	0.13	0.04	0.03	0.06
9	46.78	0.21	0.03	0.04	1.41	1.16	0.18	0.06	0.04	0.08
10	21.11	0.38	0.08	0.04	1.03	0.85	0.13	0.04	0.03	0.06
11	49.20	0.54	0.08	0.04	1.39	1.14	0.18	0.06	0.04	0.08
12	43.41	0.54	0.08	0.04	1.45	1.19	0.19	0.06	0.05	0.08
13	43.39	0.33	0.08	0.04	1.33	1.09	0.17	0.05	0.04	0.07
14	52.06	0.17	0.04	0.04	1.23	1.01	0.16	0.05	0.04	0.07
15	46.58	0.17	0.04	0.04	1.37	1.13	0.18	0.06	0.04	0.08
16	51.99	0.17	0.03	0.04	1.41	1.16	0.18	0.06	0.04	0.08
17	38.67	0.38	0.21	0.04	1.03	0.85	0.13	0.04	0.03	0.06
18	53.08	0.46	0.04	0.04	1.35	1.11	0.17	0.05	0.04	0.08
19	50.61	0.50	0.08	0.04	1.33	1.10	0.17	0.05	0.04	0.07
20	54.08	0.17	0.13	0.04	1.37	1.13	0.18	0.06	0.04	0.08
21	41.83	0.29	0.08	0.04	1.36	1.12	0.18	0.05	0.04	0.08
22	49.28	0.46	0.21	0.04	1.30	1.07	0.17	0.05	0.04	0.07
23	53.72	0.50	0.04	0.04	1.35	1.11	0.17	0.05	0.04	0.08
24	46.34	0.63	0.08	0.04	1.44	1.18	0.19	0.06	0.04	0.08
25	49.54	0.33	0.04	0.04	1.36	1.12	0.18	0.05	0.04	0.08
26	36.42	0.54	0.08	0.04	1.18	0.97	0.15	0.05	0.04	0.07
27	54.01	0.50	0.25	0.04	1.33	1.09	0.17	0.05	0.04	0.07
28	44.00	0.50	0.08	0.04	1.44	1.18	0.19	0.06	0.04	0.08
29	52.46	0.29	0.03	0.21	1.29	1.06	0.17	0.05	0.04	0.07
30	52.49	0.17	0.04	0.04	1.39	1.14	0.18	0.06	0.04	0.08
31	43.65	0.54	0.04	0.04	1.45	1.19	0.19	0.06	0.05	0.08
32	56.17	0.54	0.08	0.08	1.29	1.06	0.17	0.05	0.04	0.07
33	51.01	0.50	0.08	0.04	1.39	1.14	0.18	0.06	0.04	0.08
34	47.96	0.03	0.03	0.04	1.41	1.15	0.18	0.06	0.04	0.08
35	48.04	0.53	0.08	0.04	1.48	1.21	0.19	0.06	0.05	0.08
36	48.09	0.50	0.13	0.04	1.26	1.04	0.16	0.05	0.04	0.07
37	21.84	0.25	0.04	0.04	1.14	0.93	0.15	0.05	0.04	0.06
38	57.46	0.17	0.08	0.04	1.38	1.13	0.18	0.06	0.04	0.08
39	43.49	0.67	0.08	0.21	1.34	1.10	0.17	0.05	0.04	0.07

the process control. To account for this the regular effluent flows for the six major effluent streams were statistically modelled by assuming a normal distribution with empirically determined means and standard deviations for each of the streams. (These parameters can be found in section 3.1.4). Sampling stochastically each hour from these normal distributions a reasonable representation of the mill's regular effluent concentration is generated. To determine actual effluent loads the sub-routine multiplies each of the six stream variates by their corresponding water flows for that hour and returns the BOD and SS levels in pounds for each of the streams (see Figure 4.1). To get a true mill representation, the spills and regular effluent are superimposed.

The following steps are executed each simulated hour by the main program to generate the mill's final effluent (see also Figure 4.2)

0) T = 0

1) Read day number, hourly production and hourly water flow for six streams for current day

2) Determine water flows (MUSG/hr) for 3 main outfalls for current day (see Figure 4.1)

3) Generate this hours regular effluent levels (lbs/hr)

   CLOCK = CLOCK + 1

   T = T +1

4) Is there a spill this hour in any of the 3 major areas?

   If No go to 7

   If YES continue

5) Add BOD and SS levels of spill to the corresponding regular effluent stream
6) Read time and amount of next spill in area which just had spill
7) Record this hours effluent activity to be totalled on a daily basis
8) Add BOD and SS for the streams, which make up the three mill outfalls, together
9) Convert lbs/hr of effluent for the three outfalls into concentration units mg/l
10) Record BOD and SS for each main outfall
11) If CLOCK = specified number of hours for current experiment stop, otherwise continue
12) If T = 24 (has current day ended) go to 14, otherwise continue
13) Go to 3
14) Record BOD and SS as lbs/ton along with production, and total water usage for current day
15) T = 0
16) Go to 1.

4.1.4 VALIDATION OF PULP MILL MODEL

The validation of a simulation model is definitiely a "pandora's box". It philosophically represents the acid test for any model but in reality cannot absolutely be solved. This is a consequence of the lack of a technique or groups of techniques which can establish beyond reasonable doubt that the model is a true representation of reality. There is also the problem of reality itself since once data is gathered and interpretated we have taken the "reality" out of its natural environment and imposed our own conceptual interpretation.

However in approaching this seemingly impossible task the original purpose of the model must be kept in mind. Often a major simplification of a system can give a reasonable representation of the system's behaviour on the same scale as the model's structure. For example to model a truck carrying produce from warehouse A to warehouse B, we don't require information on engine behaviour or axle molecular structure, as long as this information is not needed to fulfill the model's purpose. For example a broken axle can usually be modelled as a stochastic event quite accurately rather than modelling the molecular behaviour resulting in an axle fracture. This example is rather extreme but the major point is all too often forgotten. You can't get more than you put in and don't put in more than you need!

Before validating the overall simulation tests were made on the various distributions used in the model to check that they were functioning as designed.

Goodness of fit tests were run for the gamma distribution to insure that the routine used was indeed generating gamma variates with the given parameters. Subroutine GAMMA was used to generate 250 variates for spill Na_2SO_4 amounts and compared to the theoretical gamma distribution with the same parameters as those used to generate the variates. The results are summarized below;

Area	R	λ	kS(.05)	D stat.
Recovery	.414	.024	.086	.039
Recaust	.515	.045	.086	.028
Pulping	1.19	.064	.086	.034

For all three areas the D statistic <kS(.05) implying that the distributions are the same.

Similarly 250 time intervals between unrelated spills were generated for the three areas using subroutine GAMMA and goodness of fit comparison were run. These results are listed below:

Area	R	λ	kS(.05)	D stat.
Recovery	.511	.0019	.086	.080
Recaust	.807	.0017	.086	.061
Pulping	1.101	.001	.086	.073

Again the distribtuions are the same at the .05 significance level. The subroutine GAMMA therefore is creating the expected variates adequately.

Next, subroutines PROD and WATER were checked. It would be expected that the real data and the data created by the model would correspond for production and water since the distributions used were empirically based. However a Kolmogorov - Smirnov two sample goodness of fit test was done for both production and water in order to reinforce confidence in the model technique. The results are summarized below:

Distribution	kS(.05)	D(N,M)
Production	.1923	.051
Water	.1923	.073

N = 100
M = 100

To test the complete model using the technique of historical verification,(1) rather than generate a spill sequence and daily-operating levels of production and water flows, real mill data was used as input. The effluent data available for the real world situation represented averages over a period of days. By forcing the model to average over the same time span as the real data, a comparison of the results was possible.

The inputs to the model were:

1. Empirical spill sequences for the three major area, converted to chemical and BOD and SS equivalents in the same manner as described earlier.

---

(1) Historical validation involves comparing the model and the real world for the same inputs.

2. Daily water usage for the six mill streams and the corresponding production, all taken from mill operating summaries, for the same time span as the spills.

The regular effluent generation was untouched since no corresponding real data for this time span was available.

For each simulated day the lbs/ton of BOD and SS were determined and averaged over a certain number of days to correspond to the "real world" data. In the mill situation the samples analyzed represented mixtures of samples taken over 4 to 7 days. The results for BOD and SS are plotted in Figure 4.4 and 4.5. These plots indicate a reasonable congruence of behaviour between model and mill data. Both plots have numerous intersections of the real and simulated results. Also the noticable or "unusual" peaks generally coincide. There is some disagreement in magnitude for the first high peak (data point at time 4); however, looking at the real data, this time interval includes a mill start up for which a considerable amount of the spill data could not be deciphered from the conductivity charts. Also the model was not designed with the ability to generate a mill start up effluent time trace. Kolmogorov-Smirnov two sample goodness of fit tests were run for both SS and BOD for these runs. The results are summarized below:

	D(N,M)	kS(.05)
SS	.327	.414
BOD	.207	.414

N = 22, M = 22

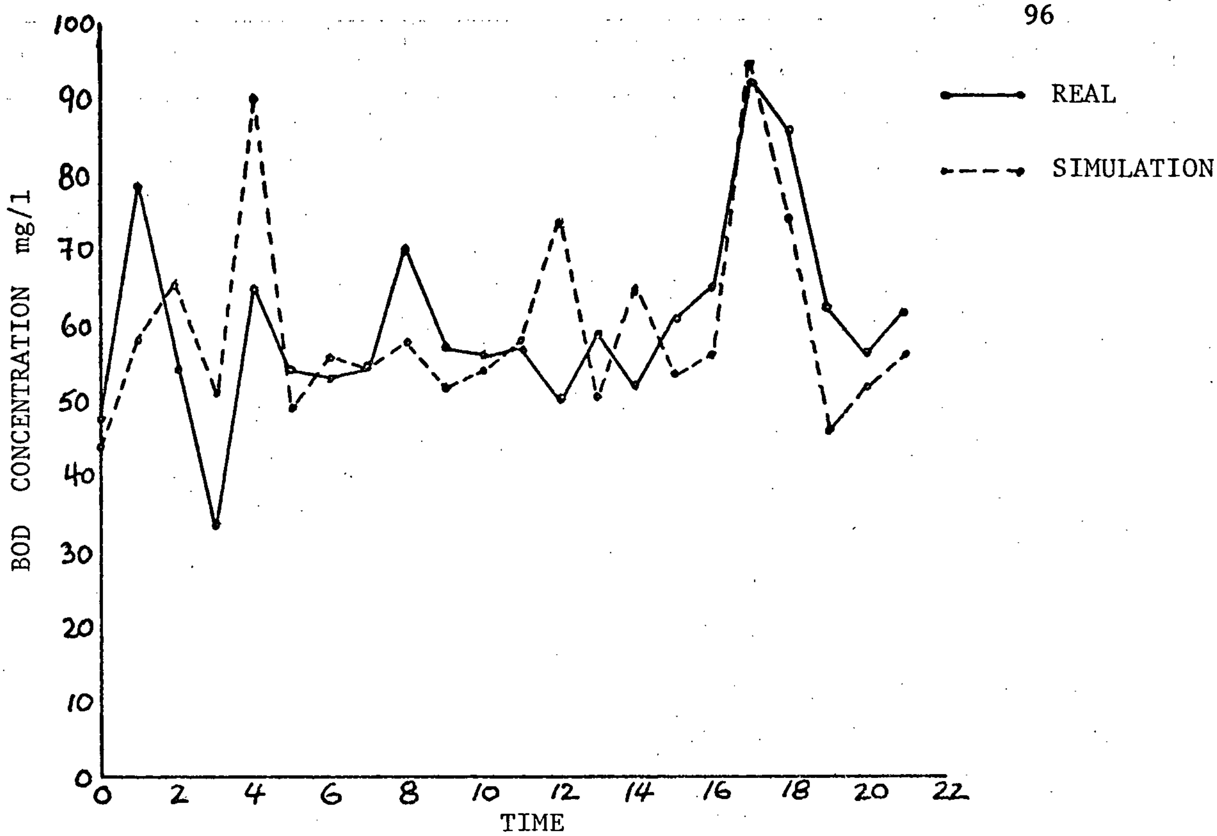


FIGURE 4.4 : BOD VALIDATION FOR PULP MILL MODEL. REAL EFFLUENT AND SIMULATION GENERATED EFFLUENT WITH IDENTICAL INPUT

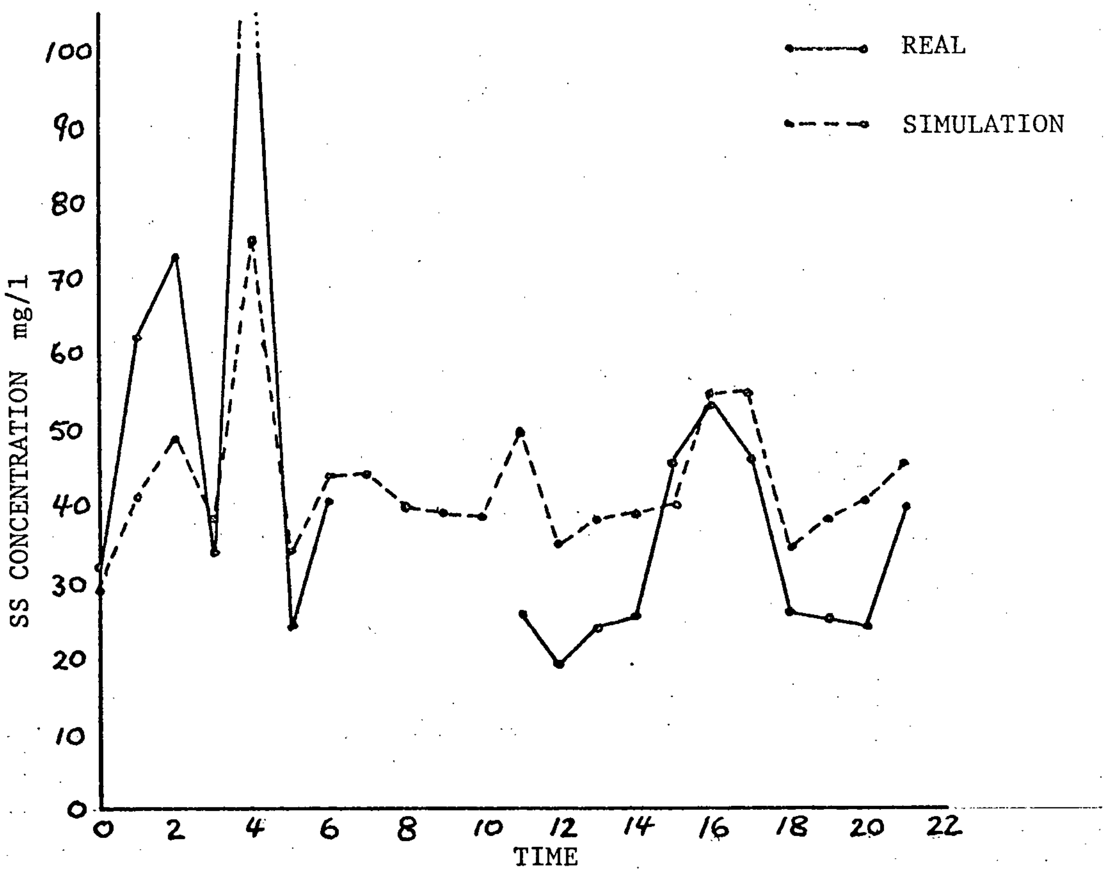


FIGURE 4.5 : SS VALIDATION FOR PULPMILL MODEL. REAL EFFLUENT AND SIMULATION GENERATED EFFLUENT WITH IDENTICAL INPUT

The final verification test for the pulp mill model consisted of a K-S goodness of fit between real world and model effluent data using model generated spill sequences. The model was run for 100 days and the BOD and SS, expressed as pounds per ton, were averaged for every 5 out of 7 days. The goodness of fit results are as follows:

	D(N,M)	KS(.05)	
SS	.471	.482	
BOD	.124	.482	N = 17, M = 15

Therefore we cannot reject the hypothesis that the two distributions are different.

4.2 WASTE TREATMENT MODEL

4.2.1 The General Structure

In Chapter III the waste treatment model's mathematical development was discussed and generalized solutions for BOD effluent from the lagoon and SS effluent from the clarifier were derived (see eqns 3.7 and 3.10). These equations were programmed in FORTRAN and a listing can be found in Appendix IV. Although the model was designed to use the pulp model's output as input, it is completely independent of the pulp mill model structure and can be used to model the systems behaviour for any given influent. The program requires certain system parameters (such as the lagoon area, depth, and clarifier depth) as input before an experiment can be run. These are listed in the appendix with typical values and units indicated. The model was designed to function as an aid to mill management in designing a clarifier-lagoon treatment system. Consequently, essential design parameters can be changed easily. The program also determines capital costs and yearly operating costs for both clarifier and lagoon in each run.

A variation of the program was written which permitted artificially increased hourly loads to the system for any given time span (up to 24 hours). The increased load is a multiplicative factor times the original load being considered as the normal operating influent time trace. For example, the pulp mill model creates a typical BOD and SS effluent time series on an hourly basis. This is then given to the treatment model as influent. On prompting from the program, the user can specify a multiplying factor, its active time span and the hour to start the increased load. For example if the user gives a factor of 10 for a time span of 5 hours starting at hour 100 the program will multiply the BOD and SS influent concentrations by 10 for the hours from 100 through to 105 and use these as influent data for those hours of simulated operation. It then returns to the original time trace for the remainder of the run. This procedure gives the user considerable versatility to experiment with the systems response to various degrees of shock loading. It also provides some interesting information on the systems recovery times. This feature was prompted by a NCASI study published in 1974 (Gove, 1974).

The model permits the user to combine the three mill outfall streams into 4 different influent combinations to the treatment model. This was introduced as a consequence of the different arrangements existing at various mills. Some mills combine the general and acid outfalls between the clarifier and the lagoon, others only feed the general and machine room streams into the treatment system and completely bypass the system with the acid stream. The combination desired is specified at the beginning of a run (see appendix IV listing and variable definition). Schematics of the 4 possible combinations are shown in Figure 4.6. The different combinations result in various hydraulic loadings to the system and therefore provide an opportunity to experiment with alternate facilities and observe their effluent outcomes.

4.2.2 The Model

The waste treatment model is a mathematical model evaluating the equations developed in Chapter 3, for $t = 1$ hour. This assumes that the system operates in a steady state over each hour. (The hydraulic load and influent concentration are constant). At the end of the hour, the final concentration of each tank in the series model is made the initial concentration for the next hour. The next hour's hydraulic load and influent concentration are determined, system parameters such as detention time are altered (if the hour begins a new day) as required and the system is run again for another hour. The process is repeated for the specified number of hours. At the end of each hour the model records the following:

1. Influent SS concentration into clarifier (mg/l)
2. SS concentration of stream which bypasses clarifier (mg/l)
3. SS concentration of clarifier effluent (mg/l)
4. BOD concentration into clarifier (mg/l)
5. BOD concentration of stream which bypasses clarifier (mg/l)
6. BOD concentration of lagoon effluent (mg/l).

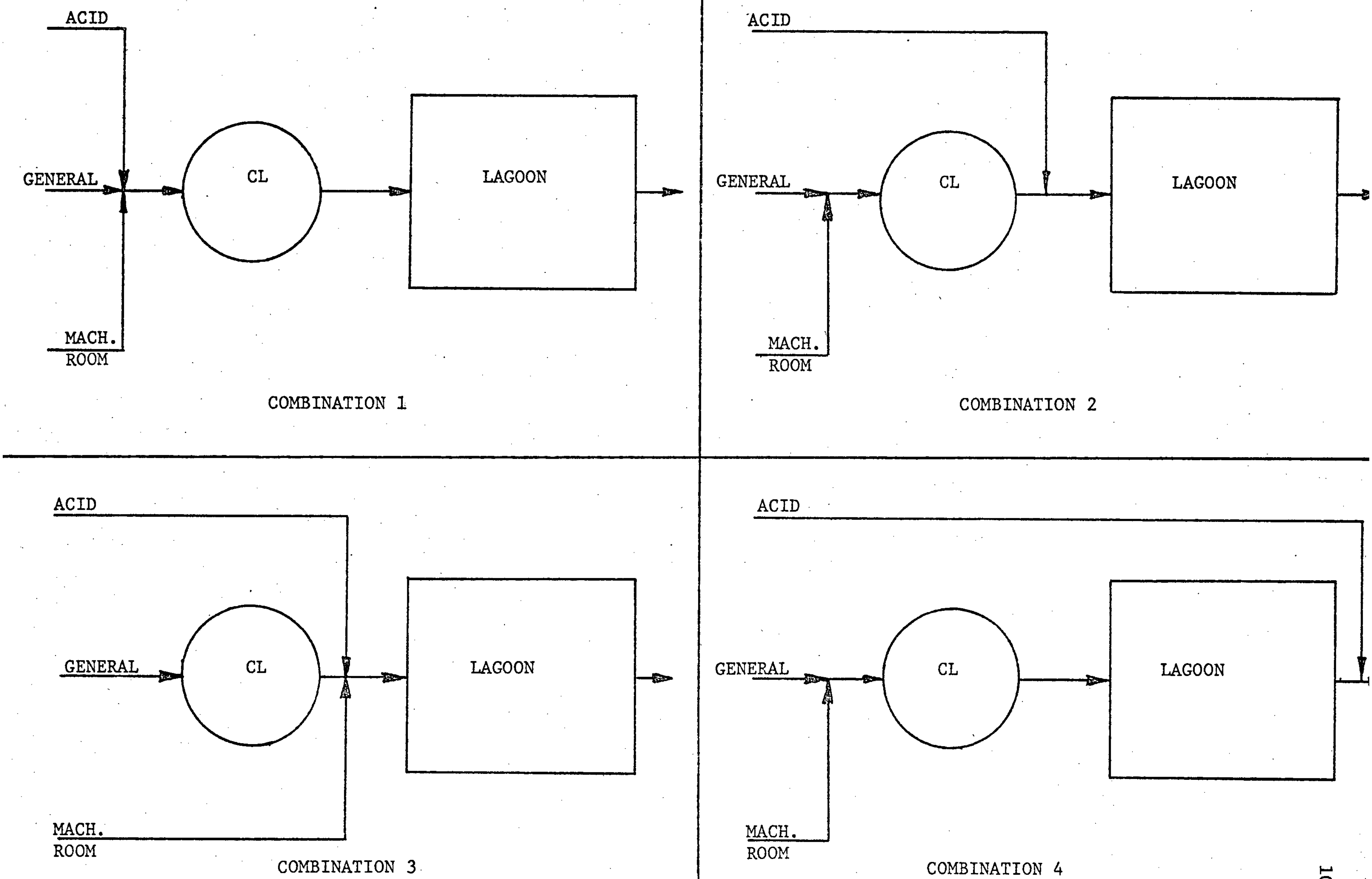


FIGURE 4.6 FOUR WASTEWATER TREATMENT PLANT CONFIGURATIONS POSSIBLE IN WASTE TREATMENT MODEL

At the end of each 24 hour period the model records the total amounts of SS and BOD which entered and left the treatment system expressed as pounds per ton of mill production. Also lagoon generated SS is given as the mg/l average for the day as well as lbs/ton.

