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The Ohio State University, Ph.D., 1974
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A COMPUTER SIMULATION OF BIOLOGICAL TREATMENT,
STORAGE, AND LAND DISPOSAL OF SWINE WASTES

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Charles Roland Mote, B.S., M.S.

The Ohio State University
1974

Reading Committee:
Richard K. White
Robert Stiefel
E. Paul Taiganides

Approved by

E. Paul Taiganides
Advisor
Agricultural Engineering
Department
ACKNOWLEDGMENTS

Dr. E. Paul Taiganides is gratefully acknowledged for his counsel and encouragement during my doctoral studies.

Acknowledgment is made of the computer time provided by the Ohio State University's Instruction and Research Computer Center and the financial support from the Environmental Protection Agency Grant R-801125 (formerly 13040 EOL) administered by the Ohio State University Research Foundation Project 2980 and the Ohio Agricultural Research and Development Center Project S-440.
VITA

July 31, 1945 . . . . Born - Lawrence County, Tennessee

1967 . . . . . . . . . B.S. Agricultural Engineering, The University of Tennessee, Knoxville, Tennessee.

1968 . . . . . . . . . M.S. Agricultural Engineering, The University of Tennessee, Knoxville Tennessee.


1972-1974 . . . . . Graduate Research Associate, The Ohio State University, Columbus, Ohio.

PUBLICATIONS


FIELDS OF STUDY

Studies in Agricultural Waste Management: Dr. E. Paul Taiganides

Studies in Sanitary Engineering: Dr. Robert Stiefel and Dr. Robert Sykes

Studies in Microbiology: Dr. Robert Miller and Dr. Bruno Kolodziej

Studies in Systems Engineering: Dr. Gordon Clark and Dr. M. Y. Hamdy
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INTRODUCTION

Increasing demands for meat and other animal products have prompted changes in the livestock production industry. Today large numbers of animals are being produced in total confinement situations where their feed and environment are being controlled in a fashion that promotes maximum growth or production.

Waste disposal is of prime importance in such confinement operations. Frequent removal of wastes from the production unit is essential to the maintenance of an optimum environment for the animals and to the maintenance of a functional operation, for a building full of manure would not be functional as a livestock production unit. In fact, the success of a confinement livestock operation often hinges on the waste handling and treatment system incorporated into the operation.

Waste systems are usually composed of several integrated components and processes. The waste is removed from the building, often in a liquid state, and usually placed into storage for subsequent application to crop-land as a source of fertilizer and soil conditioner. Often times it is necessary to treat the waste to reduce odors or to remove some of the organic and other chemical components. Treatment is especially needed when the wastes are removed from the building hydraulically and it is desired to reuse the water in some fashion, or when a limited amount of available farm land cannot assimilate all the waste without becoming polluted.
Treatment will also be very important in many cases as provisions are made to comply with the provisions of the Federal Water Pollution Control Act Amendments of 1972. This legislation requires implementation of the "best practicable technology" by July 1, 1977, "best available technology" by July 1, 1983, and has a goal of zero discharge of pollutants by 1985 (Anon., 1972).

Under the 1972 legislation, the Environmental Protection Agency (EPA) plans to require permits for feeding stations of 1000 or more animal units, and some states may require them for smaller capacity feeding stations. Current innovation concerning animal waste control has focused mostly upon biologically active systems and land spreading of wastes (Anon., 1973). In light of the new regulations and the state of the technology, it appears that biological treatment and field disposal systems for wastes from animal production units will become extensively used.

Many factors influence the operation of a waste treatment and disposal system. The number of animals present at any given time directly influence the loading on a storage tank or a treatment plant. Weather conditions and crop production stages determine whether or not it is possible to haul wastes onto the cropland. Acreage and types of crops being produced regulate the amount of waste that can be applied to the land. All of these factors, and many others, must be considered when designing and developing operating criteria for a livestock waste treatment and disposal system.

The design and operation of typical waste treatment and disposal systems lends itself to the application of a computer simulation due to
the complexity of such systems and the potential for interaction of the several factors that influence their operation. In this study a computer simulation has been developed that will aid in system design by simulating the operation of a biological treatment and field disposal system for wastes from a confinement swine production operation. Even though the program has been built for swine units, provisions have been made for its ready adaptation to other types of operations.
OBJECTIVES

The main objective of this study was to develop a computer simulation program which would simulate the operation of a biological treatment-cum-cropland disposal system for wastes from a confinement swine production unit. The computer simulation program developed should also meet the objective of providing functional design data and approximate system investment and annual costs. To fulfill the objective of this study the following specific tasks were defined for the research program:

1. Describe the real system and select a simulation technique and computer simulation language that will facilitate the conversion of a model of the system into an operating simulation program.

2. Obtain data and computational procedures for designing and describing the operation of the several components of the real system and integrate them into a computer simulation program.

3. Present the features of the computer simulation program and describe how to use it.

4. Test the validity of the computer simulation program.

5. Demonstrate the utility of the computer simulation program by using it to study waste treatment and disposal systems for several different situations.
LITERATURE REVIEW

Literature reviewed in this section has been limited to computer model studies in the area of agricultural waste management. Reviews of other literature are included in later sections as the topics to which the references apply are developed.