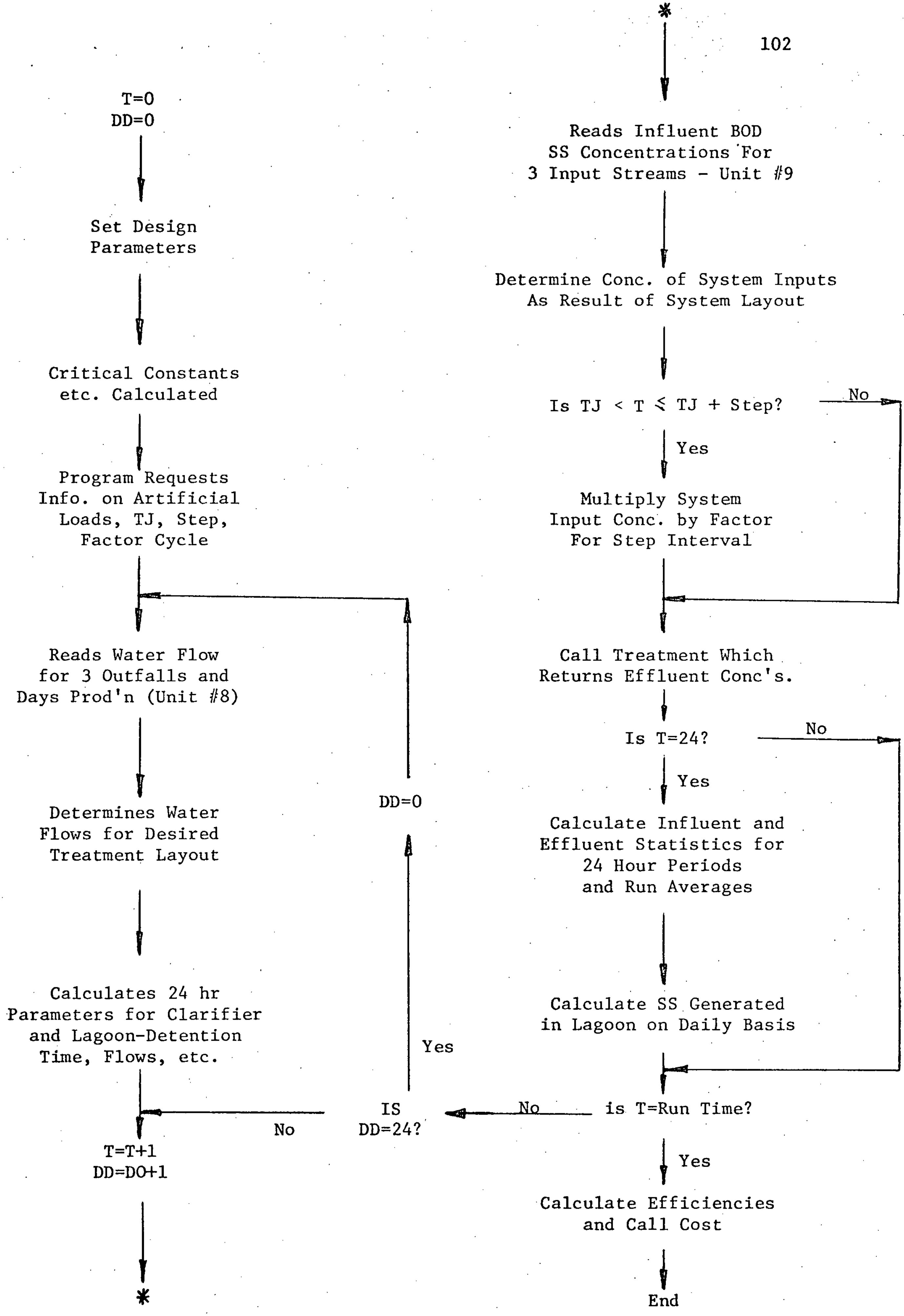
The model is composed of three parts, the MAIN program, subroutine TREAT and subroutine COST. Subroutine TREAT is called every simulated hour by MAIN while subroutine COST is called once at the end of the run. A general flow chart of the model can be found in Figure 4.7.

Note in running the model, the user has control over certain design parameters. These include:

a. Steady state time interval for clarifier (in secs) and lagoon (in hours).
b. The rate of settling as a first order linear reaction (in sec^{-1})
c. Clarifier detention time (hours)
d. Estimated average daily flow into clarifier (MUSGD)
e. Clarifier depth (ft)
f. Treatment system layout (1 to 4)
g. Biological reaction rate in lagoon (hr^{-1})
h. Lagoon water temperature °C
i. Lagoon surface area (acres)
j. Lagoon depth (ft).

To calculate the precise mass of effluent which is discharged over a time interval TI the following expression must be evaluated;

FIGURE 4.7 FLOW CHART OF WASTE TREATMENT MODEL



Mass of pollutant past any point over the interval of time 0 to TI $= \int_0^{TI} Q^*C(t)dt = Q\int_0^{TI} C(t)dt$

if we assume Q is constant for the time 0 to TI, where

C(t) = the distribution of pollutant concentration over time

Q = hydraulic flow at point of interest in equivalent units

Due to the clarifier's short detention time it may experience large changes in effluent concentration over the period of one hour. Consequently, this expression was evaluated for the clarifier SS effluent. By setting C(t) equal to equations 3.7 we get

$$\text{Mass of SS(kgs)} = Q\int_0^{TI} \frac{C_{IN}}{\alpha^2}\left[1-e^{\frac{-\alpha t}{Tc}}\right] + e^{\frac{-\alpha t}{T_c}}\left[C_2(o) + C_1(o)\frac{t}{T_c} - \frac{C_{IN}(t)}{T_c(1+k_c Tc)}\right]$$

$$= Q\left[\frac{C_{IN}{*}TI}{\alpha^2}\left[1+e^{\frac{-\alpha TI}{T_c}}\right] + C_2(0)\frac{T_c}{\alpha}\left[1-e^{\frac{-\alpha TI}{T_c}}\right] + C_1(0)\frac{T_c}{\alpha^2}\left[e^{\frac{-\alpha TI}{T_c}}-1\right] - C_1(0)\frac{TI}{\alpha}e^{\frac{-\alpha TI}{Tc}}\right]$$

Where Q in in litres/sec Eqn. 4.1

$\alpha = 1 + k_c{*}\ T_c$

TI = 3600 secs.

For the lagoon it was assumed the 5 day detention time would buffer system surges resulting in very small BOD effluent concentration changes within one hour. The hourly mass of BOD effluent is therefore the product of BOD concentration at time t = 1 hr times hydraulic flow for that hour.

At the start of a model experiment the tank volumes for the clarifier model are determined. The model determines a new one tank detention time parameter every 24 hours. This is:

$$T_C = \text{REST} = \text{clarifier tank's detention time}$$

$$= \frac{\text{Volume of tank 1 (or tank 2) in litres}}{\text{flow into tank in litres/sec}}$$

$$= \text{residence time in secs.}$$

The linear "reaction rate" settling constant is

$$CK = \frac{.104}{\text{clarifier depth in cm}} \qquad \text{(see Chapter III)}$$

Similarly for the lagoon the model determines the detention times for each of the three equal volume tanks.

$$T_L = TT = \text{lagoon tanks detention time}$$

$$= \frac{\text{Volume of a tank in litres}}{\text{flow into tank in litres/h}}$$

$$= \text{time in hours}$$

and then the BOD removal rate constant KK according to the relation

$$KK = [(1.256) * (1.032)]^{TEMP/24}$$

discussed in Chapter III.

4.2.3 Subroutine TREAT

Subroutine TREAT reads the clarifier and lagoon influent concentrations each hour and evaluates the system's effluent concentrations. The final concentrations for each tank are made the initial concentrations for the next hour. The present structure of the subroutine uses the generalized model developed in section 3.2.3 for the lagoon and the model developed in section 3.2.1 for the clarifier.

Although the primary purpose of the clarifier is to remove SS, some BOD is removed as SS. To accommodate this, the model assumes that 10% of the BOD which passes through the clarifier settles out and is not passed on to the lagoon.

4.2.4 The COST Subroutine

Using the relationships developed in section 3.3 the subroutine COST evaluates the four cost relationships at the end of the simulation experiment. These are recorded and comprise the final statements in the output of the waste treatment model.

4.2.5 Waste Treatment Model Validation

A validation of the complete waste treatment model was not possible due to lack of available data. The data which was used for historical validation was supplied by Weyerhaeuser, Kamloops for their operational aerobic stabilization lagoon. The two months of data obtained consisted of daily BOD concentration, expressed in mg/l, at the entrance to the sedimentation ponds and the exit of the lagoon, and the daily hydraulic load to the lagoon in MUSGD. The sedimentation ponds are the final stage in SS removal before entering the lagoon and have a detention time of a few hours. The influent concentration to the lagoon was assumed to be equal to the sedimentation ponds influent.

Using this data it was possible to validate tha lagoon section of the model. Referring to Figure 3.5, by making

Q1 = 0

Q2 = lagoon hydraulic load (1)

Z = influent BOD concentration (mg/1)

the lagoon formulation, as expressed in equation 3.8, can be obtained from equation 3.10. Lagoon area is 74 acres and it's depth is 15 ft. Input temperature was approximately 40°C and the effluent 30°C, therefore the average temperature of 35°C was used.

Since the data was on a daily basis the model could be run either on an hourly basis (t = 1 hour) using the same input concentration for each of the 24 hours, or on a daily basis, using each input concentration and hydraulic flow only once and running the model for t = 24 hours.

In Figure 4.8 are plots of a) recorded effluent data for the actual lagoon, b) the simulation run on an hourly basis (the point plotted is the concentration at hour 24 of each day) and c) the simulation run on a daily basis. Sixty data points are plotted. As seen from the figure the model, starting at initial concentrations of zero in all three tanks, took approximately 8 days to reach reasonable operating levels. Both the t = 1 and t = 24 plots appear to give a resonable fit to the data. The model following

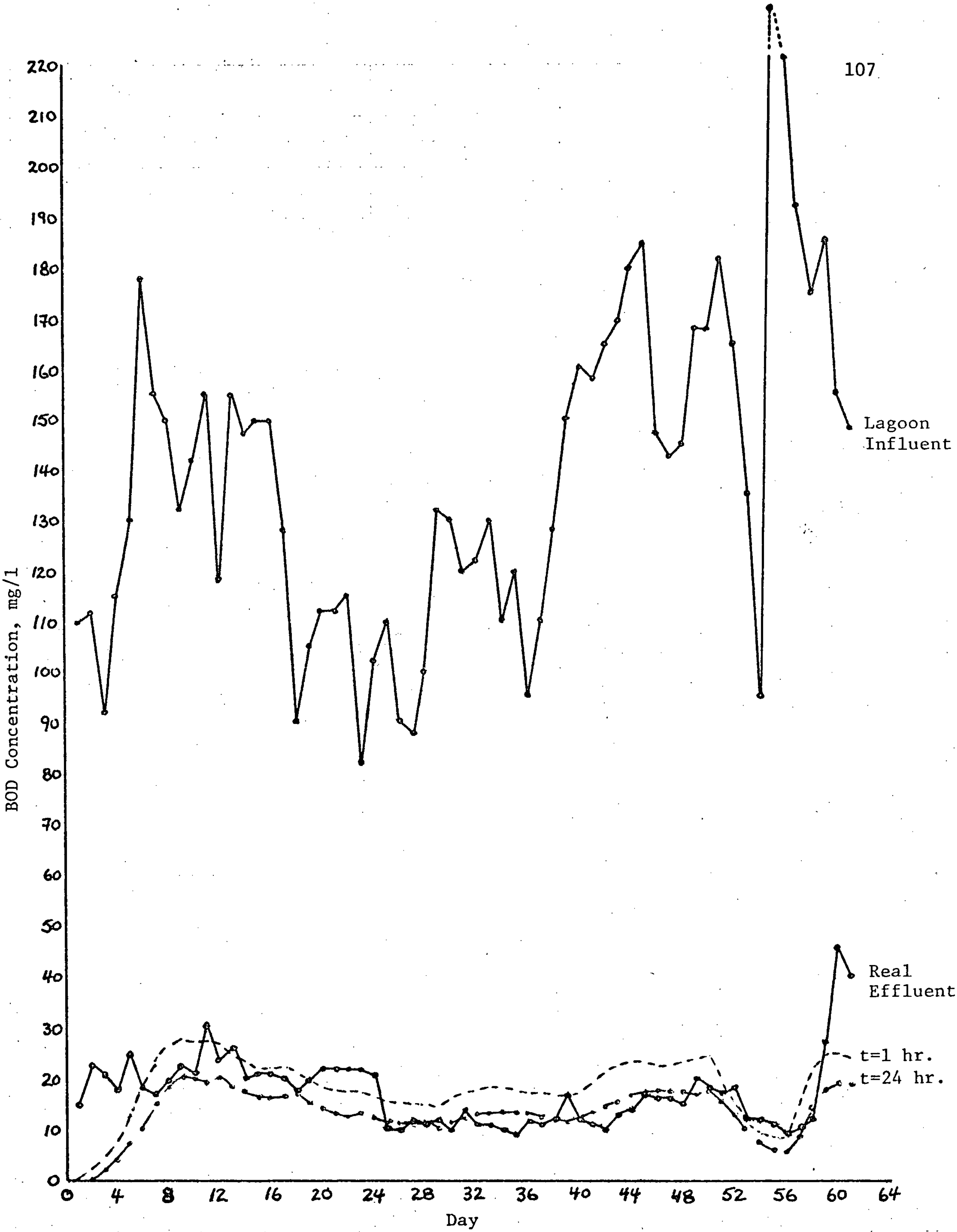
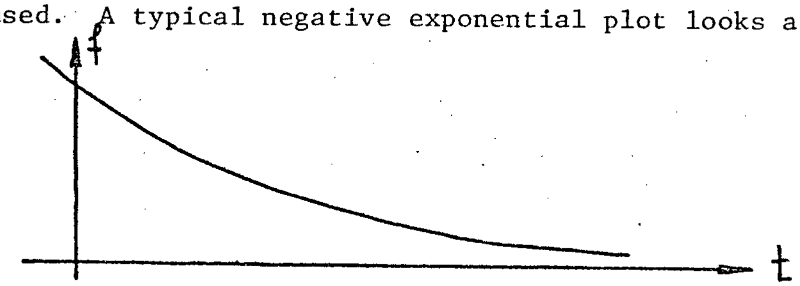


FIGURE 4.8

LAGOON VALIDATION SHOWING REAL DATA EFFLUENT AND SIMULATION GENERATED EFFLUENT (USING SAME INFLUENT) FOR STEADY STATE OPERATION TIME, t = 1 hr and t = 24 hr the sudden drop in concentration for days 50 to 56 comes as a consequence of six low flow and zero pulp production days at the mill. The flows on day 53 fell to 16.2 MUSG/day (normal is approximately 60 MUSG/day).

There are certain implications in using the model in a steady state for t = 1 hour. As seen in eqn. 3.8, there are a considerable number of exponential terms with time in their exponent. Iterating the model each hour, only a very small portion of the exponential decay curve is actually used. A typical negative exponential plot looks as follows:



where $f = e^{-ct}$ and c = constant t = time

For the lagoon model a typical value of c would be:

$$c = \frac{\alpha}{T_L} = \frac{1+k_L T_L}{T_L} = \frac{1+.0169*40.}{40.}$$

$$= .025 + .0169$$

$$= .0419$$

Therefore for

t = 1 hour $f = e^{-.0419*1} \cong .96$

while for

t = 24 hour $f = e^{-.0419*24} \cong .37$

Looking at equation 3.8 for t = 1 hour the first term becomes quite insignificant while the second term is very much the dominating element. In fact if the influent BOD concentration is considerably larger than the initial concentrations of the three tanks, the $C_{B3}(t)$ value could actually experience a drop from its previous value although the influent is high. (This predicted drop in the effluent concentration due to a sudden increase in the influent concentration actually did occur when the model was run using artificial shock loads. The model recovered within 3 hours however and still reflected the time delayed response of the system). This counter intuitive result comes from the steady state assumptions made in the model development.

For t = 24 hours the first term becomes a much more significant term while the impact of the second term is reduced by about 60%. As t approaches infinity, the output concentration approaches a lower limit.

$$\lim_{t \to \infty} C_{B3}(t) \longrightarrow \frac{CINBOD}{\alpha^3}$$

Using typical values, the time until $C_{B3}(t) = .99 * \frac{CINBOD}{\alpha^3}$

would be

$$t = \frac{40}{1,49} \times 4.6$$

$$- 123 \text{ hours} - 5 \text{ days}$$

(ie. $.99 = 1 - e^{\frac{-\alpha t}{TL}}$ $\therefore$ $\ln .01 = -\alpha \frac{t}{TL}$ or $t = \frac{TL}{\alpha} * (-\ln .01)$

or the full lagoon detention time. This is an unrealistic extreme and would not give a very dynamic representation of the lagoons operation.

K-S goodness of fit tests were done for both the t = 1 hour and t = 24 hour effluent data against the actual data. The results are seen below:

Time	D(N,M)	KS(.05)	KS(.01)
t = 1	.334	.268	.321
t = 24	.251	.268	.321

N = # of real world observations = 49

M = # of simulated observations = 53

The null hypothesis that the t = 24 run and the real data are equivalent at the .05 significance level cannot be rejected. However, for the t = 1 hour run the null hypothesis is rejected. This implies that there is a time interval between t = 1 and t = 24 which represents a threshold of acceptibility for using the steady state assumption in the model. Some experiments were run using the same lagoon influent for various time intervals and temperatures and K-S goodness of fit tests performed on the results. These are summarized in Table 4.3

A plot of time interval versus temperature can be found in Figure 4.9. There is a threshold boundary between acceptability and non acceptability which is a function of the time interval and temperature. Beak-Environment Canada (1973) state that the reaction rate reaches a maximum at about 37°C and falls off for higher temperatures. The implications of this are seen in Figure 4.9. The dotted line represents a symmetrical drop in the

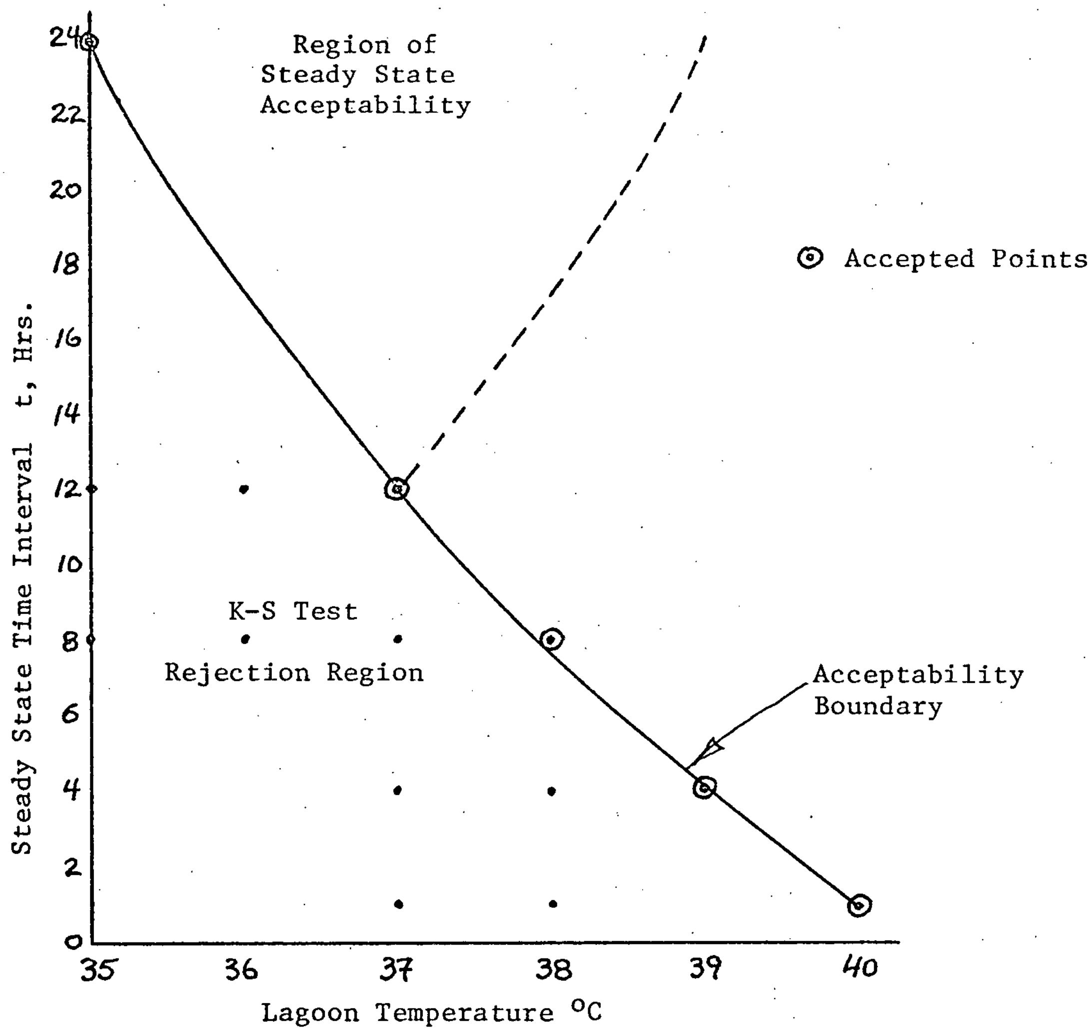


FIGURE 4.9

PLOT SHOWING REGIONS OF ACCEPTABILITY AS DETERMINED BY K-S GOODNESS OF FIT TEST FOR SIMULATION GENERATED EFFLUENT AND REAL DATA EFFLUENT USING DIFFERENT STEADY STATE TIME INTERVAL AND TEMPERATURE COMBINATIONS

TABLE 4.3

SUMMARY OF k-s TESTS FOR SIMULATION GENERATED AND REAL DATA EFFLUENT FOR DIFFERENT STEADY STATE TIME INTERVAL AND TEMPERATURE COMBINATIONS.