As pointed out by Schulte and Loehr (1971), the application of the computer model approach to agricultural waste management problems has been relatively rare. A search of many sources during the preparation for this study has produced only three previous studies which utilized computer models to study phases of agricultural waste management. Some of the literature sources reviewed include an index to M. S. Theses and Ph.D. Dissertations in Agricultural Engineering published annual in the Agricultural Engineers Yearbook (ASAE, 1973) journals such as the Journal of the Water Pollution Control Federation, (Freedman and Schroeder, 1972), and conference and symposium proceedings such as ASAE's International Symposium on Livestock Wastes (Mathers and Stewart, 1971). The computer facilities of the Ohio State University Library's Mechanized Information Center were also used to search for pertinent literature.

Reviews of the three studies which were found to be similar to this study are presented below.

Previous Studies

In a study to compare alternative duck waste treatment systems for
phosphorus removal, Schulte and Loehr (1971) developed a mathematical model of a multistage treatment system. The specific results obtained from the computer solution of their model had no direct bearing on this study. However, their work was similar in that a computer model was used to study a complex agricultural waste treatment problem and similar methods were used for obtaining the information incorporated into the computer program.

The model developed by Schulte and Loehr (1971) could accommodate systems consisting of one or more stages of treatment from primary through tertiary. The mathematical model consisted of four equations. One equation related the cost of a treatment stage to the process design and quality of the incoming wastewater. The second equation related the quality of a treatment stage effluent to the process design and influent wastewater quality. The third equation was a sum of the costs for each treatment stage as determined by the first equation, and the fourth equation was a constraint that the effluent quality, in terms of phosphorus or BOD removal, from the last stage of treatment must be equal to or greater than an effluent water quality standard.

The authors used a dynamic programming technique for a computer solution to their mathematical model. Their programming procedure enabled the computer to select the design of each treatment stage that would minimize the cost of the total treatment system and still provide a final effluent that would meet the quality constraint of the model's fourth equation.

The programming technique used by Schulte and Loehr (1971) is different from the simulation approach employed in this study. The
Authors' program provided a process design that would minimize cost. Their program could not be used to experiment with the process design and determine, for example, what the cost of some designs were that provided an effluent quality slightly above the standard. A computer simulation program provides the capability for conducting such experiments.

Even though the programming technique employed by Schulte and Loehr (1971) was different from that used in this study, the information built into their program was obtained in much the same manner as was employed in this study. Efficiencies of the various treatment processes were obtained from bench scale tests, old system operating records, and published information. Cost-size relations were built into the program for use in estimating the cost of each design.

Schulte and Loehr (1971) used their program to evaluate 1800 alternative wastewater treatment designs. Of the 1800 designs the least cost treatment system for removing 80 percent of the phosphorus from a 2.1 million gallon per day waste stream was composed of a two hour primary sedimentation basin, followed by aeration for three days, before tertiary treatment with 39 mg/l of ferric chloride.

McKenna and Clark (1970) used a computer model to study a problem more closely aligned to the subject of this study. They developed a mathematical model and used a linear programming technique to determine the economically optimum liquid manure storage period for typical swine producing farms in Ontario, Canada. Their mathematical model was similar to that of Schulte and Loehr (1971) in that it consisted of equations and restrictions, and their programming procedure enabled the computer to determine the optimum storage period and precluded experimentation to
study the economics of storage periods that were not exactly optimum.

McKenna and Clark (1970) obtained general data for their computer model, such as manure production rates and fertilizer content, from data reported in the literature by various researchers. The rate of removal of manure from the storage tank during periods of hauling was held constant at a value determined from a consideration of capacities of spreading tank wagons and average loading and travel times. Stages of crop production and ceiling levels of manure application for pollution control were considered in their model, but weather and soil trafficability conditions were not considered as constraints to the spreading operation.

The portion of the computer simulation program developed in this study that deals with storage and field spreading provides for a varying rate of removal from the storage tank to account for the variation in time required to travel to various parts of the farm. Field spreading operations are also postponed during periods of time when the soil trafficability simulation phase of the program indicates that the soil is not trafficable.

Results obtained by McKenna and Clark (1970) indicate that the optimum period of manure storage varies with the number of animals being produced and the number of acres and type of crops being grown. In general it appeared that for conditions where manure could be disposed of on a neighbors farm any time that it was necessary, the optimum period of storage was less for operations that produced larger numbers of animals and grew two or more crops that had different production cycles so as to limit the amount of time that all the land is unavailable for spreading manure.
The computer simulation program developed in this study can be used to investigate the relationship between storage capacity, the number of animals being produced, and the number of acres and types of crops being grown as was done by McKenna and Clark (1970). However, the computer simulation program permits experimentation rather than providing only an optimum value as a result. Also the computer simulation program developed in this study has the capability of studying aspects of the livestock waste management problem other than the storage and spreading of liquid manure.

Nordstedt, et al. (1971) conducted a study similar to that of McKenna and Clark (1970). Nordstedt, et al. (1971) developed a mathematical model and used dynamic programming techniques to investigate the effects of storage capacity and hauling capacity on the relative net cost of a livestock liquid manure storage and field disposal system. Their program required that such things as land availability, rate of manure application to the land, and rate of manure production be held constant during each run.

The computer simulation program developed in this study can also be used to investigate the effects of storage and hauling capacities on the cost and overall operation of a liquid manure storage and field disposal system. However, as pointed out before, an investigation with the program developed in this study will be in the form of an experiment rather than the development of only optimal values as required by the programming procedure used by Nordstedt, et al. (1971). It should also be pointed out that such things as land availability, manure production rate, and land application rate that were held constant during each run of the
program used by Nordstedt, et al. (1971), are free to vary in response to such things as crop production cycles, animal population changes, and soil moisture conditions throughout the simulation period of the computer simulation program developed in this study.