Temp °C	Time Interval	D(N,M)	KS(.05)	Accepted
36	12	.280	.261	No
37	1	.335	.261	No
37	4	.335	.261	No
37	8	.298	.261	No
37	12	.244	.261	Yes
38	1	.335	.261	No
38	4	.317	.261	No
38	8	.244	.261	Yes
39	4	.244	.261	Yes
40	1	.245	.261	Yes
35	1	.334	.261	No
35	8	.314	.261	No
35	12	.316	.261	No
35	24	.251	.261	Yes

reaction rate with increasing temperature beyond 37°C.

The minimum time interval which is accepted by the K-S test is t = 12 hours with a lagoon operating temperature of 37°C.

Despite the rejection of the null hypothesis for t = 1 hour, it was decided to proceed as originally intended. The reasons for doing so are:

1. The K-S test is not an absolute test and the plots in Figure 4.8 indicate that the t = 1 hour model gives a reasonable representation of reality.

2. The intent of the model is to try and observe the more dynamic aspects of the treatment system's behaviour. This would be lost if the model were iterated every 12 or 24 hours.
3. The t = 1 fit is bad primarily because it fails to fit real data low points in the day = 24 to day = 52 region. If the temperature gradient along the lagoon were accounted for in the model, the t = 1 plot may drop sufficiently to fit the real data. The model as it is now structured can not incorporate a temperature gradient relationship.
4. Some BOD will settle out in the sedimentation ponds in the "real world" situation while the model does not take this into account. This will result in the model effluent being somewhat higher in concentration.

For the clarifier model validation data was not available. The only data acquired were SS readings on composite samples of 5 days of operation. In order to perform a reasonable validation, data would be needed on an hourly basis due to the clarifiers short detention time. The clarifier model does not suffer from the exponential cut off experienced with the lagoon model for the t = 1 steady state approximation. For the clarifier the constant

$$C = \frac{1 + k_c T_c}{T_c}$$

$$= \frac{1 + \frac{.104}{15.*12*2.54} * 4753.5}{4753.5}$$

$$= \frac{2.2}{4753.5} \cong 4.52 \times 10^{-4}$$

Therefore for t = 1 hour = 3600 secs

$$f = e^{-4.52 \times 10^{-4} \times 3.6 \times 10^{3}}$$
$$= e^{-1.63} = .1959$$

Referring to eqn. 3.7, the implications of the second term on $C_2(t)$ are greatly reduced by the exponential factor. In fact this implies that the clarifier is typically running at about .8 of the maximum efficiency as determined by the model structure. The maximum efficiency possible is

$$\text{max eff} = 1 - \frac{C_2(t)}{C_{1N}} = 1 - \frac{1}{(1+k_c T_c)^2}$$

$$= 1 - \frac{1}{(3.2)^2} \simeq 90\%$$

Therefore the clarifier is operating at approx. .8 x 90% = 72% efficiency. This will vary each day as a result of the change in detention time. In the model, clarifier efficiency is determined for a completed run as follows;

$$\text{clarifier efficiency} = \frac{SST_{IN} - SST_{out}}{SST_{IN}}$$

Where SST_{IN} = total suspended solids which entered clarifier over complete experiment

SST_{out} = total suspended solids which left clarifier over complete experiment

In a simulated 15 day experiment, the clarifier efficiency was determined as 77%. This is a typical value for SS% removed for clarifiers with detention times between 2.5 to 3.0 hours (Bower, 1971). The data given by Bower, acquired from NCASI Tech. Bulletin #190, is reproduced below:

Detention time	% removal of SS
2.5 hrs	75
3.5	88
4.0	90
5.0	92
6.0	96

To partially validate the clarifier model some experiment runs were run for different design detention times. The results can be seen below.

Detention time	% removal of SS
3	77
4	83
5	87
6	90

The clarifier model appears to give a somewhat conservative reduction in SS when compared to the NCASI data. However the NCASI data represents ideal maximum efficiencies corresponding to long term steady state design models. The model developed here iterates every hour so it does not operate the clarifier model at maximum steady state efficiency.

CHAPTER V

MODEL EXPERIMENTS

5.1 DESIGN VERSUS COST

A series of sensitivity experiments were run for each of the four wastewater treatment plant combinations changing clarifier detention time and lagoon area sequentially. The same inputs, consisting of 65 days of pulp mill model effluent, were used for each of the experiments. At the end of each experiment the mean and variance of the lb BOD/ton and lb SS/ton for lagoon and clarifier influent and effluent were determined. Also K-S goodness of fit tests were performed comparing daily effluent time series for each of the experiments to a standard daily time series. The standard chosen was for a system with a 3 hour clarifier detention time and a 75 acre - 15' deep lagoon operating at 35^{o}C. This standard is maintained throughout this chapter.

5.1.1 The Lagoon Cost Curves

The first 3 combinations (see Figure 4.6) provide almost identical influent to the lagoon, therefore only the results for combinations 3 and 4 will be discussed.

Keeping all other factors identical to the standard, experiments were run for lagoon areas ranging from 20 acres to 125 acres. The costs, efficiency, mean and variance of input and output, and the K-S test results were generated for each of the experiments. These are summarized in Table 5.1. The costs versus mean lb BOD/ton are plotted in Figure 5.1. The shaded areas

TABLE 5.1 LAGOON CAPITAL COST AND OPERATING COSTS FOR COMBINATION 3 AND COMBINATION 4 SYSTEMS - STANDARD MILL EFFLUENT

Lag Area	Lag CC	Lag OC	Lag Eff.	Lag Flow	In BOD #/ton		Out BOD #/ton		Lag Out	
					Mean	Var.	Mean	Var.	D(N,M)	KS (.05)
20	744,219	115,296	.44	65.4	58.13	373.9	32.7	140.8	.985	.238
30	1,479,917	217,089	.56	65.4	58.13	373.9	25.3	69.7	.907	.238
40	2,010,489	367,299	.65	65.4	58.13	373.9	20.1	37.2	.89	.238
50	2,512,848	560,595	.72	65.4	58.13	373.9	16.1	22.1	.553	.238
60	3,159,961	785,020	.77	65.4	58.13	373.9	13.2	14.3	.538	.238
70	3,756,611	1,027,242	.81	65.4	58.13	373.9	10.9	9.7	.154	.238
75	4,013,043	1,163,444	.83	65.4	58.13	373.9	9.96	8.2	0	.238
80	4,255,601	1,299,584	.84	65.4	58.13	373.9	9.1	6.9	.092	.238
100	5,196,448	1,882,834	.88	65.4	58.13	373.9	6.6	3.7	.35	"
125	6,144,990	2,590,252	.92	65.4	58.13	373.9	4.6	1.9	.415	"
20	1,222,529	177,598	.64	33.9	58.13	373.9	33.7	106.9	.985	.238
30	1,898,220	381,195	.76	33.9	58.13	373.9	29.2	7.3	.985	"
40	2,586,116	633,013	.83	33.9	58.13	373.9	26.5	59.3	.938	"
50	3,164,647	921,895	.88	33.9	58.13	373.9	24.8	52.5	.938	"
60	3,655,048	1,207,746	.91	33.9	58.13	373.9	23.6	48.6	.938	"
70	4,053,501	1,476,957	.93	33.9	58.13	373.9	22.8	46.2	.938	"
80	4,364,435	1,705,257	.94	33.9	58.13	373.9	22.3	44.6	.938	"

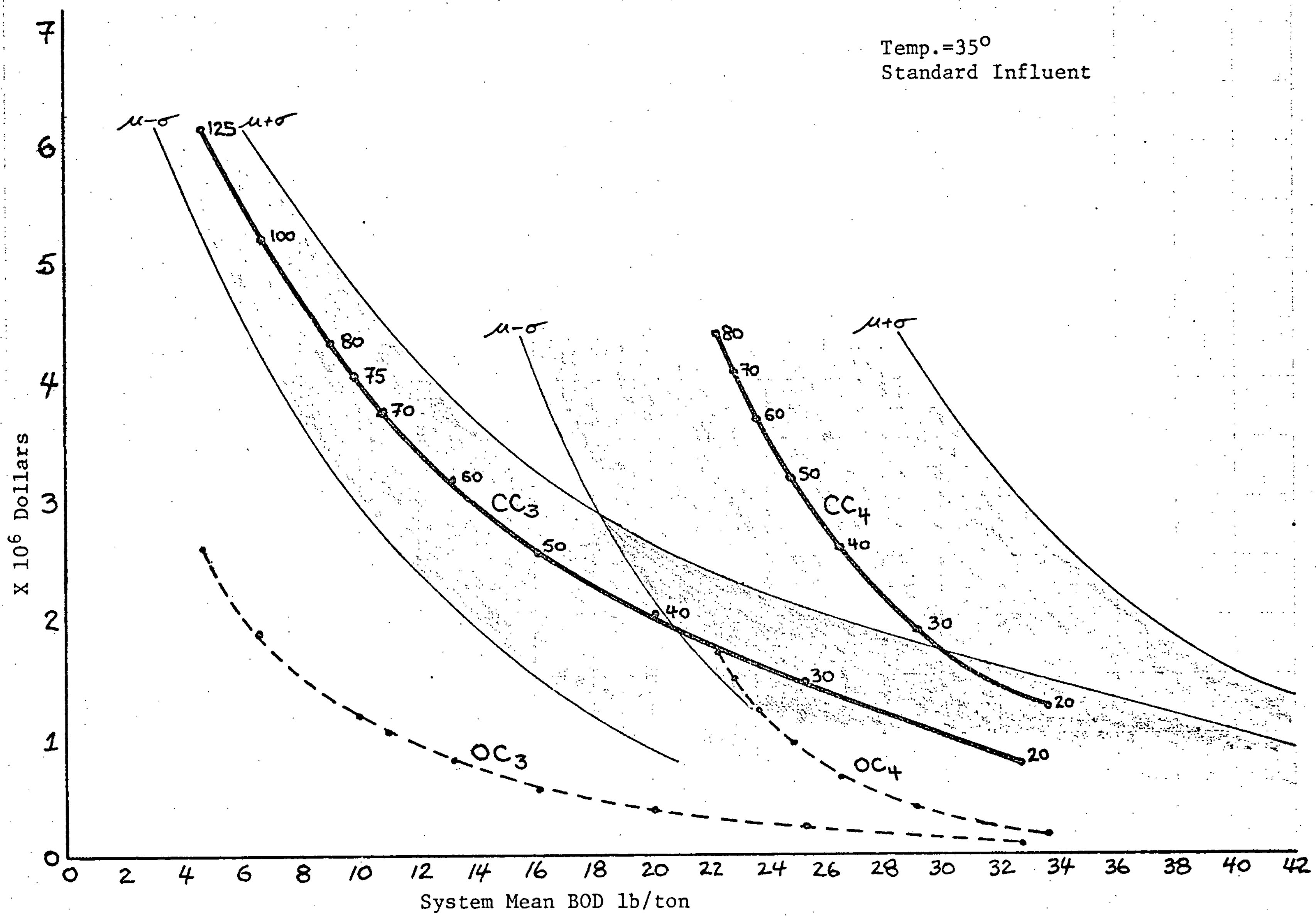


FIGURE 5.1

LAGOON CAPITAL OPERATING COST CURVES FOR COMBINATION 3 AND COMBINATION 4 SYSTEMS.
NUMBERS BESIDE DATA POINTS INDICATE LAGOON AREA IN ACRES

in Figure 5.1 represent one standard deviation regions about the effluent means for capital cost curves. The numbers beside each data point indicate lagoon acreage.

The effluent mean lb BOD/ton was chosen as the x-axis as a consequence of the 1971 report on "Pollution Control Objectives for the Forest Products Industry" (Department of Lands, et al, 1971). The objective BOD effluent levels for the chemical pulping process were given as

Level A = 15 lb/ton

Level B = 60 lb/ton

Level C = 80 lb/ton

for marine discharge. The level A applies to new mills and is the level they must meet immediately. It is to this level that the results of this chapter will be directed (Note the effluent mean lb BOD/ton includes all the outfalls. Therefore for the combination 4 system it includes the acid wastes which bypass the system).

Figure 5.1 is a plot of change in capital and operating costs of an aerated lagoon with a change in mean effluent level. One of the most striking results is the cost dominance of combination 3 over combination 4 for any effluent mean. Given an effluent level which management wants to meet it is always less costly to construct a combination 3 system, (i.e. feed all the mill outfalls through the lagoon) than a combination 4 system (bypass the lagoon with the acid effluent). In other words, given a lagoon area, the effluent quality possible is always better with a combination 3 system and at less capital and operating cost. The reason for this is that it is not necessary to operate a combination 3 lagoon at such a high efficiency in order to obtain the same quality effluent as with a combination 4 system. Operating a lagoon at high efficiencies is one of the major cost factors since it requires more aerators and power. In fact with a combination 4 system one is paying very highly for the privilege of dumping acid wastes, since it is the acid effluent that is putting a lower bound on the lb/ton level which a combination 4 system can attain. For the given mill, the combination 4 system would not be able to attain level A at any cost.

Another way to look at the plot is, given a certain amount of capital which management is willing to invest in an aerated lagoon, a higher quality effluent will always result with a combination 3 system. A combination 3 system requires a neutralization mixing basin ahead of the lagoon. However such a basin will cost approximately $10,000.00, a small investment relative to lagoon capital costs.

To meet the level A requirements with a combination 3 system, the capital investment will be approximately 2.7×10^6 dollars and expected operating costs would be about $600,000.00 per year. At an operating temperature of 35^oC the lagoon size needed is approximately 55 acres - 15' deep. Since this is mean performance, it implies that the mill will often have days with operation above and below this level. If this is of concern it may be advisable to work along the $\mu + \sigma$ curve. This would require a capital investment of approximately 3.5×10^6 dollars with operating costs at about

1 x 10^6 dollars per year. At an operating temperature of 35°C this would mean a lagoon size of approximately 65 acres - 15' deep.

Although management may be willing to invest in the larger lagoon, land availability could well be a limiting factor preventing construction of the more reliable system.

As indicated earlier these results are based on a 65 day experiment of the mill and lagoon models. A full year experiment was also run for the standard system and the results were similar. The lagoon efficiency was slightly reduced (approximately 1%) and the lagoon capital costs dropped to about 3.9 x 10^6 dollars. (From Table 5.1 the 65 day run resulted in lagoon CC = 4.01 x 10^6 dollars). Since the results are almost identical, it was decided to proceed with the 65 day operation.

5.1.2 Sensitivity Tests on Lagoon Cost Curves

To test the sensitivity of the curves in Figure 5.1 experiments were run with each of the following changes. (Note: For each of the following only the variable indicated was altered. The other variables were left as they were in generating Figure 5.1).

a. Temperature

Two experiments were run

1. temperature = 30°C
2. temperature = 40°C

b. Hydraulic Load

Two experiments were run. Hourly flows for all 3 outfalls were

1. increased by 10%
2. decreased by 10%

c. Effluent Load

Two experiments were run. The hourly SS and BOD concentration from the 3 outfalls were

1. increased by 10%
2. decreased by 10%

For all six experiments daily influent and effluent loads for the waste treatment system, expressed as lb/ton, were compared to the established standard system using the K-S goodness of fit routine. Results of these experiments are summarized in Tables 5.2 A and 5.2 B and Figure 5.2 for temperature , Tables 5.3 A and 5.3 B and Figure 5.3 for hydraulic load, and Tables 5.4 A and 5.4 B and Figure 5.4 for effluent load.

Looking at Figure 5.2 the cost curves generated for the changes in lagoon operating temperatures are identical to those in Figure 5.1. The mean lb BOD/ton is in essence a measure of the lagoon's efficiency and the efficiency for any given lagoon volume is a function of hydraulic flow and temperature. Therefore, since the flow is not altered in the temperature runs, the model is essentially working its way up a vertical flow line on Figure 4.8. No matter what the temperature of the lagoon model, it will still follow the same flow line and therefore generate the same cost versus efficiency curve. The

TABLE 5.2A

LAGOON CAPITAL COST AND OPERATING COSTS FOR COMBINATION 3 AND 4 SYSTEMS - STANDARD INFLUENT LOAD, TEMP = 30°C

Comb	Lag Area	Lag CC	Lag OC	Lag Eff	Lag Flow	In BOD #/ton		Out BOD #/ton		Lag Out		D In Lag	D In CL	D Out CL
						Mean	Var	Mean	Var	D(N,M)	KS(.05)			
3	20	582,576	97,195	.39	65.4	58.1	373.9	35.2	166.7	1.0	.238	0	0	0
	30	1,221,460	168,478	.51	"	"	"	28.1	86.0	.969	"	"	"	"
	40	1,755,114	274,445	.60	"	"	"	22.7	47.1	.908	"	"	"	"
	50	2,143,343	421,343	.67	"	"	"	18.7	29.3	.831	"	"	"	"
	60	2,618,152	595,452	.73	"	"	"	15.6	19.8	.554	"	"	"	"
	70	3,173,116	789,827	.77	"	"	"	13.1	14.1	.538	"	"	"	"
	80	3,693,615	995,000	.80	"	"	"	11.1	10.4	.215	"	"	"	"
	100	4,543,221	1,468,835	.86	"	"	"	8.2	5.98	.307	"	"	"	"
	125	5,504,752	2,094,492	.896	"	"	"	5.9	3.2	.369	"	"	"	"
4	20	1,057,085	133,395	.59	33.9	58.1	373.9	35.5	117	.984	"	"	"	"
	30	1,567,784	287,804	.72	"	"	"	30.8	79.2	.985	"	"	"	"
	40	2,230,943	483,299	.80	"	"	"	27.8	63.6	.985	"	"	"	"
	50	2,757,697	714,697	.85	"	"	"	25.9	55.5	.938	"	"	"	"
	60	3,250,358	968,576	.88	"	"	"	24.5	50.8	.938	"	"	"	"
	70	3,664,426	1,213,780	.91	"	"	"	23.6	47.9	.938	"	"	"	"
	80	4,011,143	1,447,091	.93	"	"	"	22.9	45.9	.938	"	"	"	"

TABLE 5.2B

LAGOON CAPITAL COST AND OPERATING COSTS FOR COMBINATION 3 AND 4 SYSTEMS - STANDARD INFLUENT LOAD, TEMP = 40°C

Comb	Lag Area	Lag CC	Lag OC	Lag Eff	Lag Flow	In BOD #/ton		Out BOD #/ton		Lag Out		D In Lag	D In CL	D Out Cl
						Mean	Var	Mean	Var	D(N,M)	KS(.05)			
3	20	1,019,959	143,642	.48	65.4	58.1	373.9	30.0	117.7	.985	.239	0	0	0
	30	1,779,258	282,608	.61	"	"	"	22.6	56.1	.908	"	"	"	"
	40	2,296,200	488,449	.70	"	"	"	17.4	28.7	.646	"	"	"	"
	50	3,044,594	743,269	.76	"	"	"	13.7	16.2	.554	"	"	"	"
	60	3,747,094	1,022,340	.81	"	"	"	10.9	9.9	.169	"	"	"	"
	70	4,323,528	1,338,975	.83	"	"	"	8.9	6.5	.154	"	"	"	"
	80	4,886,945	1,680,806	.87	"	"	"	7.36	4.4	.323	"	"	"	"
	100	5,844,085	2,349,295	.91	"	"	"	5.2	2.2	.415	"	"	"	"
	125	6,737,215	3,097,800	.94	"	"	"	3.5	1.1	.415	"	"	"	"
4	20	1,397,832	236,747	.69	33.9	"	"	31.9	97.3	.985	"	"	"	"
	30	2,268,214	495,210	.80	"	"	"	27.7	67.5	.985	"	"	"	"
	40	2,969,456	819,554	.86	"	"	"	25.3	55.7	"	"	"	"	"
	50	3,571,540	1,154,664	.90	"	"	"	23.8	49.9	.938	"	"	"	"
	60	4,047,108	1,472,429	.93	"	"	"	22.8	46.8	"	"	"	"	"
	70	4,403,577	1,735,125	.95	"	"	"	22.2	44.8	"	"	"	"	"

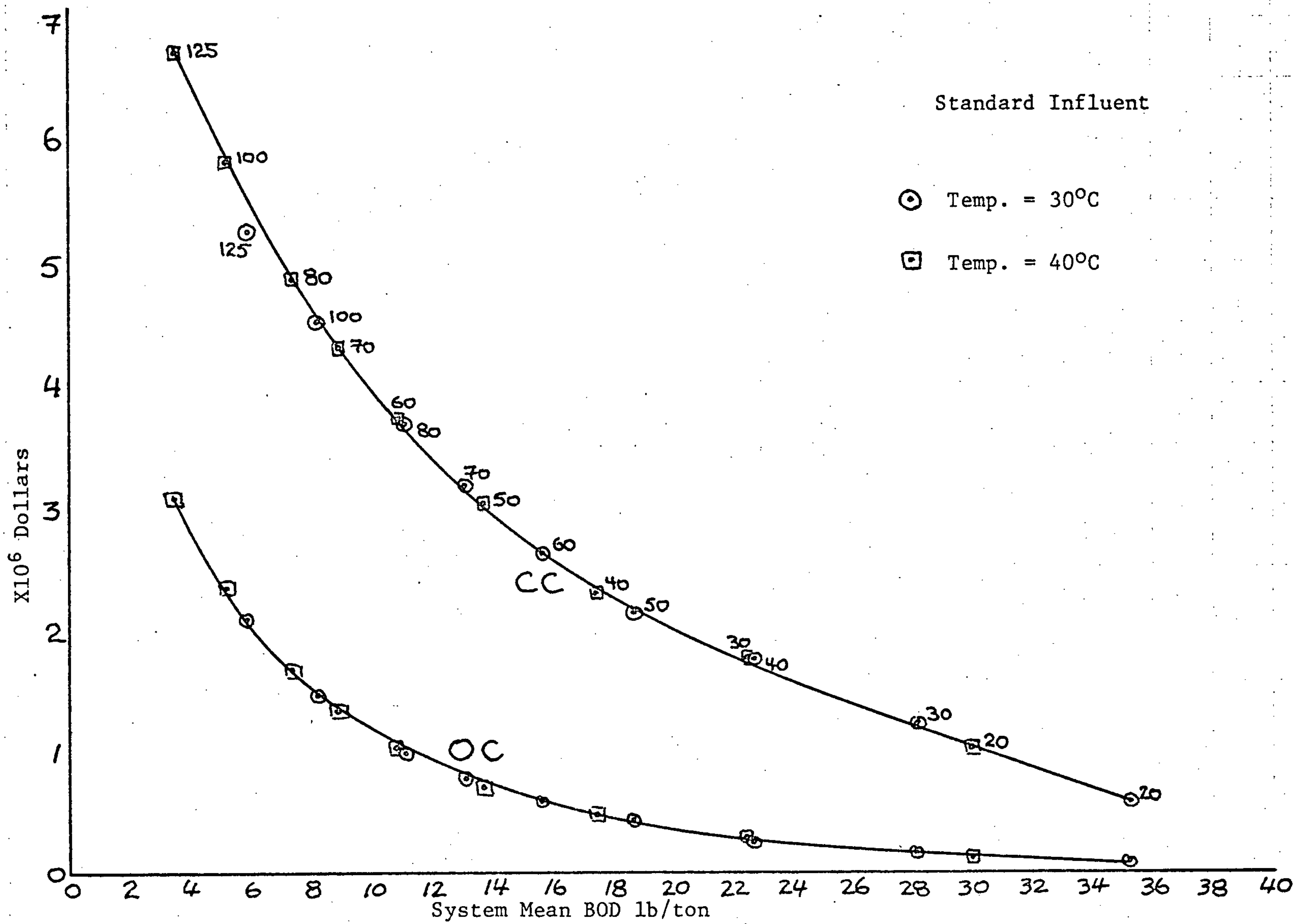


FIGURE 5.2

LAGOON CAPITAL AND OPERATING COST CURVES FOR COMBINATION 3 SYSTEM WITH STANDARD INFLUENT LOAD AND LAGOON OPERATING AT 30°C AND 40°C.
NUMBERS BESIDE DATA POINTS INDICATE LAGOON AREA IN ACRES FOR INDICATED TEMPERATURE

TABLE 5.3A

LAGOON CAPITAL AND OPERATING COSTS FOR COMBINATION 3 AND COMBINATION 4 SYSTEM - STANDARD HYDRAULIC LOAD X .9

Comb	Lag Area	Lag CC	Lag OC	Lag Eff	Lag Flow	In BOD #/Ton		Out BOD #/Ton		Lag Out		D Lag In	D CL In	D CL Out
						Mean	Var	Mean	Var	D(N,M)	KS(0.5)			
3	75	4,013,043	1,163,444	.83	65.4	58.1	374.0	9.96	8.15	0	0			
3	20	657,839	111,015	.41	71.9	60.2	397.7	36.5	182.7	.985	.239	.200	.246	.215
	30	1,401,728	203,324	.53	"	"	"	28.9	96.6	.969	"	"		
	40	1,974,161	336,183	.62	"	"	"	23,2	52.8	.908	"	"		
	50	2,406,035	513,921	.69	"	"	"	18.9	31.6	.815	"	"		
	60	3,005,475	726,484	.74	"	"	"	15.6	20.5	.554	"	"		
	70	3,623,340	956,175	.78	"	"	"	13.1	14.0	.538	"	"		
	75	4,012,049	1,126,397	.81	"	"	"	11.5	13.1	.338	"	"		
	80	4,169,655	1,211,281	.82	"	"	"	11.1	10.0	.200	"	"		
	100	5,117,131	1,777,065	.87	"	"	"	8.1	5.5	.308	"	"		
	125	6,142,215	2,496,760	.91	"	"	"	5.7	2.88	.385	"	"		
4	20	1,200,074	162,439	.61	37.3	60.2	397.7	36.9	132.3	.984	.239			
	30	1,801,808	351,732	.73	"	"	"	32.2	90.8	.984	"			
	40	2,527,544	587,199	.81	"	"	"	29.3	73.6	.984	"			
	50	3,106,911	865,218	.86	"	"	"	27.5	64.8	.984	"			
	60	3,635,840	1,156,976	.89	"	"	"	26.2	59.8	.938	"			
	70	4,077,201	1,441,087	.92	"	"	"	25.3	56.7	.938	"			
	75	4,335,058	1,623,623	.93	"	"	"	24,8	53.1	.938	"			
	80	4,435,267	1,697,411	.93	"	"	"	24,7	54.6	.938	"			
	100	4,844,983	1,990,699	.96	"	"	"	23.8	52.2	.938	"			

TABLE 5.3B

LAGOON CAPITAL AND OPERATING COSTS FOR COMBINATION 3 AND COMBINATION 4 SYSTEMS - STANDARD HYDRAULIC LOAD X 1.1

Comb	Lag Area	Lag CC	Lag OC	Lag Eff	Lag Flow	In BOD #/Ton		Out BOD #/Ton		Lag Out		Lag In	CL Out
						Mean	Variance	Mean	Variance	D(N,M)	KS(0.5)		
3	75	4,013,043	1,163,444	.83	65.4	58.1	373.9	9.96	9.96	0	0	Stand	
3	20	858,525	120,765	.47	58.8	56.1	350.9	28.8	103.9	.969	.239	.154	.16+
3	30	1,572,301	233,563	.59	"	"	"	21.9	48.3	.908	"	"	
3	40	2,047,783	403,529	.68	"	"	"	16.9	25.3	.600	"	"	
3	50	2,669,224	615,209	.75	"	"	"	13.5	14.9	.538	"	"	
3	60	3,316,581	846,445	.80	"	"	"	10.8	9.6	.138	"	"	
3	70	3,851,704	1,115,489	.83	"	"	"	8.9	6.5	.185	"	"	
3	75	4,191,905	1,307,630	.85	"	"	"	7.7	6.2	.338	"	"	
3	80	4,349,930	1,400,199	.86	"	"	"	7.4	4.5	.338	"	"	
3	100	5,239,442	1,976,666	.90	"	"	"	5.21	2.39	.415	"	"	
3	125	6,092,680	2,650,693	.93	"	"	"	3.6	1.2	.415	"	"	
4	20	1,246,026	195,298	.67	30.5	56.1	350.9	30.5	84.0	.989	"	"	
	30	1,997,521	412,605	.79	"	"	"	26.1	57.3	.938	"	"	
	40	2,639,093	680,808	.85	"	"	"	23.6	46.8	.938	"	"	
	50	3,200,079	972,175	.89	"	"	"	22.0	41.5	.938	"	"	
	60	3,649,124	1,252,717	.92	"	"	"	21,0	38.6	.938	"	"	
	70	3,992,827	1,492,375	.94	"	"	"	20.4	36.9	.892	"	"	

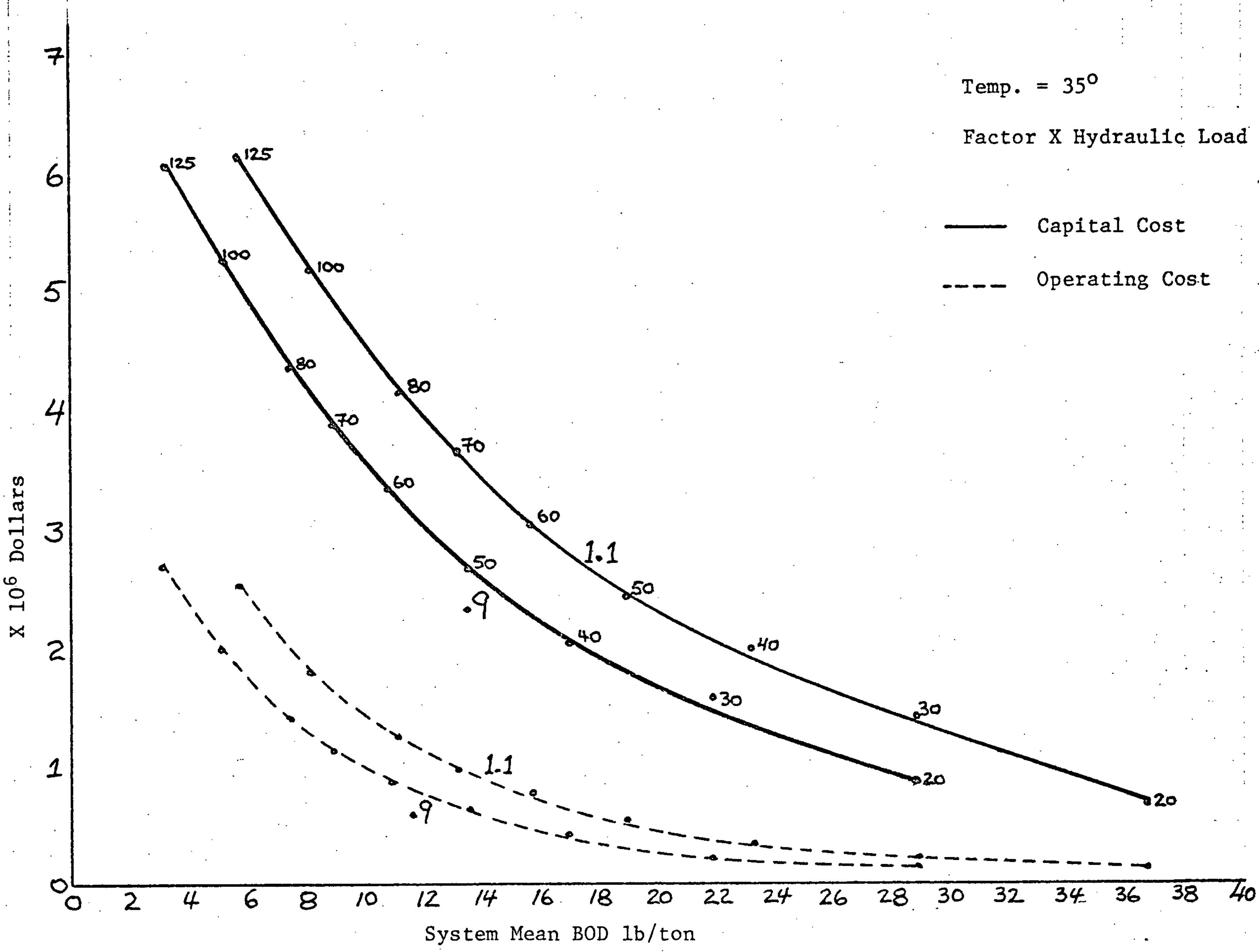


FIGURE 5.3

LAGOON CAPITAL AND OPERATING COST CURVES FOR COMBINATION 3 SYSTEM WITH STANDARD HYDRAULIC LOAD MULTIPLIED BY 1.1 AND .9. NUMBERS BESIDE DATA POINTS INDICATE LAGOON AREA IN ACRES.

LAGOON CAPITAL COST AND OPERATING COST FOR COMBINATION 3 AND 4 SYSTEMS - STANDARD INFLUENT LOAD X .9

Comb	Lag Area	Lag CC	Lag OC	Lag Eff	Lag Flow	In BOD #/Ton		Out BOD #/Ton		Lag Out		D In Lag	D In CL	D Out CL
						Mean	Var	Mean	Var	D(M,M)	KS(.05)			
3	20	744,249	115,300	.44	65.4	63.9	452.4	35.9	170.4	.985	.239	.246	.277	.215
	30	1,479,950	217,095	.56	"	"	"	27.9	84.3	.954	"	"	"	"
	40	2,010,533	367,296	.65	"	"	"	22.0	45.0	.908	"	"	"	"
	50	2,512,910	5,60,616	.72	"	"	"	17.7	26.7	.708	"	"	"	"
	60	3,160,015	785,040	.77	"	"	"	14.5	17.3	.554	"	"	"	"
	70	3,756,705	1,027,290	.81	"	"	"	11.9	11.8	.431	"	"	"	"
	75	4,107,108	1,215,400	.83	"	"	"	10.5	11.2	.169	"	"	"	"
	80	4,255,723	1,299,654	.84	"	"	"	10.0	8.3	0.0	"	"	"	"
	100	5,196,483	1,882,857	.88	"	"	"	7.2	4.5	.338	"	"	"	"
	125	6,145,002	2,590,265	.92	"	"	"	5.04	2.3	.415	"	"	"	"
4	20	1,222,553	177,606	.64	33.9	"	"	37.1	129.3	.985	"			
	30	1,898,313	381,223	.76	"	"	"	32.1	88.3	.985	"			
	40	2,586,126	633,017	.83	"	"	"	29.1	71.8	.985	"			
	50	3,164,641	921,892	.88	"	"	"	27.2	63.5	.969	"			
	60	3,655,051	1,207,748	.91	"	"	"	25.9	58.8	.938	"			
	70	4,053,494	1,476,951	.93	"	"	"	25.1	55.9	.938	"			
	75	4,281,726	1,642,975	.94	"	"	"	24.6	52,5	.938	"			
	80	4,364,427	1,705,253	.94	"	"	"	24.5	54.0	.938	"			

TABLE 5.42

LAGOON CAPITAL AND OPERATING COSTS FOR COMBINATION 3 AND COMBINATION 4-SYSTEMS STANDARD INFLUENT X 1.1

Comb	Lag Area	Lag CC	Lag OC	Lag Eff	Lag Flow	In BOD #/Ton		Out BOD #/Ton		Lag Out		D In Lag	D In CL	D Out CL
						Mean	Var	Mean	Var	D(N,M)	KS(.05)			
3	75	4,013,043	1,163,444	.83	65.4	58.1	373.9	9.96	8.15	0	.239		Standard	
	20	744,086	115,282	.44	"	52.32	302.9	29.4	114.1	.984	"	.277	.308	.169
	30	1,479,887	217,083	.56	"	"	"	22.8	56.5	.907	"	"	"	"
	40	2,010,499	367,302	.65	"	"	"	18.0	30.1	.738	"	"	"	"
	50	2,512,810	560,583	.72	"	"	"	14.5	17.9	.554	"	"	"	"
	60	3,159,880	784,990	.77	"	"	"	11.9	11.5	.385	"	"	"	"
	70	3,756,650	1,027,186	.81	"	"	"	9.8	7.9	.015	"	"	"	"
	75	4,106,861	1,215,264	.83	"	"	"	8.6	7.5	.200	.239	"	"	"
	80	4,255,414	1,299,478	.84	"	"	"	8.2	5.6	.292	"	"	"	"
	100	5,196,448	1,882,835	.88	"	"	"	5.9	3.0	.385	"	"	"	"
	125	6,144,984	2,590,247	.92	"	"	"	4.1	1.5	.415	"	"	"	"
4	20	1,222,499	177,589	.64	33.9	"	"	30.4	86.6	.984	.239	.277	.308	.153
	30	1,898,068	381,151	.76	"	"	"	26.3	59.1	.954	"	"	"	"
	40	2,586,104	633,007	.83	"	"	"	23.8	48.1	.938	"	"	"	"
	50	3,164,620	921,881	.88	"	"	"	22.3	42.5	.938	"	"	"	"
	60	3,655,045	1,207,744	.91	"	"	"	21.3	39.4	.938	"	"	"	"
	70	4,053,494	1,476,951	.93	"	"	"	20.5	37.4	.923	"	"	"	"
	75	4,281,730	1,642,976	.94	"	"	"	20.2	35.2	.877	"	"	"	"
	80	4,364,419	1,705,246	.95	"	"	"	20.0	36.2	.877	"	"	"	"

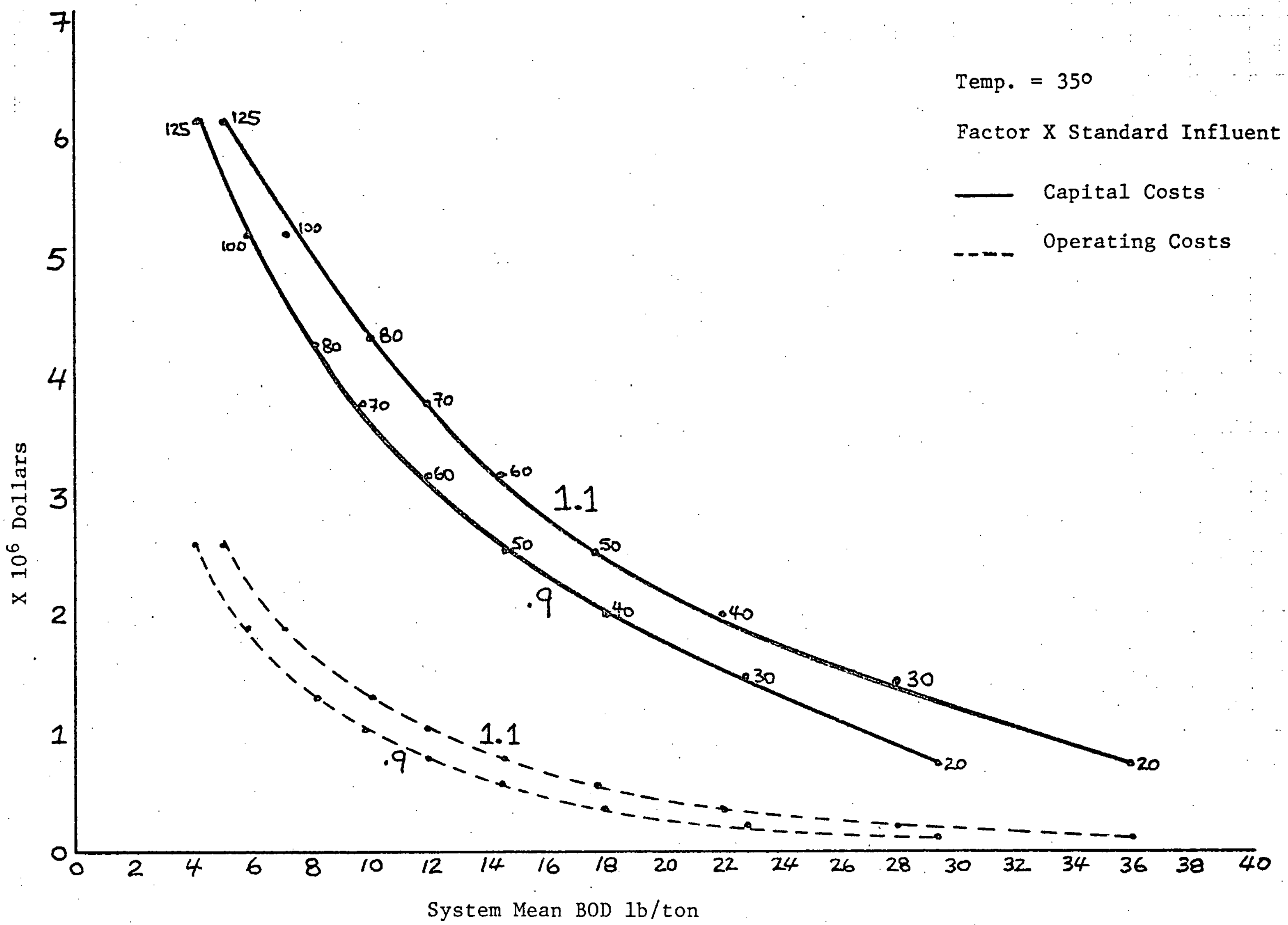


FIGURE 5.4

LAGOON CAPITAL AND OPERATING COST CURVES FOR COMBINATION 3 SYSTEM WITH STANDARD INFLUENT LOAD MULTIPLIED BY 1.1 AND .9. NUMBERS BESIDE DATA POINTS INDICATE LAGOON AREA IN ACRES.

expected difference however is that the efficiency of any given size lagoon has gone up for higher temperatures and down for lower. The data points on Figure 5.2 are labelled according to lagoon temperature and size. Notice also that the capital costs of any given sized lagoon increase with temperature. With an increased reaction rate more oxygen is required in order to maintain first, the biological activity and, second, the assumption that the reaction rate is constant, therefore more aerators and/or more power are needed, resulting in increased capital cost.