Results obtained by Nordstedt, et al. (1971) indicate that increasing storage capacity produces slightly nonlinear increase in the total, annual, and net cost of the system. The program also showed a linear increase in net system cost as the cost of labor increased.

A decrease in the net cost was found, however, as the capacity of the liquid manure wagon increased. The decrease in net cost is probably a reflection of the reduction in time required for the tractor to pull the tank wagon to the field and a resulting decline in labor time.
THE APPROACH TO THE COMPUTER SIMULATION PROGRAM

Development of a computer simulation program requires initially an understanding of the real system to be simulated and secondly the development of a computer program that converts a model (i.e., a mathematical and logical representation) of the system into an operating simulation program. The swine waste treatment and disposal system simulated in this study, and the basic approach taken for the simulation are discussed in this section. GASP II, a FORTRAN based simulation language that was used for converting the model of the real system into a simulation program, is also discussed briefly in this section.

Swine Waste Treatment and Disposal System

To insure that the computer simulation program would be as useful as possible, a system was chosen for simulation that had promise of meeting the present and future needs of the swine producing industry. Some of the requirements for such a system are that it be readily susceptible to various levels of automation, have good potential for controlling pollution, and incorporate the best available technology. Such a system is illustrated in Figure 1.

In the system illustrated in Figure 1 the stream of hydraulically removed waste from the swine production unit passes through a liquid-solid separator, where the larger solids are diverted to storage and the liquid effluent goes into an aerobic biological reactor. Treated water
Figure 1: Typical Swine Waste Treatment and Disposal System Simulated by Computer Simulation Program
from the treatment plant is pumped back into the production unit for reuse in the hydraulic removal of wastes. Sludge wasted from the reactor goes into the storage tank.

The production unit and waste system are located on a farm which is being used for the production of typical midwest farm crops such as corn, soybeans, and wheat. Contents of the storage tank are applied to the cropland from time to time by use of liquid manure tank wagons.

In many situations biological treatment will not be essential to the waste management system. For this reason the computer simulation program is designed to have the capability of readily neglecting the treatment plant and considering a more conventional liquid manure system where the waste is simply stored until it is applied to the cropland.

Simulation Technique

Simulation is representation of the behavior of a system by moving it from state to state in accordance with well-defined operating rules. This can be accomplished by considering the operations of a system at points in time called events. Events cause the status of the system to change at a point in time and the behavior of the system can be reproduced by examining the system at the event times (Pritsker and Kiviat, 1969, p. 4-8).

The events defined for simulating the swine waste treatment and disposal system are presented schematically in Figure 2. One of the events is a biological treatment event (TMT). At the time of the treatment event, the microorganism growth and metabolism rates, the oxygen demand, the mass of VSS, and the resulting COD of the reactor effluent
are determined. The treatment event occurs at fixed intervals of one-one hundredth of a day so that the rapid changes of the microbial culture may be accurately simulated.

A second event is the storage event (SOLID). At the time of the storage event (i.e., the beginning of each day of the simulation period), the fraction of the storage tank being utilized is determined and a decision is made as to whether or not hauling operations should be initiated. If so, a haul event (HAUL) is scheduled. At the time of the haul event, stages of crop production, previous application history, and soil trafficability conditions are checked to determine if it is possible to apply a load of material from the storage tank onto the cropland. If so, the quantity of material in the storage tank is reduced by an amount equivalent to the per load hauling capacity and an end of hauling event (EHAUL) is scheduled. At the time of the end of hauling event a record is made of the cropland onto which the manure sludge was applied and the cumulative amount hauled is increased. Also at the time of the end of hauling event a check is made on the quantity of material in the storage tank and another haul event is scheduled if a load or more remains.

Two other events have been defined that do not actually represent a state of the system. They have been included however because they represent facets of the system environment that directly influence the operation of the system and it was desirable to simulate them as well. One of these events is the soil trafficability event (WETHR) which occurs once each day during simulation period. At the time of this event the precipitation and drying conditions are predicted and the resulting soil moisture content is calculated. The soil moisture content is compared
Figure 2: Schematic Presentation of the Events Defined For Simulating the Swine Waste Treatment and Disposal System
with the trafficability criteria and a decision is made as to whether or not the soil will support the traffic of the hauling equipment. The results of this decision are recorded and are used in the decision making process at the time of subsequent haul events.

The other event is an animal population event (POP) which occurs each time some finished animals are sold or some new animals are brought into the production unit. At the time of the population event, the number of animals in the production unit and the resulting rate of waste production are determined.

**GASP II**

**The Simulation Language**

The simulation language GASP II was selected for use in this study for two primary reasons. One is that GASP is well suited to the representation of a real system in the form of a simulation program (Pritsker and Kiviat, 1969, p. 5). The other reason is that GASP was available on the IBM 370 Model 165 digital computer of Ohio State University's Instruction and Research Computer Center.

GASP is a set of FORTRAN subprograms that in general make sure that each event defined for simulating the operation of the real system occurs at the right time and keeps a record of what happens during each event. For purposes of initiating the events at the proper time, GASP employs a filing array called NSET into which each of the events are entered in code along with the scheduled time of their next occurrence. After each event is completed, the GASP executive program checks NSET to determine which event should occur next, and then causes the subroutine describing
that event to be called and processed.

At the beginning of a simulation run, the program user must enter into NSET the time for the first occurrence of each event that is not scheduled during the course of the simulation period by something that happens in another event. Thereafter statements in the subroutine schedule subsequent events as they are processed each time.

Records of the system behavior during each event are kept by one or more of the three statistical routines included in the package of GASP subprograms. The builder of the simulation program specifies which system parameters statistics are to be kept on, and which GASP statistical routines are to be used. At the end of the simulation run, GASP causes reports to be printed of the statistical information collected on each system parameter.

Use of GASP for the development of a simulation program requires a user prepared main program, a subroutine for each of the system events, an EVENTS subroutine for linking the event code numbers from NSET to the proper event subroutines, and usually an end of simulation routine for ending the processing of the program in the desired manner. The purpose of the main program as far as GASP is concerned is to initialize non-GASP variables and call the GASP executive. However, in this study the main program was also used for calculating design parameters for the system to be simulated.

Development of the main program and each subroutine included in the computer simulation program developed in this study is presented in subsequent sections. A more detailed discussion of GASP may be found in the book, *Simulation With GASP II* by Pritsker and Kiviat (1969).
THE BOTKINS PLANT

A discussion of the Botkins Plant is presented here, because much of the data used in the development of the computer simulation program were collected from the Botkins Plant and several references are made in the following sections to the Botkins Plant.

The Botkins Plant is a swine waste handling and treatment plant that has been operated as a demonstration project on the Research Farm of the Botkins Grain and Feed Company since 1971. The plant was designed by Professors E. Paul Táiganides and Richard K. White (1971). Construction and operation of the plant has been sponsored by the Agricultural and Marine Pollution Control Section of the Environmental Protection Agency (Grant No. 13040 EOL), the Ohio State University (Research Foundation Project 2980), and the Ohio Agricultural Research and Development Center (Project 440) in cooperation with the Botkins Grain and Feed Company. A description of the plant is presented below.

Handling of Waste

The treatment plant receives all the waste produced in a 500 head capacity swine growing and finishing barn. Pigs are brought into the barn at about 40 pounds and taken out for marketing at about 220 pounds. During their stay in the barn, the pigs are in pens equipped with a dunging channel across the back. One of the channels is a two inch deep by three foot wide exposed gutter which the pigs have access to. The
other four dunging channels are four feet deep and are covered with slats. As long as the proper population density is maintained in the pens and the feeder is located near the front, the pigs will defecate in the gutter or on the slats. The movement of the pigs forces the solid waste through the cracks in the slatted floor and into the channel below.

Removal of the waste from the building is accomplished by periodically flushing each dunging channel with water. The flushing is performed automatically by siphon flush tanks installed at the end of each channel. Frequency of flushing is controlled by the flow rate of water into the tank.

Tanks on three of the channels have a capacity of 190 gallons and a fourth tank has a 270 gallon capacity. During the operation of the system, the time between flushes for each channel has varied from 30 minutes to two and one half hours. The various flushing frequencies have produced no significant differences in the quality of the environment inside the barn. The pigs are always clean and there is never any strong manure odor.

Treatment of Waste

The slurry of animal waste and flush water from the dunging channels flows into a sump from which it is pumped at a 75 gpm rate to a non-corroding stationary screen. (See Figure 3 for a schematic of the treatment plant.) The screen is 18 inches wide and is composed of bars placed with a 40 mil spacing. Solids removed by the screen drop into the solids treatment unit. The liquid effluent from the screen goes into an oxidation ditch where the dissolved and suspended organic matter is decomposed by aerobic microorganisms.
Figure 3: Schematic of Major Unit Operations and Components of the Botkins Plant
A commercial cage rotor, 27 inches in diameter and five feet six inches long is installed in the ditch. The rotor is immersed six inches in the mixed liquor and rotates at 80 rpm. The motion of the rotor aerates the mixed liquor and keeps the solids in suspension. It was necessary to install a baffle in the ditch to slow the velocity of the mixed liquor down to 1 foot per second.

Effluent mixed liquor from the ditch flows into the center of a gravity clarifier. Clarified effluent flows over a saw tooth weir around the circumference of the clarifier into a storage well. Water from the storage well is pumped into the flush tanks inside the barn and is thus reused as flush water.

Settled sludge from the bottom of the clarifier is pumped with an air lift pump back into the ditch. Satisfactory operation of the ditch is maintained by regularly wasting some of the sludge from the clarifier to the solids treatment unit.

The solids treatment unit was designed to utilize an aerator consisting of a propeller type agitator mounted on the end of a hollow, air draft tube. Two aerators, each from a different commercial manufacturer, have been used. Temperatures in the treatment vessel as much as 7°C above ambient have been observed. Little or no degradation of solids has been observed.

The plant has also been operated for long periods of time both with no agitation device and with a fertilizer type mixer in the solids treatment unit. No offensive odors have been observed under either method of operation.

Effluent from the solids treatment unit flows into the solids storage
tank. Periodically solids from the storage tank are field spread using a conventional tank wagon.

More detailed descriptions of plant components and daily variations in performance parameters may be found in publications by Taiganides and White (1971, and 1972).
DEVELOPMENT OF THE MAIN PROGRAM

The objectives of the main program are to read in basic data and initial conditions, define the limiting operating conditions of the waste treatment and disposal system and design the system as to component sizes, flow rates and estimated costs. In performance of these objectives consideration must be given to many details. Therefore, several specific tasks must be performed by the main program. A flow chart and FORTRAN listing of the main program which present the several tasks and the manner in which they are performed are presented as Figures 4 and 5 respectively.