From these results, we would therefore anticipate the change in flow and effluent load to enclose the curve in Figure 5.1. Looking at Figures 5.3 and 5.4 we see that this is the case. The higher load and higher flow curves are both above the standard curve and similarly the lower load and lower flow curves are below.

Note also from Tables 5.3 A and 5.3 B the lb BOD/ton inflow into the lagoon is not changed significantly (at .05 significance level), according to the K-S test, for the 10% change in flows (.200 <.239). Similarly the output from the 80 acre lagoon is not significantly different from the 75 acre standard for the 10% increased flow, while for the 10% decreased flow both the 60 and 70 acre lagoon effluents are accepted by the K-S test. Looking at Tables 5.4 A and 5.4 B the lagoon influent into the lagoon differs significantly for both factor loading experiments. The effluent is significantly identical for a 70 acre lagoon with a .9 factor loading and for an 80 acre lagoon with a 1.1 factor loading.

Referring to Tables 5.3 A and 5.4 A, despite the lower mean and variance for the influent in Table 5.3 A (and noticeably its significant similarity to the standard influent), lagoon efficiencies for any given area are less in Table 5.3 A than in 5.4 A as are also the means and variances of lagoon effluent. This implies the lagoon model is more sensitive to change in flow than changes in influent concentration. The cause is probably the decreased residence time with increased flow resulting in a lower operation efficiency.

To test the implications of spill frequency on the waste treatment cost curves, an experiment was run using a pulp mill effluent trace with spill frequency drastically increased. All characteristics of the mill were maintained except for the "time between unrelated spills" distribution for the recovery area.

For the standard mill trace the time between unrelated spills (in the recovery area) had a mean of 207.45 hours and a standard deviation of 290.13 hours. To increase spill frequency the mean and standard deviation were both changed to 100 hours. To accomplish this the gamma distribution parameters had to be changed. From Kita and Morley (1973), the parameters are related as

$$\lambda = \frac{\bar{x}}{\sigma^2} = \frac{100}{(100)^2} = .01$$

and

$$\beta = \frac{(\sigma)^2}{(\bar{x})^2} = 1.0$$

These changes were introduced into the pulp mill model, a new effluent time series was generated and was given as influent to the waste treatment model. The daily influent and effluent levels, expressed as lb BOD/ton, were compared to the standard system treating the standard mill effluent trace, using the K-S goodness of fit test. The results are summarized in Table 5.5 and Figure 5.5.

Comparing Tables 5.1 and 5.5 we can see that the increased number of spills had little effect on lagoon efficiency and costs for a given lagoon area, although it did increase the mean and variance of the lb BOD/ton of the lagoon effluent. As a consequence, the size of lagoon necessary to maintain a below 15 lb BOD/ton effluent average increases significantly. This is more easily seen in Figure 5.5. For the increased spills experiment a 70 acre lagoon is required at a capital cost of 3.75 million dollars, while for the standard mill a 55 acre lagoon is sufficient at a cost of 2.7 million dollars, a saving of up to a million dollars.

5.1.3 The Clarifier Cost Curves

Table 5.6 is a summary of experiments run for different clarifier detention times for system combinations 1 and 2. The cost curves are plotted in Figure 5.6.

The clarifier doesn't have the clear dominance property that was observed for the lagoon model. The capital cost curves intersect at a mean of 11.6 lb SS/ton with a capital cost of approximately 750,000 dollars. For effluent

TABLE 5.5

LAGOON CAPITAL AND OPERATING COST FOR COMBINATION 3 AND COMBINATION 4 SYSTEMS - INCREASED SPILL FREQUENCY IN RECOVERY AREA OF MILL

Comb	Lag Area	Lag CC	Lag OC	Lag Eff	Lag Flow	In BOD #/Ton		Out BOD #/Ton		Lag Out	
						Mean	Var	Mean	Var	D(M,M)	KS(.05)
3	20	734,982	114,920	.43	66	76.0	542.1	43.7	189.2	.923	.239
	30	1,472,846	215,871	.56	"	"	"	34.1	109.7	.908	"
	40	2,008,340	364,419	.65	"	"	"	27.2	76.4	.831	"
	50	2,499,467	555,974	.72	"	"	"	21.9	57.3	.554	"
	60	3,145,531	779,420	.77	"	"	"	18.0	32.9	.354	"
	70	3,747,071	1,018,655	.81	"	"	"	14.9	16.4	.123	"
	80	4,248,220	1,290,683	.84	"	"	"	12.5	13.7	.231	"
	100	5,189,286	1,871,823	.88	"	"	"	9.1	8.4	.477	"
	125	6,145,750	2,580,405	.92	"	"	"	6.3	4.1	.569	"
4	20	1,222,285	176,539	.64	"	"	"	44.5	146.3	.923	"
	30	1,891,877	379,161	.76	"	"	"	38.4	97.9	.923	"
	40	2,583,722	629,646	.83	"	"	"	34.8	79.2		"
	50	3,162,426	917,664	.88	"	"	"	32.4	66.9	.892	"
	60	3,656,087	1,203,548	.91	"	"	"	30.8	57.2	.861	"
	70	4,059,416	1,475,186	.93	"	"	"	29.7	56.1	.862	"
	80	4,375,071	1,706,449	.94	"	"	"	28.96	55.7	.862	"

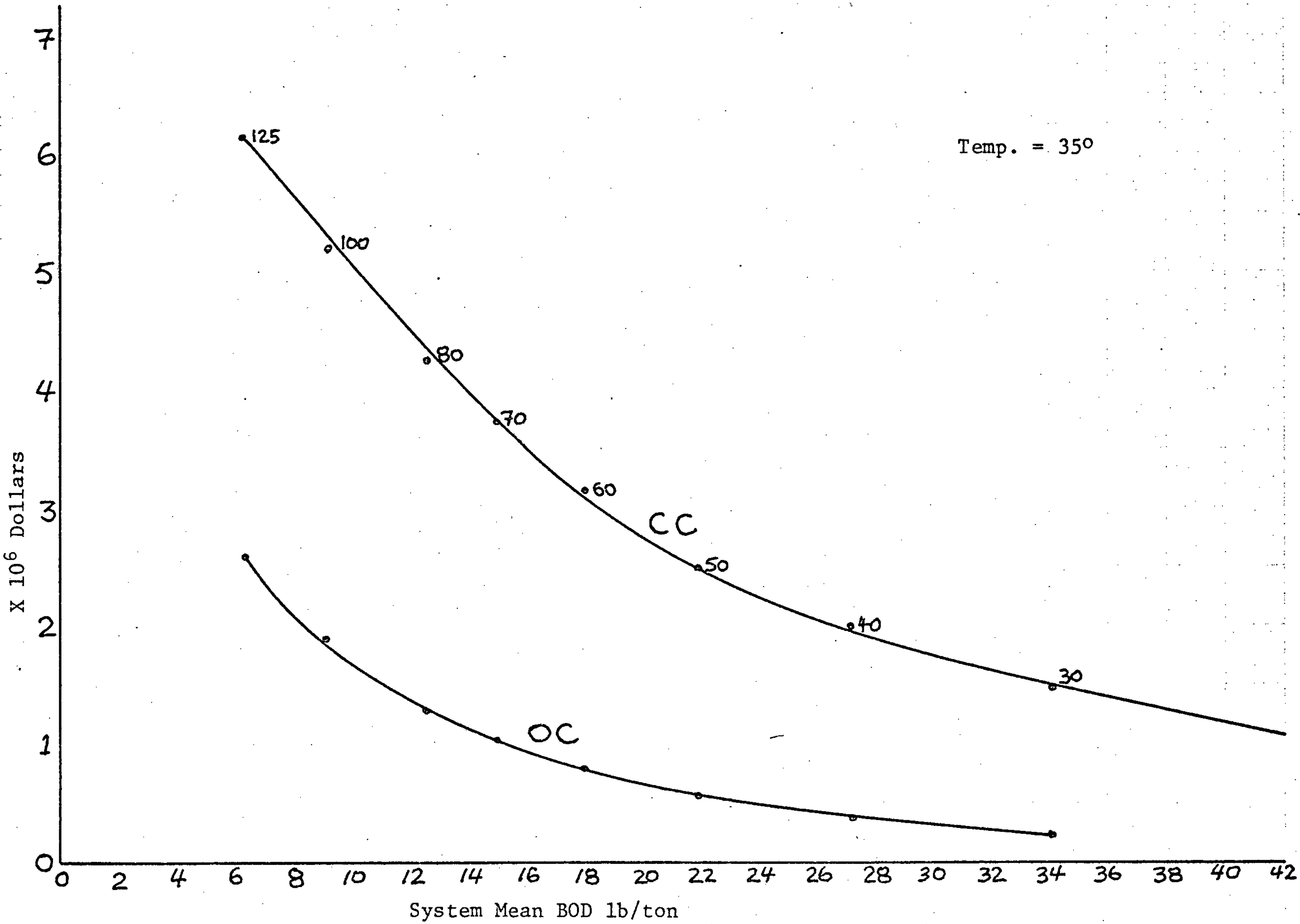


FIGURE 5.5

LAGOON CAPITAL AND OPERATING COST CURVES FOR COMBINATION 3 SYSTEM WITH INCREASED SPILL FREQUENCY IN RECOVERY AREA OF MILL. NUMBERS BESIDE DATA POINTS INDICATE LAGOON AREA IN ACRES.

TABLE 5.6

CLARIFIER CAPITAL AND OPERATING COST FOR THE COMBINATION 1 AND 2 SYSTEMS WITH DIFFERENT CLARIFIER DETENTION TIME

Comb	Det. Time Hrs	Clar. CC	Clar. OC	Clar. Eff.	In SS #/Ton		Out SS #/Ton		CL Out	
					Mean	Var	Mean	Var	D(M,M)	KS(.05)
3	3	584,190	47,566	.82	42.6	187.7	9.96	8.2	0	0
1	2	711,020	74,555	.69	42.6	187.7	12.7	13.0	.092	.238
	4	1,345,351	74,555	.85	"	"	6.1	2.9	.938	"
	5	1,651,934	"	.89	"	"	4.7	3.1	.923	"
	6	1,953,617	"	.91	"	"	3.7	2.7	.938	"
	7	2,251,286	"	.93	"	"	3.0	2.6	.938	"
2	2	402,300	47,566	.70	42.6	187.7	17.1	24.9	.538	.238
	4	761,199	"	.86	"	"	11.5	11.7	.262	"
	5	934,663	"	.90	"	"	10.3	9.5	.523	"
	6	1,105,355	"	.92	"	"	9.5	8.2	.723	"
	7	1,273,776	"	.94	"	"	8.9	7.3	.830	"

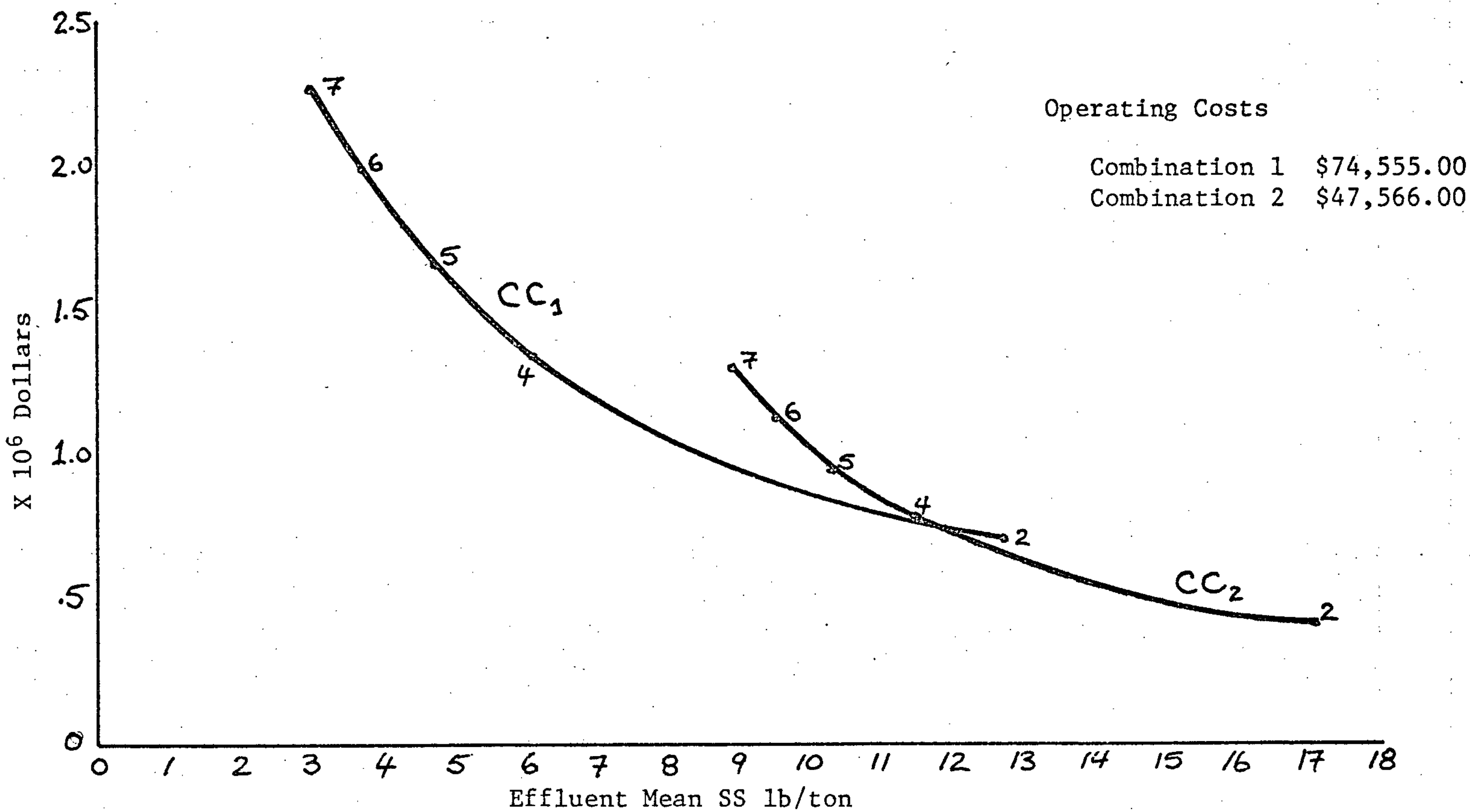


FIGURE 5.6

CLARIFIER CAPITAL COST CURVES FOR COMBINATION 1 AND COMBINATION 2 SYSTEMS. NUMBERS BESIDE DATA POINTS INDICATE THEORETICAL DETENTION TIME.

TABLE 5.7

SENSITIVITY EXPERIMENTS ON CLARIFIER MODEL FOR HYDRAULIC LOADS ±10% OF STANDARD AND EFFLUENT LOADS ±10% OF STANDARD

Experiment	Clar.	Input Clar.		Output Clar		KS Tests		
	Det. Time	Mean	Var	Mean	Var	D In	D Out	KS(.05)
.9* Hydraulic	3	39.04	157.6	12.1	12.9	.231	.169	.239
1.1* Hydraulic	3	46.2	220.5	14.9	19.1	.246	.215	.239
.9* Standard Influent Load	3	38.3	152.1	12.1	12.7	.307	.169	.239
1.1* Standard Influent Load	3	46.9	227.2	14.8	19.0	.215	.215	.239
Standard	3	42.6	187.7	13.4	15.7			

levels greater than or equal to 11.6 lb SS/ton the combination 2 cost curves dominate since both its capital and operating costs are least.

Some experiments were run with the clarifier model for ±10% changes in the hydraulic load and the effluent load for a 3 hour detention time clarifier in a combination 3 system. K-S goodness of fit tests were performed against the earlier described standard. The results are summarized in Table 5.7. In all cases the null hypothesis cannot be rejected for clarifier output although it can for all inputs except the .9x hydraulic load experiment.

5.2 SHOCK LOAD EXPERIMENTS

Various experiments were run with the previously defined standard system for shock loads of various intensities and over various time periods. These are summarized in Table 5.8. All the experiments were monitored for 11 days after the shock was initiated and the daily levels represent lb BOD/ton. All the experiments peak on day six as a consequence of the exponential form of the lagoon model. Remember it was assumed that the hydraulic flow is not altered by spills (and therefore shock loads).

To illustrate the lagoons response to a shock load, Figure 5.7 is a plot of the change in BOD concentration with time as a consequence of various size shocks over a 24 hour period. The time until the lagoon reaches its normal operational effluent concentration (approximately 20 mg/l) is about 3 days less for the 10 x normal than the 100 x normal shock load. The 100 x normal curve results in an effluent concentration 30 x normal for a period of 40 hours

TABLE 5.8

BOD lbs/TON EFFLUENT FROM A COMBINATION 2 SYSTEM FOR VARIOUS FACTOR SHOCK LOADS OVER VARIOUS TIME INTERVALS

		48 HOUR			24 HOUR				10 HOUR		5 HOUR		1 HOUR
Day	Factor =	5	10	100	5	10	50	100	10	100	5	100	100
1		15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4
2		7.4	7.6	11.4	7.4	7.6	9.3	11.5	7.9	15.1	10.7	14.3	10.7
3		17.7	26.3	180.4	17.6	26	93.3	177.3	19.6	106.8	41.8	73.2	34.6
4		28.4	50.1	442.1	22.5	36.9	152.4	296.8	22	133.2	47.6	85.0	37.6
5		31.2	57	523.3	21.2	34.5	141.6	275.5	19.7	112	40.2	70.5	31.6
6		61.1	110.6	1002.7	39.6	62.2	243.2	469.5	36.3	184.4	68.5	116.5	54.6
7		28.2	48.9	420.1	18.6	27.2	95.9	181.8	17.1	71.2	28.7	46	23.6
8		37	59.6	466.1	26	34.8	105.5	193.7	24.3	78.3	35.8	53	30.6
9		17.6	25.8	173	13.5	16.6	41.1	71.8	12.9	31.3	16.8	22.6	15.0
10		18.4	24	123.6	15.6	17.6	33.6	53.6	15.2	27.0	17.6	21.4	16.5
11		15.4	18.1	67.6	14	14.9	22.6	32.3	13.8	19.4	14.9	16.7	14.4
12		11	12.2	32.9	10.4	10.8	14.0	17.9	10.3	12.6	10.8	11.5	10.6

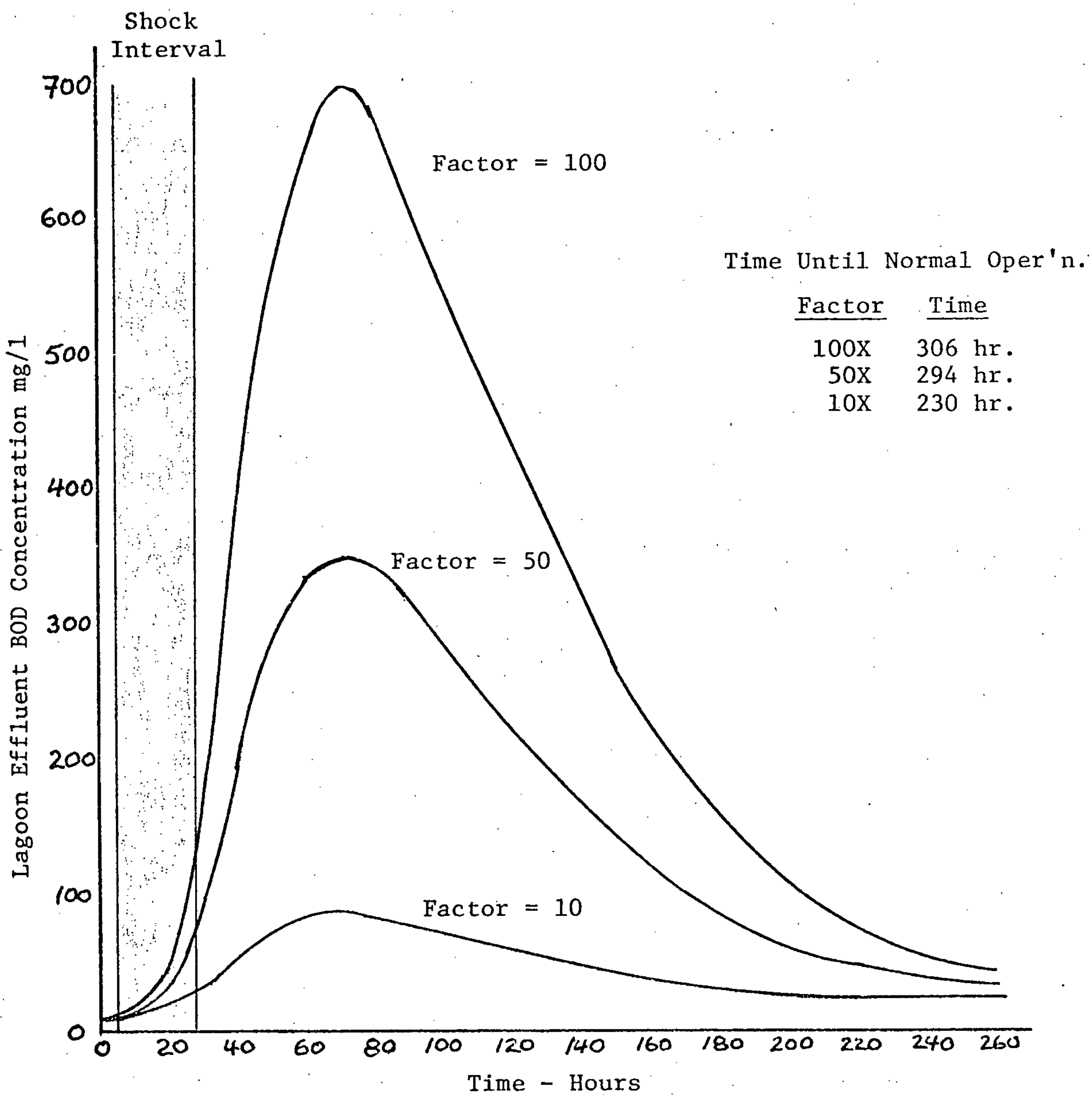


FIGURE 5.7

LAGOON RESPONSE CURVES FOR SHOCK INTERVAL OF 24 HOURS

TABLE 5.9

TABLE SHOWING LAGOON MAXIMUM CONCENTRATIONS AND RECOVERY TIMES AS A CONSEQUENCE OF VARIOUS SHOCK LOADS

Size of Factor	Time Interval	Time to Max	Max Conc.	Time From Max to Normal	Normal Conc
100	1	54 hrs	81 mg/l	244 hrs	21 mg/l
100	5	53 hrs	185 mg/l	270 "	"
50	"	"	105 "	250 "	"
100	10	43 "	300 mg/l	300 hrs	"
10	"	54 "	50 "	176 "	"
100	24	44 hrs	700 mg/l	306 "	"
50	"	"	350 mg/l	294 "	"
10	"	"	90 mg/l	230 "	"
100	48	29 hrs	1230 mg/l	337 hrs	"
10	"	29	140 mg/l	264 "	"

which according to the results in Gove (1974) will almost surely result in a fish kill. (Note a spill of this size is somewhat unlikely since it would represent several hundred thousand gallons of weak black liquor).