A discussion follows of the information and computational procedures that are integrated into the main program.

Data Initialization

Information such as the situation limiting conditions and trial design conditions as well as certain basic data such as precipitation probabilities and ambient temperature records must be provided by the program user. These data are read into storage from data cards. A complete description of the necessary cards for data input can be found in Appendix A.

Livestock Waste Application Rates to Cropland

The contents of livestock waste originate from the food that they eat (Taiganides and Hazen, 1966). Since livestock eat primarily plants
Main Program

Read in Data and Zero Storage Arrays

Determine the Maximum Annual Sludge Application for Each Crop

Estimate Maximum Sludge Hauling Distance

Estimate Size and Construction Cost of Production Unit

Calculate Waste Volumes and Flow Rates

Yes

Is a Biological Treatment Plant to be Designed?

Correct Kinetic Parameters for Temperature

Calculate Reactor Volume & Mixed Liquor Waste Rate

Initialize Kinetic Rates

Design Clarifiers

Calculate Oxygen Requirement and Estimate Size of Aeration Equipment

Determine Storage Tank Capacity

No

Zero All Treatment Design Values

Determine Storage Tank Capacity

Calculate Oxygen Requirement and Estimate Size of Aeration Equipment

Determine Storage Tank Capacity

Estimate Construction and Annual Costs

Call GASP

End

Figure 4: Flow Chart of Main Program
Figure 5: FORTRAN Listing of the Main Program
Figure 5: (Continued)
and plant products, their waste primarily consists of plant material that can be decomposed into basic plant nutrients and reused for plant production. Because plants are grown in the soil and since natural soil contains a population of microorganisms that are capable of converting the residual plant material in livestock wastes to forms that are useable by growing plants, the soil is a good place for the ultimate disposal of livestock waste (Brock, 1970, p. 481-483, and Bartholomew, 1965, p. 285-306).

Consideration must be given, however, to the rate of livestock waste application to the soil, for there is a pollution potential associated with excessive application rates. One type of pollution that can arise from the application of livestock waste to cropland that is of prime concern in humid areas such as Ohio, is the accumulation of nitrates in the groundwater.

When livestock waste is applied to the soil several different genera of microorganisms (i.e., Pseudomonas, Bacillus, Clostridium) convert the organic nitrogen in the waste (i.e., proteins and amino acids) to ammonia. The rate at which this occurs, as is the case with most soil microbial reactions, is greater during the months of warm soil temperatures (Harmsen and Kolenbrander, 1965, p. 43-92). The ammonia thus produced is available for use by the plants and is readily retained in the soil against leaching, for the ammonium ion is cationic and is held by the negative charges on clay and organic soil colloids. However, there are autotrophic organisms of the genera Nitrosomonas and Nitrobacter present in the soil that sequentially oxidize the ammonium ion to nitrite and nitrate. This conversion of the ammonium ion to nitrate is known as

The result of nitrification is the source for potential groundwater pollution, for although the nitrate ion can be readily used by plants, it is negatively charged and is thus not held by the negative charges on the soil particles. Therefore any nitrate present in the soil in excess of the amount that can be taken up by plants or incorporated into microbial cell material is subject to being leached by water percolating through the soil.

Other primary fertilizer elements, namely phosphorus and potassium, that are mineralized from animal waste are in forms that are readily bound by the soil particles or they rapidly form compounds that are highly insoluble (Bear, 1964, p. 382-383 and Teuscher and Adler, 1960, p. 211). They are therefore not as subject to being leached into the groundwater as are nitrates.

Because of the potential for pollution originating from the nitrogen in livestock waste, and since nitrogen is the most abundant fertilizer element in livestock waste (O.S.U. Extension Service, 1974, p. 45, and Taiganides and Hazen, 1966), optimum application rates may be determined from a consideration of the nitrogen content of the animal waste and the nitrogen requirement of the crop being grown. In the literature several philosophies of animal waste application rates can be found. The Ohio State University Cooperative Extension Service (1974, p. 45) recommends that for the first year of application to a particular land area, a quantity of animal waste that will contain an amount of nitrogen equal to three times the annual requirement of the crop being grown can be applied. In subsequent years of continued application the quantity must
be reduced until year twenty-five, after which a quantity of waste should be applied that will have a nitrogen content equal to the requirement of the crop.

McKenna and Clark (1970) report that the Department of Soil Science at Guelph suggests that for corn a quantity of animal waste be applied that will contain twice the amount of nitrogen which can be efficiently used by the crop. On the other hand, Mathers and Stewart (1971) state that pollution hazards can be eliminated only when most of the nitrogen applied is used by the crop, and that the potential hazards of applying large amounts of animal waste may be of more concern than the benefits warrant.

Determination of the maximum rate of application of animal waste to the cropland is accomplished in the computer simulation program by matching the nitrogen content of the waste to the annual nitrogen requirement of the crop being grown. This approach was taken because the computer simulation program considers that the waste will be applied to the same land year after year.

The nitrogen content of the waste from systems incorporating a biological treatment plant was obtained from data collected from the Botkins Plant. Weekly samples from August 15 to December 14, 1972, of the influent to the solids storage tank were analyzed for total Kjeldahl nitrogen. Results of the nitrogen analyses are presented in Table 1. The nitrogen content of the stored material was found to average 0.00802 lb/gal (0.962 g/l, 0.00212 lb/l) and ranged from a maximum of 0.0122 lb/gal to a minimum of 0.0055 lb/gal and had a standard deviation of 0.002.

The nitrogen content of the waste from systems with no treatment
Table 1. Kjeldahl Nitrogen Data for the Influent to the Solid Storage Tank of the Botkins Plant

<table>
<thead>
<tr>
<th>SAMPLE DATE</th>
<th>Kjeldahl Nitrogen Content (lb/gal)</th>
<th>(g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-15-72</td>
<td>0.0067</td>
<td>0.803</td>
</tr>
<tr>
<td>8-22-72</td>
<td>0.0069</td>
<td>0.827</td>
</tr>
<tr>
<td>9-5-72</td>
<td>0.0062</td>
<td>0.743</td>
</tr>
<tr>
<td>9-12-72</td>
<td>0.0068</td>
<td>0.815</td>
</tr>
<tr>
<td>9-18-72</td>
<td>0.0068</td>
<td>0.815</td>
</tr>
<tr>
<td>10-2-72</td>
<td>0.0069</td>
<td>0.827</td>
</tr>
<tr>
<td>10-5-72</td>
<td>0.0066</td>
<td>0.791</td>
</tr>
<tr>
<td>10-12-72</td>
<td>0.0055</td>
<td>0.659</td>
</tr>
<tr>
<td>10-24-72</td>
<td>0.0063</td>
<td>0.755</td>
</tr>
<tr>
<td>11-2-72</td>
<td>0.0091</td>
<td>1.091</td>
</tr>
<tr>
<td>11-9-72</td>
<td>0.0098</td>
<td>1.174</td>
</tr>
<tr>
<td>11-16-72</td>
<td>0.0091</td>
<td>1.091</td>
</tr>
<tr>
<td>11-24-72</td>
<td>0.0122</td>
<td>1.462</td>
</tr>
<tr>
<td>11-30-72</td>
<td>0.0090</td>
<td>1.079</td>
</tr>
<tr>
<td>12-7-72</td>
<td>0.0084</td>
<td>1.007</td>
</tr>
<tr>
<td>12-14-72</td>
<td>0.0121</td>
<td>1.450</td>
</tr>
</tbody>
</table>
plant was estimated by using published swine waste characteristic data (Taiganides and Stroshine, 1971) and calculating the daily quantity and nitrogen content of the waste produced by a 100 pound pig. It was assumed that the waste would be diluted with 1.6 gallons of flush water (see succeeding section on flush water requirements). The results of these calculations were that swine waste from a system with no treatment would have a nitrogen content of 0.0018 lb/gal (5.33 g/l, 0.0031 lb/l).

Common crops produced in the Midwest that might be grown on a livestock farm are corn, soybeans, wheat, and forage (i.e., pasture and hay). The annual nitrogen application rate recommended for these crops by the Ohio State University, Cooperative Extension Service (1972) is as follows:

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield Goal</th>
<th>Nitrogen Application (lb/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>175+bu/A</td>
<td>260</td>
</tr>
<tr>
<td>Soybeans</td>
<td>70 bu/A</td>
<td>15</td>
</tr>
<tr>
<td>Wheat</td>
<td>65+bu/A</td>
<td>60</td>
</tr>
<tr>
<td>Forage</td>
<td>2+ton/A</td>
<td>60</td>
</tr>
</tbody>
</table>

Using the above recommendations and the nitrogen content of 0.00212 lb/l for treated waste and 0.0031 lb/l for untreated waste, the maximum application rates are as follows:

<table>
<thead>
<tr>
<th>Crop</th>
<th>Treated Waste (l/A)^a</th>
<th>Untreated Waste (l/A)^a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>123,000</td>
<td>84,000</td>
</tr>
<tr>
<td>Soybeans</td>
<td>7,100</td>
<td>4,840</td>
</tr>
<tr>
<td>Wheat</td>
<td>28,400</td>
<td>19,300</td>
</tr>
<tr>
<td>Forage</td>
<td>28,400</td>
<td>19,300</td>
</tr>
</tbody>
</table>
It is assumed that any uncultivated land will be planted to corn the next year, so its maximum application rate is the same as that for corn.

Hauling Distance

Travel distance for the field spreading operation is important to the simulation of time spent hauling animal waste onto the cropland, as will be seen later during the discussion of subroutine HAUL. The maximum distance of travel is a function of the size of the farm. As a means of determining the travel distance as a function of farm size, it has been assumed that the farm acreage is laid out in a rectangle with the length being twice the width, and that the treatment plant is located at the center of the farm. Thus the travel distance to the farthest boundary of the farm is equal to the square root of twice the area of the farm in square feet divided by two. Since it is unlikely that all travel will be in straight lines perpendicular to the centerline of the treatment plant, the maximum travel distances calculated as above are increased by a factor of 30 percent before travel times are calculated.

Size and Cost of the Animal Production Unit

The basic size of an animal production unit is a function of the number of animals that will occupy the unit at one time. Proper animal husbandry requires a finite amount of space for each animal. The recommended area is 6 - 8 ft$^2$ per each pig in a confinement finishing unit (Midwest Plans Service, 1972). On the basis of this recommendation it was decided that the area of the production unit would be estimated on

\[ \text{To convert to } 1/\text{ha multiply values by 0.405.} \]
the basis of 7 ft$^2$/pig.