Some other response curves are summarized in Table 5.9. Their implications on the environment however, are not interpreted here.

To test whether the action of collecting a spill in a spill basin and then releasing it over time makes a considerable difference on a lagoon's performance, two experiments were run. The first with a factor of 10 x normal for 10 hours and the second with a factor of 2 x normal for 70 hours. (The 10 x normal spill for 10 hours represents a spill equivalent to approximately 100,000 gallons of weak black liquor, the 2 x normal for 70 hours represents approximately the same BOD loading). The results are presented below.

Experiment	Normal Conc. (mg/1)	Max. Conc. Reached (mg/1)	Time of Max.	Time Max. to Normal	lb/ton Max. Out	lb/ton Max. In
10 x 10 hr	20	40.9	33 hr	178 hr	32.7	102.1
2 x 70 hr	20	23.0	33 hr	170 hr	21.0	106.3

Both experiments reached maximum concentration at the same time and took the same length of time to recover. However, the 2 x 70 experiment resulted in considerably lower effluent concentrations over the same time span. This implies that if adequate spill monitoring is maintained enabling a spill to be diverted to a collection basin, releasing it at controlled levels over time will greatly decrease the spill's impact on the treatment system and the receiving stream.

5.3 SUGGESTED DATA COLLECTION SCHEMES AND MODEL IMPROVEMENTS

5.3.1. The Pulp Mill Model

One definite improvement for the pulp mill model is a better data base. The following is a list of the ideal data base that would facilitate the development of a better pulp mill model.

1. Hourly samples from the six major mill sewers indicated in Chapter III, determination of their BOD and SS loadings, and pH Also a record of the hourly flow past each of the monitored points. Continue for one week of operation.
2. For a period of 2 to 4 months daily samples at the same locations determining their BOD and SS loadings, pH and daily flows.
3. Complement #1 and #2 with conductivity charts for each of the six sewers with complete identification of spill locations and the chemical spilled.
4. Possibly make a more extensive study of the related spill concept developed in Chapter III. Such things as repetitive equipment failures can often be modelled very well with simple stochastic models.
5. Maintain a record of mill production etc., such that implications of a production stoppage can be correlated with the data gathered in 1, 2 and 3.

6. Monitor chlorine and hypochlorite spills adequately since they represent a sever shock to secondary waste treatment systems.
7. For the same periods as #1 and #2, hourly and/or daily samples from the main mill outfalls determining their BOD and SS loadings, pH, temperature and flow.

Another possible improvement is an increase in the number of major areas considered by the model. However, ignoring the increased data requirements this would entail, it may also destroy the validity of the stochastic "black box" approach used. To maintain the model's validity, development of more exact transform functions to generate the regular effluent would probably be necessary. This then gets back to the problems of modelling the kraft and bleaching process details. Such an approach should give a more definitive model but may not increase the applicability of the model to the purposes at hand.

5.3.2. The Waste Water Treatment Model

Data was not as crucial to development of the waste treatment model since it was a mathematical model of the process. However a better data base is needed for model validation. The ideal data base here would be the following.

1. Hourly analysis of influent and effluent for both the clarifier and lagoon, recording BOD and SS loadings, pH, temperature and flow. For the clarifier one week of data should suffice. For the lagoon at least two weeks is recommended. Also the clarifier should have samples taken every 10 or 15 minutes over one or two days to get a

better picture of its dynamic behaviour.

2. This should be complemented with continuous conductivity charts of the influent and effluent for both clarifier and lagoon.

One improvement of the waste treatment model would be the inclusion of models and cost curves for other process often used to treat pulp mill wastes. (i.e., Activated sludge, trickling filters, etc.) By making it possible for a user to experiment with various process combinations, other reliable systems, within a mills budget and/or space limitations could be explored. These models could be of a steady state nature, iterating on a reasonable dynamic time scale. Of course the validity of the steady state approach would have to be explored.

Another improvement would be the development and validation of a better clarifier model. It appears from a recent communication with Dr. Silveston, at Waterloo University that the linear reaction assumption for clarifier settling may be an oversimplication of the process. Silveston is currently developing another approach to modelling the dynamic operation of a clarifier.

CONCLUSIONS

The purposes of this study as stated at the beginning of Chapter II were to:

1. Develop two simulation models, one of the wastewater from a kraft pulp mill and another of a typical waste modification system common to the pulping industry.
2. Study the cost variability of waste treatment as a function of different system designs.

It is felt that these purposes were satisfied. The first four chapters describe the development, structure and validation for the two models in #1. Chapter V describes a sequence of experiments run with the models to determine the waste treatment systems sensitivity both in terms of cost and quality of effluent, fulfilling purpose #2.

The models developed are not perfect by many means and often represent simplifications of the processes involved. They have however served a number of useful functions. These are now summarized:

1. A "black box" approach was successfully used to provide a reasonably dynamic approximation of the water borne effluents from the pulping process.
2. A first attempt was made to analyze chemical spill data and try and incorporate the effluent implications of the spills in a model of the mill's effluent production.
3. A reasonably well validated model of a lagoon was developed and found to be more sensitive to changes in flow than influent

concentration. Also it was shown that operation of a spill basin can greatly reduce the impact of a spill on an aerated lagoon.

4. The frequency of spills, which although observed to have little effect on the efficiency of a lagoons performance, greatly affected the mean lbs BOD/ton of the effluent. The cost implications of this were found to be quite substantial. Also the size of lagoon required to meet the Pollution Control Boards Level A was also greatly affected.
5. A clear cost dominance relationship was found for three of the four waste treatment system configurations experimented with. When attempting to satisfy any effluent BOD quality level it was always less expensive, given any size lagoon over 25 acres, to operate the lagoon less efficiently and feed all the mill outfalls through the lagoon rather than bypass the lagoon with the acid sewer.
6. The level A standard for clarifier operation was demonstrated to be satisfied with less cost, by feeding only the general and machine room outfalls to the clarifier.

These are the major results. Many more observations and conclusions can be drawn from the experiments run. Also the experiments described in Chapter V do not exhaust the possibilities available with the models as they now stand. For example shock load experiments for different size lagoons could be tried. Shock load cycles could be experimented with to see if there are any natural frequencies at which the system reaches a stability threshhold. More experiments could be run for different spill distributions to determine the marginal costs of reducing the mean levels, etc.

It would appear in conclusion that the techniques employed in this study could be of considerable use to pulp mill management in making a waste treatment system investment decision. The trade offs become much clearer and alternate designs can be examined without the "real world" consequences. The imperfections of the models should be kept in mind but only as indicators for future development. Through continued experimentation and development, the validity of a model and therefore its usefulness grows. It is hoped that this study has provided another step in that direction.

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APPENDIX I

SEMI-MARKOV ANALYSIS OF RELATED SPILLS

In Chapter III a semi-markov approach was introduced as a convenient way to describe a spill sequence. In the following few pages this semi-markov approach will be carried through to determine the processes limiting probabilities and passage times. The notation and logic of development is borrowed from a set of notes written by Raiffa and Blaydon called "An Introduction to Markov Chains". To the author's knowledge these notes have not been published, however, the necessary definitions are included in the development and the logic should be clear to a reader familiar with Markov-Chains.

A stochastic process $\{X_n, n = 0, 1, 2, \ldots.\}$ with a finite or countable state space, is said to be a Markov chain if for all states $i_0, i_1, \ldots {}_{n-1}, \; ,j$ and all $n \geq 0$

$$P\{X_{n+1} = j \mid X_o = i_o, X_1 = i_1, \ldots, X_{n-1} = i_{n-1}, X_n = i\}$$
$$= P\{X_{n+1} = j \mid X_n = i\}$$

A stochastic process which makes transitions from state to state in accordance with a Markov chain, but in which the amount of time spent in each state before a transition occurs is random, is called a semi-Markov chain.

Now in the context of Chapter III we have a state being defined as the sequential location of a spill in the current related spill sequence of an area. A related spill is a spill in the same mill location as the immediately preceding spill for the current major area. For example say we have the following time sequence of spills in major area 1 of the mill (recovery area)

Time of Spill	Time Difference (hrs)	State of System
0		1
25	25	1
38	13	1
39	1	1 } related
43	4	2 } spill
52	9	3 } sequence
64	12	1 }
69	5	2 } related
73	4	3 } spill
75	2	4 } sequence
80	5	5 }
100	20	1
120	20	1

In the above there are 6 related spill sequences. The first 3 are only 1 spill long, the fourth is 3 spills long and the fifth is 5 spills long followed by the sixth which is again only 1 spill long. The sequences must always start with the system in state 1, no state can be missed in moving along the chain from state 1, and at the end of a related sequence the system returns to state 1.

From the data described in Chapter III the following transition matrix was derived for spills in sub area 3 (weak black liquor spills) See Table A1.

State	1	2	3	4	5	6
1	11/31	20/31	0	0	0	0
2	9/20	0	11/20	0	0	0
3	2/11	0	0	9/11	0	0
4	2/3	0	0	0	1/3	0
5	2/3	0	0	0	0	1/3
6	1	0	0	0	0	0

Table A1

Note the system has only 6 possible states.

From a K-S goodness of fit routine the times between related spills for sub area 3 fit the negative binomial with

p = prob of success = .288

$k = .801$

This implies a mean residence time in the states, 2, 3, 4, 5, 6 equal to the mean of the negative binomial distribution:

$$\text{mean} = \frac{k \times (1 - p)}{p} = \frac{.8 \times .71}{.29} = 1.95 \text{ hrs}$$

For the times between unrelated spills a K-S goodness of fit test found the exponential distribution, with mean Θ = 156.4 hours, to give a good fit. Therefore the mean residence time in state 1 is 156.4 hours.

Now if we take the transition matrix given in Table A1 we can solve for the stationary probabilities that would be operative if the process were an ordinary Markov chain.

Solving we get:

$$\Pi_1 = \frac{11}{31}\Pi_1 + \frac{9}{20}\Pi_2 + \frac{2}{11}\Pi_3 + \frac{2}{3}\Pi_4 + \frac{2}{3}\Pi_5 + \Pi_6$$

$$\Pi_2 = \frac{20}{31}\Pi_1$$

$$\Pi_3 = \frac{11}{20}\Pi_2$$

$$\Pi_4 = \frac{9}{11}\Pi_3$$

$$\Pi_5 = \frac{1}{3}\Pi_4$$

$$\Pi_6 = \frac{1}{3}\Pi_5$$

and $\sum_{i=1}^{6} \Pi_i = 1$

Solving the above simultaneous equations

$\Pi_1 = .414$

$\Pi_2 = .266$

$\Pi_3 = .22$

$\Pi_4 = .12$

$\Pi_5 = .04$

$\Pi_6 = .0133$

These six probabilities then are the limiting probabilities of finding the system in each of the states ignoring the state residence times. The following is the semi-Markov analysis which will take into account the different time distributions.

Define:

S_i = state i

$\overline{T}_{ij}$ = expected waiting time for a transition from S_i to S_j given that the transition is definitely going to take place.

(Note:
$$\overline{T}_{11} = \overline{T}_{21} = \overline{T}_{31} = \overline{T}_{41} = \overline{T}_{51} = \overline{T}_{61} = 156.4 \text{ hrs}$$
$$\overline{T}_{12} = \overline{T}_{23} = \overline{T}_{34} = \overline{T}_{45} = \overline{T}_{56} = 1.95 \text{ hrs}$$
)

P_{ij}: = probability of a transition from S_i to S_j by $t = \infty$ (i.e. given that a transition from S_i is definitly going to occur, P_{ij} is the probability that the system will be going to S_j)

Therefore define

$\bar{T}_i$ = expected waiting time in S_i

$= \sum_j P_{ij} \bar{T}_{ij}$

Solving for all the states

$\bar{T}_1 = P_{11}\bar{T}_{11} + P_{12}\bar{T}_{12} = \frac{11}{31} \times 156.4 + \frac{20}{31} \times 1.95$

$= 56.8$ hrs

$\bar{T}_2 = P_{21}\bar{T}_{21} + P_{23}\bar{T}_{23} = \frac{9}{20} \times 156.4 + \frac{11}{20} \times 1.95$

$= 71.5$ hrs

$\bar{T}_3 = P_{31}\bar{T}_{31} + P_{34}\bar{T}_{34} = \frac{2}{11} \times 156.4 + \frac{9}{11} \times 1.95$

$= 30.0$ hrs

$\bar{T}_4 = P_{41}\bar{T}_{41} + P_{45}\bar{T}_{45} = \frac{2}{3} \times 156.4 + \frac{1}{3} \times 1.95$

$= 104.95$ hrs

$\bar{T}_5 = P_{51}\bar{T}_{51} + P_{56}\bar{T}_{56} = \frac{2}{3} \times 156.4 + \frac{1}{3} \times 1.95$

$= 104.95$ hrs

$\bar{T}_6 = P_{61}\bar{T}_{61} + P_{67}\bar{T}_{67} = 1 \times 156.4$

$= 156.4$ hrs

Now if we compute the proportion of time that the process spends in S_j as $t \to \infty$, this should be the same as the limiting probability of being found in that state or ϕ_j^*.

Since for the imbedded process the limiting probability of a transition to S_j is Π_j, the proportion of time spent in S_j should equal ϕ_j^*.

Therefore $\phi_j^* = \frac{\Pi_j \bar{T}_j}{(\Sigma_i \Pi_i \bar{T}_i)}$

Solving for the six states

$$\phi_1^* = \frac{\Pi_1 \bar{T}_1}{\Sigma_i \Pi_i \bar{T}_i} = \frac{.414 \times 56.8}{71.5} = .33$$

$$\phi_2^* = \frac{.266 \times 71.5}{71.5} = .266$$

$$\phi_3^* = \frac{.22 \times 30}{71.5} = .094$$

$$\phi_4^* = \frac{.12 \times 105}{71.5} = .176$$

$$\phi_5^* = \frac{.04 \times 105}{71.5} = .0585$$

$$\phi_6^* = \frac{.013 \times 156.4}{71.5} = .0283$$

Note that ϕ^* does not depend on the form of the holding time distribution but only on the mean holding times.

Define the limiting probability e_j^* as the limiting probability that on any step the process is entering state S_j. Now arguing intuitively, since $\bar{T}_j$ is the expected length of stay in S_j then dividing ϕ_j^*, the limiting probability of being in state j, by $\bar{T}_j$, should be roughly the probability of entering S_j on any step of that interval.

Therefore e_j^* = limiting probability that on any step the process is entering $S_j = \frac{\phi_j^*}{\bar{T}_j}$

Solving for the six states

$$e_1^* = \frac{.33}{56.8} = .0058$$

$$e_2^* = \frac{.266}{71.5} = .0037$$

$$e_3^* = \frac{.094}{30} = .0031$$

$$e_4^* = \frac{.176}{105} = .00167$$

$$e_5^* = \frac{.0585}{105} = .00056$$

$$e_6^* = \frac{.0283}{151.4} = .00018$$

Define the limiting destination probabilities γ_{ij}^* as the limiting joint probability that on any step the process is in S_i and the next transition will be to S_j.

We know the long run probability of finding the process in S_i is ϕ_i^*. The total expected holding time in S is $\bar{T}_i = \sum_{K=1}^{N} P_{ik}\bar{T}_{ik}$. The fractions of this holding time that is due to transitions from S_i to S_j is $\frac{P_{ij}\bar{T}_{ij}}{\bar{T}}$

Therefore $\gamma_{ij}^{*} = \phi_{i}^{*} \frac{P_{ij}\bar{T}_{ij}}{\bar{T}_{i}}$

Therefore we get

$$\gamma_{11}^{*} = \phi_{1}^{*} \frac{P_{11}\bar{T}_{11}}{\bar{T}_{1}} = \frac{.33 \times .355 \times 156.4}{56.8}$$

$$= .32$$

Similarly

$\gamma_{12}^{*} = .0104$

$\gamma_{21}^{*} = .261$

$\gamma_{22}^{*} = 0$

$\gamma_{23}^{*} = .0057$

$\gamma_{31}^{*} = .087$

$\gamma_{34}^{*} = .007$

$\gamma_{41}^{*} = .172$

$\gamma_{45}^{*} = .0011$

$\gamma_{51}^{*} = .0574$

$\gamma_{56}^{*} = .00356$

$\gamma_{61}^{*} = .0283$

Now to get the limiting transition probabilities we can get them back by noting

$$\phi_{i}^{*} = \sum_{j=1}^{N} \gamma_{ij}^{*}$$

Again note that the limiting entrance probabilities do not depend on the holding time distributions but only on the expected holding times. If however we were not interested in limiting probabilities but want intermediate step probabilities, the expressions do depend on the holding time distributions. This will not however be pursued here.

One final limiting parameter of interest is the mean first passage times. Define $\bar{\theta}_{ij}$, the expected time of passage from state i to state j. For a semi-Markov chain, the mean recurrence time, $\bar{\theta}_{jj}$, is $\frac{i}{e_j^*}$, the reciprocal of the limiting probability of entering state j.

Therefore

$$\bar{\theta}_{11} = \frac{1}{e_1^*} = 174 \text{ hrs}$$

$$\bar{\theta}_{22} = 271 \text{ hrs}$$

$$\bar{\theta}_{33} = 327 \text{ hrs}$$

$$\bar{\theta}_{44} = 600 \text{ hrs}$$

$$\bar{\theta}_{55} = 1785 \text{ hrs}$$

$$\bar{\theta}_{66} = 5550 \text{ hrs}$$

From this we can conclude that in the long run (as $t \to \infty$) every 174 hours there will be a spill in sub area 3 which could be the initiator of a related sequence of spills. Every 271 hours there will be a related sequence of spills at least 2 spills long. Every 327 hours there will be a related sequence of spills at least 3 spills long and so on.

These results although not used in the model developed in this study could be useful for an analytic examination of spills and their related costs. By establishing a semi-Markov decision process for all the major areas within the mill, it may be possible to associate some costs with the spills and optimize the process.

Since a spill has both a cost consequence (the cost of replacing chemical, and possible above effluent level fines) and a benefit consequence (if a spill is ignored, maintenance costs, etc., are reduced), the results may be quite informative as to the tradeoffs involved in spill monitoring and prevention.

APPENDIX II

DERIVATION OF CONVERSION FACTORS TO CONVERT Na_2SO_4 EQUIVALENT SPILLS TO GALLONS OF CHEMICAL

As noted in Chapter III the generation of spill amounts in the pulp model is in terms of pounds of Na_2SO_4 (saltcake) equivalent. The model then determines the spill sublocation and converts the Na_2SO_4 amount to the equivalent number of gallons of chemical typical to that sublocation. Knowing the BOD and SS mg/l values for each of the chemicals (see Table 3.9), the spill can be converted to its BOD and SS equivalent.

The conversion factors to convert pounds Na_2SO_4 to gallons of chemical for the four liquors are derived below. All the analysis figures are taken from C.E. Libby (1962).

1. Weak Black Liquor (W.B.L.) Total sodium in W.B.L. taken as Na_2O equivalent $= 49.23 \frac{\text{gms}}{\text{litre}}$

   Therefore since 1 gm of Na_2O = 2.29 gms Na_2SO_4 for equivalent amounts of sodium the total sodium in W.B.L. taken as a Na_2SO_4 equivalent $= 49.23 \times 2.29 = 112.74$ g/l

   Therefore concentration (in terms of Na_2SO_4) $= 112.74 \frac{\text{gms}}{\text{litre}} \times 3.785 \frac{1}{\text{gal}} \times 10^{-3}\frac{\text{kg}}{\text{gm}} \times 2.2 \frac{\text{lb}}{\text{kg}} = .94 \frac{\#Na_2SO_4}{\text{US gal of W.B.L.}}$ or 1.06 gal W.B.L. = 1# Na_2SO_4

2. Strong Black Liquor (S.B.L.) For W.B.L. the percentage of solids by weight $\cong$ 16%. For S.B.L. the percentage of solids by weight $\cong$ 52.9%.

Assuming that only water is lost in the evaporators and that all the solids are transferred through, then the difference in % of solids is a consequence of the loss of water only. Now say we have 1 # of solids. Then

$$1 \# \text{ of solids } \frac{1\#}{.16} = 6.06 \# \text{ W.B.L.}$$

$$\text{or } \frac{1\#}{.529} = 1.869 \# \text{ S.B.L.}$$

Therefore in W.B.L. there are 5.06 # H_2O and in the S.B.L. .869 # H_2O.

This implies that the evaporators, evaporate $\frac{5.06 - .869}{5.06} \times 100 = 83\%$ of the water

From Libby (1962) specific gravity W.B.L. = 1.087, specific gravity S.B.L. = 1.325.

Therefore 1 gal W.B.L. = $1.087 \times 8.3 \frac{\text{lbs}}{\text{gal } H_2O} = 9.1\#$

(<u>note</u>: 1.5# are solids, 7.6# are H_2O)

Therefore after evaporation this 9.1# of W.B.L. will be reduced to

$$9.1\# - .83 \times 7.6\# \frac{H_2O}{\text{gal of W.B.L.}} = 2.8\# \text{ S.B.L.}$$

This 2.8# of S.B.L. will have the same Na_2SO_4 equivalent as the 9.1# of W.B.L.

Now 1 gallon S.B.L. = $1.325 \times 8.3 \frac{\text{lbs}}{1 \text{ gal } H_2O} = 11.0\#$

Therefore 2.8# S.B.L. .941 # Na_2SO_4

11.0# S.B.L. 1 gal S.B.L. $.941 \times \frac{11}{2.8} = 2.7 \# Na_2SO_4$

In other words 1 gal S.B.L. has a 3.7# Na_2SO_4 equivalent

Therefore 1# Na_2SO_4 = .27 gal S.B.L.

3. <u>Green Liquor</u> (G.L.) From an example G.L. analysis in Libby (1962)

1 ft^3 G.L. contains	Na_2S	- 1.4# Na_2O equivalent
	$NaOH$	- 1.1# Na_2O equivalent
	Na_2CO_3	- 5.9# Na_2O equivalent

Total alkali content = 8.4# ft^3 as Na_2O

This is equivalent to 8.4 x 2.290 = 19.2 # $\frac{Na_2SO_4 \text{ equivalent}}{ft^3 \text{ of G.L.}}$

Therefore 1# $Na_2SO_4 \cong 19.2 \frac{Na_2SO_4}{ft^3} \times 1605 \frac{ft^3}{gal} \approx .325$ gal G.L.

4. White Liquor (W.L.) From an example W.L. analysis in Libby (1962).

In one cubic foot of W.L. there is

Na_2S - 1.4# as Na_2O equivalent

$NaOH$ - 5.5# as Na_2O equivalent

Na_2CO_3- 1.5# as Na_2O equivalent

Total alkali content = 8.4# $\frac{Na_2O}{ft^3 \text{of W.L.}}$

Therefore 1# $Na_2SO_4$is equivalent to 19.2# $\frac{Na_2SO_4}{ft^3} \times .1605 \frac{ft^3}{gal}^{-1}$ = .325 gal

APPENDIX III

A LISTING OF THE PULP MILL MODEL (FORTRAN)

The logical units are assigned in the model as follows

Logical Unit	Task
#1	Record of Daily production, water usage and fiber losses - is generated by the model
#2	Record of spills in major area 1 - generated by model
#3	Record of spills in major area 2 - generated by model
#4	Record of spills in major area 3 - generated by model
#6	Record of total lbs of BOD, TS and SS generated by mill each hour
#7	Input file to be supplied by user for distribution parameters and other empirical data needed to run model
#8	Record of BOD, TS and SS concentrations for each of the 3 outfalls each hour (mg/l) - generated by model
#9	Record of hourly flows for each of the 3 outfalls (in MUSG) and the hourly production (in tons) - generated by model.

Note: Units #8 and #9 are used as input into the Waste treatment model.

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LISTING OF FILE PULP-MODEL   11:31 A.M.   AUG. 19, 1975   ID=XT23

```
      COMMON ALPHQ(4),LAMQ(4),ALPHT(4),LAMT(4),ASP(3),TIME(3),TIM(3),T,
     1P(4,3),LOC(4,3),AMT(3),TRA [illegible](3,3,9),CONV(13),BOD(3),TS(3)
     1,SS(4),[illegible](3),[illegible](6),[illegible](3),ASS(6),ATS(6),STS(6),[illegible]T(6),[illegible]PR(
     16),XSSPR(3), TSPR(3),[illegible](6),[illegible](6),[illegible](6),[illegible](6),RTS(6),RSS(6)
     1,BOD(3),DTS(3),DSS(3),[illegible](3),TSP[illegible](3),SSP[illegible](3),[illegible]AX(3),
     1SBMIN(3),STMAX(3),STMIN(3),[illegible]AX(3),[illegible](3),P[illegible](4),[illegible](6)
      COMMON SPL(3),[illegible](3),[illegible](3), [illegible](6),[illegible](6),[illegible](1)
      COMMON PROD(23,2),FIB(3,25,2),SSS(6),KF,
     1WATERR(2,13,2),BODF(14),TSF(14),SSF(14),[illegible](6)
     1,FIBERR(3),FIBHR(3),P[illegible],START(10),ITIME,XSS(6)
     1,WATT(3),CBOD(3),CTS(3),CSS(3)
      INTEGER T,J,TIM,SPL,LOC,TIME
      REAL LAMQ,LAMT
      ITIME=8600
      GC=0.
C DAILY PRODUCTION DISTRIBUTION
      DO 91 J=1,2
      READ(7,90)(PROD(I,J),I=1,11)
   90 FORMAT(3F10.4/3F10.4)
   91 CONTINUE
C FIBER LOSS AMTS DISTRIBUTIONS
      DO 2 I=1,25
      READ(7,11)(FIB(J,I,1),J=1,3)
    2 CONTINUE
      DO 3 I=1,25
      READ(7,12)(FIB(J,I,2),J=1,3)
    3 CONTINUE
   11 FORMAT(3F10.5)
   12 FORMAT(3F10.0)
C AVERAGE LEVELS AND STANDARD DEV'NS FOR BOD,SS,TS IN MG/L
      DO 4 I=1,6
      READ(7,13)ABOD(I),SBOD(I),ATS(I),STS(I),ASS(I),SSS(I)
   13 FORMAT(6F10.3)
    4 CONTINUE
C
C DAILY WATER USAGE DISTRIBUTIONS
C
      DO 5 I=1,2
      READ(7,25)(WATERR(I,J,1),J=1,13)
      READ(7,26)(WATERR(I,J,2),J=1,13)
   25 FORMAT(13F6.5)
   26 FORMAT(13F6.0)
    5 CONTINUE
C
C PARAMETERS FOR SPILL TIME AND AMOUNT DISTRIBUTIONS
C
      DO 30 K=1,3
      READ(7,31)ALPHQ(K),LAMQ(K),ALPHT(K),LAMT(K),PR(K),SS(K)
   31 FORMAT(6F10.4)
   30 CONTINUE
C
C SPILL SUBLOCATION DISTRIBUTIONS
C
      DO 35 I=1,4
      READ(7,36)(P(I,J),J=1,3)
   36 FORMAT(3F10.5)
   35 CONTINUE
      DO 37 I=1,4
```

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LISTING OF FILE FILP-MODEL 11:01 A.M. NOV. 14, 1975 ID=M123

```
      READ(7,38)(LOC(I,J),J=1,3)
 38   FORMAT(3I5)
 37   CONTINUE
C
C TRANSITION MATRIX PROBABILITIES FOR SELECTED SPILLS AREAS 1,2,3
C
      DO 40 M=1,7
      L=M+1
      READ(7,41)(TRAN(I,M,L),I=1,3)
 41   FORMAT(3F10.5)
 40   CONTINUE
C
C CONVERSION SALTCAKE EQUIV TO GALS FOR EACH KIND OF SPILL AND BOD,SS,TS
C FACTORS TO CONVERT GALS OF SPILL TO POUNDS OF BOD,TS
C
      DO 45 I=1,14
      READ(7,46)CONV(I),BODF(I),TSF(I),SSF(I)
 45   CONTINUE
 46   FORMAT(4F10.5)
      READ(7,28)(W(I),I=1,6)
 28   FORMAT(6F10.5)
      DO 42 I=1,3
      NSP(I)=0
      SPL(I)=0
      DBOD(I)=0.
      DTS(I)=0.
      DSS(I)=0.
      HBOD(I)=0.
      HTS(I)=0.
      HSS(I)=0.
      SBMAX(I)=0.
      SBMIN(I)=0.
      STMAX(I)=0.
      STMIN(I)=0.
      SSMAX(I)=0.
      SSMIN(I)=0.
   42 CONTINUE
      DO 44 I=1,3
      ZBOD(I)=0.
      ZTS(I)=0.
      ZSS(I)=0.
      START(I)=1.
   44 CONTINUE
      DO 47 I=1,10
      START(I)=1.
  47  CONTINUE
      HTBOD=0.
      HTSS=0.
      HTTS=0.
      T=0
      D=0
      FN=RAND(.333)
      RD=RANDN(.555)
      IF(GO.EQ.1.)GO TO 64
      CALL SPILL
      IDTIME=ITIME/24+1
      DO 70 I=1,IDTIME
      CALL PRODN(PROD,PRODT,PRODHR)
```

```
      CALL WATER(FECOT,WAT[illegible],F[illegible]AT,[illegible]T,W)
      CALL FIBER(FIB,FI[illegible],FI[illegible])
      WRITE(1,60)I,PRODHR,(FI[illegible](J),J=1,3),(WAT(K),K=1,6)
   60 FORMAT(1X,I5,10F10.2)
   70 CONTINUE
      T=0
      REWIND 1
      REWIND 2
      REWIND 3
      REWIND 4
   64 CONTINUE
      READ(2,126)TIM(1),BOD(1),TS(1),XSS(1)
      READ(3,126)TIM(2),BOD(2),TS(2),XSS(2)
      READ(4,126)TIM(3),BOD(3),TS(3),XSS(3)
  126 FORMAT(5X,I10,15X,3F15.0)
   65 T=T+1
      D=D+1
      IF(D.NE.1)GO TO 129
  124 READ(1,125)I,PRODHR,(FIBER(J),J=1,3),(WAT(K),K=1,6)
  125 FORMAT(I6,10F10.2)
      WATT(1)=WAT(1)
      WATT(2)=WAT(2)+WAT(3)+WAT(4)+WAT(5)
      WATT(3)=WAT(6)
      PRODT=PRODHR*24.
      WRITE(9,122)(WATT(I),I=1,3),PRODT,T
  122 FORMAT(1X,3F6.2,F10.1,I3)
  129 CALL REGUL
      DO 75 I=1,3
      IF(TIM(I).EQ.T)GO TO 76
      GO TO 75
   76 CONTINUE
      ZBOD(I)=BOD(I)*2.2
      ZSS(I)=XSS(I)*2.2
      ZTS(I)=TS(I)*2.2
      IF(ZBOD(I).GT.SBMAX(I))SBMAX(I)=ZBOD(I)
      IF(ZBOD(I).LT.SBMIN(I))SBMIN(I)=ZBOD(I)
      IF(ZTS(I).GT.STMAX(I))STMAX(I)=ZTS(I)
      IF(ZTS(I).LT.STMIN(I))STMIN(I)=ZTS(I)
      IF(ZSS(I).GT.SSMAX(I))SSMAX(I)=ZSS(I)
      IF(ZSS(I).LT.SSMIN(I))SSMIN(I)=ZSS(I)
      GO TO(130,135,140),I
  130 READ(2,126)TIME(1),BOD(1),TS(1),XSS(1)
      TIM(1)=TIME(1)+T
      GO TO 101
  135 READ(3,126)TIME(2),BOD(2),TS(2),XSS(2)
      TIM(2)=TIME(2)+T
      GO TO 101
  140 READ(4,126)TIME(3),BOD(3),TS(3),XSS(3)
      TIM(3)=TIME(3)+T
  101 SPL(I)=SPL(I)+1
   75 CONTINUE
      HBOD(1)=RBODPH(1)
      HTS(1)=RTSPH(1)
      HSS(1)=RSSPH(1)
      DO 100 I=2,5
      HBOD(2)=HBOD(2)+RBODPH(I)+ZBOD(I-1)
      HTS(2)=HTS(2)+RTSPH(I)+ZTS(I-1)
      HSS(2)=HSS(2)+RSSPH(I)+ZSS(I-1)
```

```
100   CONTINUE
      HBOD(3)=HBODPH(6)
      HTS(3)=HTSPH(6)
      HSS(3)=HSSPH(6)
      DO 110 I=1,3
      DBOD(I)=DBOD(I)+HBOD(I)
      DTS(I)=DTS(I)+HTS(I)
      DSS(I)=DSS(I)+HSS(I)
      TWADAY=HRWAT*24.
110   CONTINUE
      IF(J.EQ.24)GO TO 111
      GO TO 120
111   DO 112 I=1,3
      PRODT=PRODHR*24.
      BODPTN(I)=DBOD(I)/PRODT
      TSPTON(I)=DTS(I)/PRODT
      SSPTON(I)=DSS(I)/PRODT
112   CONTINUE
      BODTN=(BODPTN(1)+BODPTN(2)+BODPTN(3))
      TSTON=TSPTON(1)+TSPTON(2)+TSPTON(3)
      SSTON=SSPTON(1)+SSPTON(2)+SSPTON(3)
      DO 113 J=1,3
      HRWAT=HRWAT+WAT(J)
113   CONTINUE
      TWADAY=HRWAT*24.
120   CONTINUE
      DO 121 I=1,3
      HTBOD=HTBOD+HBOD(I)
      HTTS=HTTS+HTS(I)
      HTSS=HTSS+HSS(I)
121   CONTINUE
      CBOD(1)=HBOD(1)/(2.205*WATT(1)*3.785)
      CTS(1)=HTS(1)/(2.205*WATT(1)*3.785)
      CSS(1)=HSS(1)/(2.205*WATT(1)*3.785)
      CBOD(2)=HBOD(2)/(2.205*WATT(2)*3.785)
      CTS(2)=HTS(2)/(2.205*WATT(2)*3.785)
      CSS(2)=HSS(2)/(2.205*WATT(2)*3.785)
      CBOD(3)=HBOD(3)/(2.205*WATT(3)*3.785)
      CTS(3)=HTS(3)/(2.205*WATT(3)*3.785)
      CSS(3)=HSS(3)/(2.205*WATT(3)*3.785)
      WRITE(6,300)(CBOD(L),L=1,3),(CSS(J),J=1,3),(CTS(K),K=1,3)
300   FORMAT(1X,9F10.2,I8)
      WRITE(6,200)HTBOD,HTTS,HTSS
200   FORMAT(1X,3(F15.2,2X))
      IF(J.NE.24) GO TO 210
      PRODT=PRODHR*24
      WRITE(6,201)BODTN,TSTON,SSTON,PRODT,TWADAY,T
      DO 202 I=1,3
      SBMAX(I)=0.
      SBMIN(I)=0.
      STMAX(I)=0.
      STMIN(I)=0.
      SSMAX(I)=0.
      SSMIN(I)=0.
      DBOD(I)=0.
      DTS(I)=0.
      DSS(I)=0.
202   CONTINUE
```

```
            PRODT=C.
            PRANT=C.
            TNDAY=0.
            J=C
  201       FORMAT(/.I5,5(F15.2,2X),I5,/)
  210       IF(T.EQ.ITIME)GC TC 250
            DO 220 I=1,5
            HBOD(I)=0.0
            HTS(I)=0.0
            HSS(I)=0.0
            ZBOD(I)=0.0
            ZSS(I)=0.0
            ZTS(I)=0.0
  220       CONTINUE
            HTBOD=C.
            HTTS=C.
            HTSS=0.
            GO TO 65
  250       STOP
            END
      C
             SUBROUTINE SPILL
      C
            COMMON ALPHO(4),LAMO(4),ALPHT(4),LAMT(4),NSP(3),TIME(3),TIM(3),T,
           1P(4,3),LOC(4,3),AMT(3),TRAN(3,9,9),CLAV(15),ROD(3),IS(3)
           1,SS(4),LSUB(3),ABOD(6),SBOD(6),ASS(6),ATS(6),STS(6),WAT(6),RRCFFH(
           16),RSSPH(6),RTSPH(6),ZBOD(6),ZTS(6),ZSS(6),D,HBOD(6),HTS(6),HSS(6)
           1,DBOD(3),DTS(3),DSS(3),BODPTN(3),TSPTCN(3),SSPTCN(3),SBMAX(3),
           1SBMIN(3),STMAX(3),STMIN(3),SSMAX(3),SSMIN(3),W(4),AAMT(6)
            COMMON SPL(3),RBOD(6),RBOD(6),RSS(6), TS(6),RA(10)
            COMMON PBOD(20,2),FIB(3,25,2),SSS(6),KK,
           1WATERR(2,13,2),BODF(14),TSF(14),SSF(14),X(6)
           1,FIBERP(3),FIBHR(3),PRODPP,START(10),ITIME,XSS(6)
            INTEGER T,D,TIM,SPL,LOC,TIME
            REAL LAMO,LAMT
      C THIS SUBROUTINE GENERATES SPILLS,DETERMINES ITS HOUR OF OCCURENCE,ITS
      C SALTCAKE ECUIVALENT,AND ITS SUBLOCATION
      C TIME AND AMCUNT OF INITIAL SPILL OF POSSIBLE SEQUENCE
            DO 100 KK=1,3
            T=C
            DD=ALPHO(KK)
            E=LAMO(KK)
    1       IF(NSP(KK).NE.0) GC TO 10
    5       A=ALPHT(KK)
            B=LAMT(KK)
            NSP(KK)=0
             KKK=KK+3
          6 CALL GAMMA(A,B,START,KKK,C)
            TIME(KK)=C+1.0
            IF(TIME(KK).LE.10)TIME(KK)=TIME(KK)+10
            CALL GAMMA(DD,E,START,KK,F)
            AMT(KK)=F*1000.
            TIM(KK)=TIME(KK)
            T=T+TIM(KK)
            RN1=RAND(0.0)
            IF(RN1.LT.P(1,KK))LSUB(KK)=LOC(1,KK)
            IF(RN1.GE.P(1,KK).AND.RN1.LT.P(2,KK))LSUB(KK)=LOC(2,KK)
            IF(RN1.GE.P(2,KK).AND.RN1.LT.P(3,KK))LSUB(KK)=LOC(3,KK)
```

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```
      IF(RN1.??.P(3,KK))LSUB(KK)=L?(?,KK)
      LS=LSUB(KK)
      AAMT(KK)=AMT(KK)*CONV(LS)
      GO TO 20
C
C TIME AND AMOUNT OF RELEASE SPILL
C
10    RN2=RAND(0.0)
      M=NSP(KK)
      RPROB(KK)=TRAN(KK,M,M+1)
      IF(RN2.GT.RPROB(KK))GO TO 5
      R=RR(KK)
      S=SS(KK)
      L=KK+5
      IF(L.EQ.9)GO TO 5
11    CALL NEGBIN(R,S,START,L,TR)
      TIME(KK)=TR+1.0
      IF(TIME(KK).GT.10)GO TO 11
      TIM(KK)=TIME(KK)
      T=T+TIM(KK)
      CALL GAMMA(BO,L,START,KK,F)
      AMT(KK)=F*1000.
      LS=LSUB(KK)
      AAMT(KK)=AMT(KK)*CONV(LS)
20    CONTINUE
      BOD(KK)=BODF(LS)*AAMT(KK)
      TS(KK)=TSF(LS)*AAMT(KK)
      XSS(KK)=SSF(LS)*AAMT(KK)
      NSP(KK)=NSP(KK)+1
      GO TO(70,75,80),KK
70    WRITE(2,71)LS,TIM(KK),AAMT(KK),BOD(KK),TS(KK),XSS(KK)
      GO TO 90
75    WRITE(3,71)LS,TIM(KK),AAMT(KK),BOD(KK),TS(KK),XSS(KK)
      GO TO 90
80    WRITE(4,71)LS,TIM(KK),AAMT(KK),BOD(KK),TS(KK),XSS(KK)
71    FORMAT(1X,I5,I10,4F15.4)
90    IF(T.GE.ITIME)GO TO 100
      GO TO 1
100   CONTINUE
      RETURN
      END
C
C
      SUBROUTINE WATER(PRODT,WATERR,HRWAT,WAT,W)
C
C WATER USAGE BY DAY AND HR,TWO DIST,NS DEPENDENT ON PROD,N
      DIMENSION WAT(3),WATERR(2,13,2),W(6)
      REAL PRODT
      M=1
      IF(PRODT.GT.1000.)M=2
      RND=RAND(0.0)
      DO 40 I=2,13
      IF(RND.LE.WATERR(M,I,1).AND.RND.GT.WATERR(M,I-1,1))L=I-1
40    CONTINUE
   45 TWADAY=WATERR(M,L,2)+((WATERR(M,L+1,2)-WATERR(M,L,2))/(WATERR(M,L+
     11,1)-WATERR(M,L,1)))*(RND-WATERR(M,L,1))
      HRWAT=TWADAY/24.
      DO 20 K=1,3
```