Since the size of the production unit is a function of capacity, it seems reasonable to think that the cost might also be a function of capacity. Shuyler, et al. (1973, p. VII-12) noted that the cost-capacity relationship of most sets of similar items can be described by the equation

$$C_2 = C_1 (Q_2/Q_1)^x$$

where $C_2$ = the unknown cost of capacity $Q_2$

$C_1$ = known cost of capacity $Q_1$

$x$ = cost-capacity factor

The cost-capacity factor has been found to range from less than 0.2 to more than 1.0 for various products. However a value of 0.6 has been found in many cases and is recommended for use in the absence of better data. This is known as the "six-tenths factor rule". (Shuyler, et al., 1973, p. VII-12).

A 500 pig place production unit was built for the Botkins Plant in 1969 for about $50.50 per pig capacity. The cost of the Botkins production unit, which has partially slatted floors, compares favorably with a $60 per pig capacity estimate for a total slatted floor unit for the year 1970 (Blickle, 1973). The cost of a production unit in 1969 dollars shall therefore be estimated by applying the "six-tenths factor rule" and substituting $50.50 and 500 for $C_1$ and $Q_1$ respectively into Equation 1.

The cost estimate in 1969 dollars can be converted to current day levels by the use of a cost index. The conversion is made by multiplying the 1969 cost by the ratio of the cost index value for the current year to the cost index value for 1969. There are several cost indices avail-
able that would be suitable for this application. The Chemical Engineering Plant Cost Index as published regularly in Chemical Engineering (Anon., 1974) has been used in the development of the program, for it was readily available at the time the program was being initially written.

Quantification of Waste and Wastewater

As will be shown later in the section on subroutine TMT, the operation and required volume of a biological waste reactor depends on the substrate concentration (measured as COD) of the waste being treated, the magnitude of the waste stream, and the biomass in the reactor, which is a portion of the mixed liquor VSS. Therefore the waste and wastewater parameters that needed to be evaluated for this study were volume, chemical oxygen demand (COD), and volatile suspended solids (VSS) concentration.

A summary of the parameter values that were determined and incorporated into the computer simulation program is presented in Table 2. A more detailed presentation of the determination of each value follows.

Volume
Flush Water Volume. In an example illustrating the application of hydraulic transport principles, Jones, et al. (1971) indicate that a water flow rate of 180 gpm per foot of gutter width with a 10 second discharge will adequately clean a gutter serving 120 pigs. The gutter under consideration was 60 feet long, 4 feet wide, and had a slope of one percent. Thus the average flow velocity was 1.6 feet/second (assuming flow in the gutter is 3 inches deep), and the 10 second discharge indicates 120 gallons of water used. In the same article, Jones, et al. (1971) report that a flush of 160 gallons once a day kept a 46 inch wide by 64 feet long gutter serv-
Table 2. Summary of the Wastewater Parameter Values Used in the Computer Simulation Program

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SOURCE OF INFORMATION</th>
<th>VALUES USED IN SIMULATION PROGRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Data Reported in Literature</td>
<td>Measurements</td>
</tr>
<tr>
<td>FLUSH WATER VOLUME FOR:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systems Using Recycle Water</td>
<td>19.2 gal/pig/day&lt;sup&gt;a&lt;/sup&gt;</td>
<td>----</td>
</tr>
<tr>
<td>Systems Using Fresh Water</td>
<td>1.6 gal/pig/day&lt;sup&gt;a&lt;/sup&gt;</td>
<td>----</td>
</tr>
<tr>
<td>Wastewater Production</td>
<td>1 to 5 gal/pig/day&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.7 gal/pig/day&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.71 gal/pig/day&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>COD of Produced Waste</td>
<td>59625 mg/1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>67638 mg/1&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>VSS of Produced Waste</td>
<td>68993 mg/1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>69751 mg/1&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Values estimated on basis of information in references by Jones, et al. (1971), Metcalf and Eddy (1972, p. 108), and Koelliker, et al. (1972).

<sup>b</sup>From observations reported by Koelliker, et al. (1972).

<sup>c</sup>Calculated from data reported by Taiganides and Stroshine (1971).

<sup>d</sup>Calculated from measurements of flush water influent and total waste stream effluent from production unit of the Botkins Plant.

<sup>e</sup>Calculated from flow measurements described in footnote d and lab analysis data of samples of the flush water and production unit effluent waste stream at the Botkins Plant.
ing 96 pigs free from solids buildup.

Metcalf and Eddy (1970, p. 108) state that a minimum flow velocity of 1 foot per second is sufficient to prevent serious deposition of solids in sanitary sewers. They also point out, however, that it is desirable to have a velocity of 3 feet per second or more whenever practicable. In 3 feet wide by 3 inch deep gutters, as recommended by Koelliker, et al. (1972), a 3 feet per second velocity indicates a flow rate of 16.8 gallon per second or a total of 168 gallons for a 10 second flush.

An analysis of the above data suggests that the use of 160 gallons of water per flush should be adequate for gutters serving 100 pigs. However, the optimum frequency of such flushes is not so well defined. Some reports indicate that one flush per day is adequate (Jones, et al., 1971). However, when recycle water is used for flushing, many flushes use little if any more water than few flushes. By flushing more frequently the animal waste stays in the production unit for a shorter time and thus the environment is improved. Therefore a more frequent flushing scheme seems preferable. A flushing frequency of once every 2 hours was assumed for use in the simulation of recycle flush systems.