```
            WAT(K)=[illegible](K)
   20       CONTINUE
            RETURN
            END
      C
            SUBROUTINE [illegible]
      C
      C GENERATES DAILY [illegible] PRODUCTION [illegible]
            DIMENSION PROD(20,2)
            RN1=RAN(0.0)
            DO 25 I=2,11
            IF(RN1.LE.PROD(I,2).AND.[illegible].PROD(I-1,2)) GO TO 26
            GO TO 25
   26       L=I-1
            GO TO 30
   25       CONTINUE
   30       PRODT=PROD(L,1)+((PROD(L+1,1)-PROD(L,1))/(PROD(L+1,2)-PROD(L,2)))*
           1(RN1-PROD(L,2))
            PRODHR=PRODT/24.
            RETURN
            END
      C
      C
            SUBROUTINE FIBER(FIB,FIBER,FIBHR)
      C
      C FIBER LOSSES IN TONS/DAY AND TONS/HR , 1=UNBLEACHED 2=BLEACHED 3=MACHIN
            DIMENSION FIBER(3),FIBHR(3),FIB(3,25,2)
            DO 20 K=1,3
            RND=RAND(0.0)
            DO 10 I=1,25
            IF(RND.LE.FIB(K,I,1))GO TO 11
   10       CONTINUE
   11       FIBER(K)=FIB(K,I,2)
            FIBHR(K)=FIBER(K)/24.
   20       CONTINUE
            RETURN
            END
      C
            SUBROUTINE REGUL
      C
            COMMON ALPHQ(4),LAMQ(4),ALPHT(4),LAMT(4),NSP(3),TIME(3),TIM(3),T,
           1P(4,3),LOC(4,3),AMT(3),TRAN(3,3,5),CONV(15),BOD(3),TS(3)
           1,SS(4),LSUB(3),ABOD(6),SBOD(6),ASS(6),ATS(6),STS(6),WAT(6),RBODPH(
           16),RSSPH(6),RTSPH(6),ZBOD(6),ZTS(6),ZSS(6),C,HBOD(6),HTS(6),HSS(6)
           1,DBOD(3),DTS(3),DSS(3),BODPTN(3),TSPTON(3),SSPTON(3),SBMAX(3),
           1SBMIN(3),STMAX(3),STMIN(3),SSMAX(3),SSMIN(3),IP(4),AAMT(6)
            COMMON SPL(3),RBOD(3),RBOD(6),RSS(6),RTS(6),RA(10)
            COMMON PROD(20,2),FIB(3,25,2),SSS(6),KK,
           1WATER(3,13,2),BODH(14),TSH(14),SSH(14),W(6)
           1,FIBERR(3),FIBHR(3),PRODHR,START(10),ITIME,XSS(6)
            INTEGER T,D,TIM,SPL,LOC,TIME
      C CALCULATES REGULAR BOD,SS,AND SS [illegible] PRIMARY AREAS IN LBS/HR & KG/HR
      C 1=ACID 2=ALKALINE 3=RECOVERY 4=FLYASH CLAR 5=RECAUST 6=MACH. RM.
            DO 20 I=1,6
            RBOD(I)=(ABOD(I)+RANDN(0.0)*SBOD(I))*WAT(I)*3.79
            RSS(I)=(ASS(I)+RANDN(0.0)*SSS(I))*WAT(I)*3.79
            RTS(I)=(ATS(I)+RANDN(0.0)*STS(I))*WAT(I)*3.79
            RBODPH(I)=RBOD(I)*2.2
```

```
              RSSPH(I)=RDS(I)*2.2
              RTSPH(I)=RTS(I)*2.2
      20      CONTINUE
              RETURN
              END
      C
              SUBROUTINE GAMMA(ALPHA,[illegible],START,[illegible])
      C
      C THIS SUBROUTINE GENERATES A GAMMA DISTRIBUTED VARIATE WITH SHAPE
      C PARAMETER ALPHA AND MEAN RATE CLAMDA
              DIMENSION AA(10),A(10),B(10),START(10)
              J=0
      50      IF(START(KK).GT.1.5)GO TO 100
              X3=1.0
              BB=.2174(2.10299768*ALPHA)-(4.34511961*ALPHA**2)+
             1(6.0001+75+*ALPHA**3)-(3.99[illegible]772[illegible]ALPHA**4)+
             1(.97279[illegible]51*ALPHA**5)
              BETA=1./CLAMDA
              X=1.0+(1.0/BB)
              START(KK)=5.0
              IF(X.GE.1.0)GO TO 60
      51      IF(X-2.)110,60,55
      55      X=X-1.0
              X3=X3*X
              GO TO 51
      110     Y=X-1.
              GY=1.0+Y*(-.5711017+Y*(.9558[illegible]+Y*(-.8764218+Y*(.8328212+
             1Y*(-.566[illegible]729+Y*(.25[illegible]8235+Y*(-.051+[illegible]))))))
              X3=X3*GY
      60      A(KK)=(X3/(ALPHA*BETA))**BB
              B(KK)=1./BB
      100     CONTINUE
              RN=RAND(0.0)
              WW=(-(1./A(KK)*ALOG(RN)))**B(KN)
      35      RETURN
              END
      C
              SUBROUTINE NEGBIN(R,P,START,L,X)
      C THIS SUBROUTINE GENERATES A NEGATIVE BINOMIAL VARIATE R=#OF SUCCESS'S
      C
      C AND P IS THE PROB OF SUCCESS
              REAL P,START(10)
              CLAMDA=P/(1-P)
              CALL GAMMA(R,CLAMDA,START,L,Y)
              S=1.
              A=EXP(-Y)
              X=0.
      10      RN=RAND(0.0)
              S=S*RN
              IF(S.LE.A) GO TO 20
              X=X+1.
              GO TO 10
      20      RETURN
              END
```

APPENDIX IV

A LISTING OF THE WASTEWATER TREATMENT MODEL

The logical units are assigned in the model as follows

Logical Units	Task
#5	To set the design parameters for the current experiment
#6	Record of hourly effluent from the mill in mg/l and lbs/Ton at the end of each day
#7	A file or interactive device which can answer the questions regarding factor loadings
#8	The influent concentrations for the 3 outfalls in mg/l. This is read each hour by the model
#9	The pulp mill production and water usage record as input into the model

The design variables which can be altered by the user and read from unit #5 are

TIME = time step for lagoon model = 1 hr

A = settling rate constant derived in text = .104 cm^{-1}

DET = desired detention time for clarifier (3 hrs)

QQ = theoretical hydraulic load which clarifier will have as influent (35,000,000 USG for ICOMB = 2,3,4)

H = depth of clarifier = 15 ft

TI = time step for clarifier model = 3600 secs

ICOMB = system layout desired for run = 1, to 4

Ak = dummy variable

TEMP = Lagoon operating temperature = °C

AREA = area of Lagoon in acres

DEPTH = depth of Lagoon in ft

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```
      COMMON BETA,REST,CBINCL,Q1,Q2,D,TT,Z,ALPHTA,CZERO1,CZERO2,CB1ZER,
     1CB2ZER,CB3ZER,EP,XX,YY,CXX,T148,CBOD1T,CBOD2T,CBOD3T,CIN1,ALPH,IE,
     1TI,WATT(3),CBOD(3),CSS(3),CZERO1,CZERO2,CS1,CS2,ECX
C
C LAGOON AND CLARIFIER SIMULATION  5=START 6=PRINT 7=*SOURCE 8=MILL OUT 9=WATER AND PREC
C ASKS FOR SHOCK LOADS STEP,FACTOR AND CYCLE
C
      REAL KSTAR,KK
      READ(5,5)TIME,A,DET,QO,H,TI,ICD48
    5 FORMAT(6(F10.0),I5)
      READ(5,5)AK,TEMP,AREA,DEPTH
C
C CLARIFIER DESIGN PARAMETERS
C
      QIDEAL=QO/24.
      VOL=DET*QIDEAL
      V=VOL/2
      VM=V*3.785
      HM=H*12.*2.54
      CK=A/HM
C
C LAGOON DESIGN PARAMETERS
C
      VLAG=AREA*4046.86*(DEPTH/3.2808)*1E3
      VT=VLAG/3.
      TEM=TEMP-20.
      KK=((.256)*((1.032)**TEM))/24.
      KSTAR=KK*.1
      KK=KK-.1*KSTAR
C
      T=C.
      D=C.
      CZERO1=0.
       CZERO2=0.
      CB1ZER=0.
      CB2ZER=C.
      CB3ZER=0.
      CZERO1=0.
      CZERO2=0.
      DAYBOD=0.
      DAYSS=0.
      DINBOD=0.
      DINSS=C.
      SSLA=0.
      BBLA=C.
      BIN=C.
      BOUT=0.
      SIN=C.
      SOUT=C.
      FL=0.
C
C PROGRAM ASKS FOR LEVEL OF ARTIFICIAL SHOCK LOAD DESIRED
C
      WRITE(7,15)
   15 FORMAT(1X,'TO INTRODUCE SHOCK LOAD--INPUT A 1.',/,
     1'IF NO SHOCK LOAD IS WANTED--INPUT A 0.',/)
      READ(7,16)ANS
   16 FORMAT(F5.0)
```

```
      IF(ANS.NE.0.)GO TO 14
      TJ=0.
      STEP=0.
      FACTOR=0.
      CYCLE=0.
      GO TO 13
   14 WRITE(7,6)
    6 FORMAT(1X,'INPUT TJ AND STEP IN 2F5.0')
      READ(7,7)TJ,STEP
    7 FORMAT(2F5.0)
      WRITE(7,8)
    8 FORMAT(1X,'INPUT FACTOR FOR SHOCK LOADS IN F5.0')
      READ(7,9)FACTOR
    9 FORMAT(F5.0)
      WRITE(7,11)
   11 FORMAT(1X,'INPUT CYCLE IN F5.0')
      READ(7,12)CYCLE
   12 FORMAT(F5.0)
   13 WRITE(6,2)A,DET,CO,H,ICOMB
    2 FORMAT(1X,'A=',F5.3,5X,'DET=',F5.1,5X,'CO=',F10.0,5X,'H=',F5
     1.2,5X,'ICOMB=',I3,/)
      WRITE(6,3)AK,TEMP,AREA,DEPTH,KK,VLAG
    3 FORMAT(1X,'AK=',F8.5,4X,'TEMP=',F5.0,4X,'AREA=',F6.0,4X,'DEPTH=',
     1F4.0,4X,'KK=',F8.5,4X,'VLAG=',F15.1,//)
      WRITE(6,10)TJ,FACTOR,STEP,CYCLE
   10 FORMAT(1X,'TJ=',F8.0,5X,'FACTOR=',F8.0,5X,'STEP=',F8.0,5X,'CYCLE='
     1,F8.0,///)
C
C READS THE DAILY WATER FLOW FOR 3 AREAS IN MUSG/HR --AND DAILY PULP PRODN
C
  100 CONTINUE
      READ(9,40,END=200)(WATT(I),I=1,3),PROD
   40 FORMAT(1X,3F6.0,F10.0)
C
C FLOW ARRANGEMENTS IN RESPONSE TO ICOMB
C
      GO TO(65,70,75,76),ICOMB
   65 Q1=(WATT(1)+WATT(2)+WATT(3))
      Q2=0.
      Q3=0.
      GO TO 80
   70 Q1=WATT(2)+WATT(3)
      Q2=WATT(1)
      Q3=0.
      GO TO 80
   75 Q1=WATT(2)
      Q2=WATT(1)+WATT(3)
      Q3=0.
      GO TO 80
   76 C1=WATT(2)+WATT(3)
      Q2=0.
      Q3=WATT(1)
   80 CONTINUE
C
C LAGOON 24 HR PARAMETERS
C
      FLAG=Q1+Q2
      TT=VT/(FLAG*3.785*1E6)
```

```
      ALPHTA=1.+KK*TT
      EP=EXP((-ALPHTA)*TIME/TT)
      P=TIME/TT
      BETA=(ALPHTA/TT-1./TT)
      EXX=EXP(-TIME/TT)
      Q=Q1+Q2
C
C CLARIFIER 24 HOUR PARAMETERS
C
      QQQ=Q1/3600.
      QM=QQQ*3.785
      REST=VM/(QM*1E6)
      ALPH=(1.+CK*REST)
      EE=EXP((-ALPH*TI/REST))
      EEX=EXP(-TI/REST)
C
 81   CONTINUE
      T=T+1.
      D=D+1.
C
C READS INFLUENT CONCENTRATION--MG/L OF BOD AND SS FROM EACH OF 3 MILL AREAS
C
      READ(3,35,END=200)(CBOD(I),I=1,3),(CSS(J),J=1,3)
 35   FORMAT(1X,6F10.0)
C
C INFLUENT CONC IN RESPONSE TO SYSTEM LAYOUT -- ICOMB
C   CIN1=CLARIFIER SS INFLUENT--MG/L
C   CSSOTH=SS IN STREAM THAT BYPASSES CLARIFIER -- MG/L
C   CBINCL=BOD INTO CLARIFIER AND THEN TO LAGOON--MG/L
C   Z=BOD INTO LAGOON WHICH BYPASSED CLARIFIER--MG/L
C   CSSBYE=SS OF STREAM WHICH BYPASSES COMPLETE SYSTEM--MG/L
C   CBODBY=BOD OF STREAM WHICH BYPASSES COMPLETE SYSTEM--MG/L
      GO TO(82,83,84,88),ICOMB
 82   CIN1=(CSS(1)*WATT(1)+CSS(2)*WATT(2)+CSS(3)*WATT(3))/Q1
      CSSOTH=0.
      CBINCL=(CBOD(1)*WATT(1)+CBOD(2)*WATT(2)+CBOD(3)*WATT(3))/Q1
      Z=0.
      CSSBYE=0.
      CBODBY=0.
      GO TO 85
 83   CIN1=(CSS(2)*WATT(2)+CSS(3)*WATT(3))/Q1
      CSSOTH=CSS(1)
      CBINCL=(CBOD(2)*WATT(2)+CBOD(3)*WATT(3))/Q1
      Z=CBOD(1)
      CSSBYE=0.
      CBODBY=0.
      GO TO 85
 84   CIN1=CSS(2)
      CSSOTH=(CSS(1)*WATT(1)+CSS(3)*WATT(3))/Q2
      CBINCL=CBOD(2)
      Z=(CBOD(1)*WATT(1)+CBOD(3)*WATT(3))/Q2
      CSSBYE=0.
      CBODBY=0.
      GO TO 85
 88   CIN1=(CSS(2)*WATT(2)+CSS(3)*WATT(3))/Q1
      CSSOTH=0.
      CBINCL=(CBOD(2)*WATT(2)+CBOD(3)*WATT(3))/Q1
      Z=0.
```

```
      CSSBYE=CSS(1)
      CBODBY=CBOD(1)
   85 CONTINUE
C
C ARTIFICIAL SHOCK LOADS TIME IS SET
C
C
C TREAT THIS HOURS INFLUENT
C
      TK=TJ+STEP
      IF(T.GE.TJ.AND.T.LE.TK)GO TO 86
      GO TO 87
   86 CONTINUE
      ADDS=3.785*(CIN1*Q1+CSSOTH*Q2)*(FACTOR-1.)
      ADDB=3.785*(CBINCL*Q1+Z*Q2)*(FACTOR-1.)
      ABLEQV=ADDB/(.0367*3.785)
      CIN1=FACTOR*CIN1
      CBINCL=FACTOR*CBINCL
      CSSOTH=CSSOTH*FACTOR
      CSSBYE=CSSBYE*FACTOR
      CBODBY=CBODBY*FACTOR
      Z=FACTOR*Z
      IF(T.EQ.TK)TJ=TK+CYCLE
   87 CONTINUE
      CALL TREAT
      WRITE(6,90)CIN1,CS2,CSSOTH,CBINCL,Z,CBOD3T,T
   90 FORMAT(1X,6(F8.1,4X),F8.0)
C
C DAILY INPUT & OUTPUT STATISTICS DETERMINED
C
      DAYBOD=DAYBOD+(CBOD3T*Q+CBODBY*Q3)*3.785
      SSS=(CIN1*TI/(ALPH**2))*(1.+EE)+(CZERO1*REST/(ALPH**2))*(EE-1.)
     1+(CZERO2*REST/ALPH)*(1.-EE)-CZERO1*TI*EE/ALPH
      SSS=SSS/3600.
      DAYSS=DAYSS+(SSS*Q1+CSSOTH*Q2+CSSBYE*Q3)*3.785
      DINBOD=DINBOD+(CBINCL*Q1+Z*Q2+CBODBY*Q3)*3.785
      DINSS=DINSS+(CIN1*Q1+CSSOTH*Q2+CSSBYE*Q3)*3.785
      BIN=BIN+CBINCL*Q1+Z*Q2
      BOUT=BOUT+CBOD3T*Q
      FL=FL+Q1+Q2
      SIN=SIN+CIN1*Q1
      SOUT=SOUT+SSS*Q1
      SSLA=SSLA+SSS+CSSOTH*Q2*3.785
      BBLA=BBLA+(CBINCL*Q1+Z*Q2)*3.785
      IF(D.NE.24.)GO TO 81
      BODTON=DAYBOD*2.205/PROD
      SSTON=DAYSS*2.205/PROD
      BINTON=DINBOD*2.205/PROD
      SINTON=DINSS*2.205/PROD
      SSAV=SSLA/(Q*3.785*24.)
      BBAV=BBLA/(Q*3.785*24.)
      SSLAG=.12*(SSAV+BBAV)/(1.+.2*IT*.125)
      SSEXT=SSLAG*Q*24./PROD
      WRITE(6,91)SINTON,SSTON,BINTON,BODTON,SSLAG,SSEXT
   91 FORMAT(/,F9.2,4X,F8.2,16X,F8.2,16X,F8.2,10X,F8.2,10X,F8.2,/)
      D=0.
      DAYBOD=0.
      DAYSS=0.
```

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LISTING OF FILE WASTE-MODEL                11:51 A.M.  AUG. 19, 1975     ID=MT23

          CS2=T1+T2
          CS1=(CIN1/ALPH)*(1.-EE)+CZERO1*EE
          CZERO1=CS1
          CZERO2=CS2
          RETURN
          END
      C
          SUBROUTINE COST(LO,KK,VT,FLAVE,V,H,EFF)
      C
          REAL KK,LOC(2,10),INT(2,10),LOPCST
          DATA INT/0.,0.,3E4,.4,6E4,.5,9E4,.6,1.2E5,.7,1.6E5,.8,
         12.3E5,.85,2.9E5,.9,3.7E5,.95,5.0E5,1./
          DATA LOC/0.,0.,1.48E3,.4,2.4E3,.5,4.1E3,.6,7.6E3,.7,1.47E4,.8,
         12.15E4,.85,3.3E4,.9,5.3E4,.95,5.6E4,1.0/
          TT=(VT/(FLAVE*3.785*1E6))*24.
      C
      C CAPITAL COST FOR LAGOON
      C
          FLOW=FLAVE
          DO 10 I=1,9
          IF(EFF.GT.INT(2,I).AND.EFF.LE.INT(2,I+1))GO TO 20
          GO TO 10
       20 M=I
          GO TO 30
       10 CONTINUE
       30 AA=INT(1,M)
          BB=INT(1,M+1)
          GA=ALOG(AA)+((EFF-INT(2,M))/(INT(2,M+1)-INT(2,M)))*(ALOG(BB)
         1-ALOG(AA))
          A=EXP(GA)
          COLAG=A*FLOW**.708
      C
      C LAGOON OPERATING COSTS
      C
          CA=LOC(1,M)
          CB=LOC(1,M+1)
          CC=ALOG(CA)+((EFF-LOC(2,M))/(LOC(2,M+1)-LOC(2,M)))*(ALOG(CB)
         1-ALOG(CA))
          LOPCST=EXP(CC)*FLOW
       55 CONTINUE
      C
      C CAPITAL COST CLARIFIER
      C
          AREA=(V *.1605)/H
          COCLA=29.5*(AREA)**.92
      C
      C OPERATING COST CLARIFIER
      C
          COPCST=3600.*(CC/1E6)**.726
      C
          WRITE(6,60)COLAG
       60 FORMAT(1X,'LAGOON CAPITAL COST=',F10.0,' DOLLARS',/)
          WRITE(6,61)LOPCST
       61 FORMAT(1X,'LAGOON OPERATING COSTS=',F10.0,' DOLLARS',/)
          WRITE(6,62)COCLA
       62 FORMAT(1X,'CLARIFIER CAPITAL COST=',F10.0,' DOLLARS',/)
          WRITE(6,63)COPCST
       63 FORMAT(1X,'CLARIFIER OPERATING COST=',F10.0,' DOLLARS',/)
```

LISTING OF FILE WASTE-MODEL   11:31 A.M. AUG. 19, 1975   ID=VT23

```
      RETURN
      END
```