In summary, for purposes of the computer simulation program it was assumed that for systems using recycle water for flushing, 160 gallons of flush water will be used for each 100 pigs every 2 hours. This amounts to a daily flush water requirement of 19.2 gallons/pig (72.6 l/pig). On the basis of the information reported by Jones, et al. (1971), it was assumed that for systems not using recycle water for flushing, one flush of 160 gallons per 100 pigs per day will be used. This amounts to a
daily flush water requirement of 1.6 gallon per pig (6.1 l/pig).

Volume of Produced Wastewater. From August 7, 1973, through September 13, 1973, the total amount of cleaning water (flush water) going into, and the total waste volume coming out of the production unit of the Botkins Plant was measured. The recycle water used for flushing was measured with a two inch rotary meter installed in the flush water line leaving the storage well (see Figure 3). Water added to the flushing system to make up for evaporation losses was estimated by calibrating the flow from the make up line with a stopwatch and a bucket and then keeping a record of the amount of time make up water ran into the system. The total waste effluent from the building was measured with a magnetic flow meter installed in the discharge line from the sump (see Figure 3).

The estimated volume of make up water and the accumulated volumes read from the flow meters during the 37 day measurement period are:

<table>
<thead>
<tr>
<th>Volume</th>
<th>(gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flush Water</td>
<td>525,995</td>
</tr>
<tr>
<td>Evaporation Loss Make Up</td>
<td>24,302</td>
</tr>
<tr>
<td>Total Effluent from Production Unit</td>
<td>571,152</td>
</tr>
</tbody>
</table>

These measurements indicate an average daily wastewater production rate inside the production unit of 564 gallons per day (2135 l/day).

The number of animals in the building during the measurement period varied from 304 to 356 and averaged 332. The live weight of the animals averaged 118 pounds. The 332 average number of pigs and the average daily waste production rate of 564 gallons indicates an average wastewater production rate of 1.7 gallons per pig per day (6.4 l/pig/day).

Published data indicates that pigs will produce a daily quantity of
raw manure equivalent to 5.1 percent of their live weight (Taiganides and Stroshine, 1971). The average live weight of the pigs in the production unit of 118 pounds during the measurement period would thus indicate a manure production rate of 6 pounds per day (2.7 kg/day), which is approximately equivalent to 0.7 gallons per day (2.7 l/day).

Koelliker, et al. (1972) report observations indicating that during cool weather the wastewater generation rate for pigs is about 1 gallon per pig per day (3.8 l/pig/day). However, during the Summer when water sprinklers were used for animal cooling, the production rate was observed to be as great as 5 gallons per pig per day (18.9 l/pig/day).

The waste production rate calculated from the measurements taken at the Botkins Plant is thus significantly greater than the value calculated from the data reported by Taiganides and Stroshine (1971), as well as the 1 gallon per pig per day value reported by Koelliker, et al. (1972). However, measurements at the Botkins Plant included the feces and urine excreted by the animals as well as spilled drinking water, wasted feed, and any other material dropped, spilled or intentionally washed into the gutters by the operators of the production unit. The wastewater production rate calculated from the measurements should therefore be greater than that estimated from the data reported by Taiganides and Stroshine, since their data are for feces and urine alone.

Since the measurements were taken at an actual, operating production unit where there is potential for material other than the feces and urine excreted by the animals to find its way into the waste stream, the value calculated from the measurements was used in the computer simulation program.
COD of the Produced Wastewater

Weekly COD measurements were made for several sample points in the Botkins Plant for over two years. For this determination the COD data taken between February 6, 1973, and September 11, 1973, of the total effluent from the production unit and the flush water were averaged. The COD of the total effluent was found to range from a maximum of 19393 mg/l to a minimum of 557 mg/l with the average being 4652 mg/l. The COD of the flush water ranged from 13853 mg/l to 336 mg/l and averaged 2369 mg/l.

Using the volume measurements made between August 7, 1973, and September 13, 1973, that were discussed earlier and the average flush water COD of 2369 mg/l, the contribution of the flush water to the COD of the total effluent was determined to be $12.75 \times 10^7$ mg/day. Similarly the daily COD of the total effluent was determined to be $27.18 \times 10^7$ mg/day. The difference between these two values indicate that the waste produced in the animal production unit contributed approximately $14.43 \times 10^7$ mg of COD each day. Combination of the $14.43 \times 10^7$ mg COD/day with the average daily waste volume during the measurement period of 564 gallon per day (2135 l/day) indicates a COD concentration in the produced waste of 67,638 mg/l.

Taiganides and Stroshine (1971) report that pigs will produce daily a quantity of manure solids equivalent to 0.69 percent of their live weight, that the daily BOD of pig wastes is equivalent to 31.8 percent of the total solids produced, and that the ratio of the daily BOD to COD production is 0.307. Application of this data to 332 pigs with an average live weight of 118 pounds indicates a daily COD of $12.73 \times 10^7$ mg.
bining this value with the measured volume of produced waste of 564 gallon/day (2135 l/day) indicates a COD concentration of 59625 mg/l.

The difference between the COD concentration of the produced waste as calculated from the measured values and that estimated from the data reported by Taiganides and Stroshine (1971) is approximately 12 percent, which doesn't seem very significant when it is considered that the measured values take into account wasted feed as well as animal excreta. The value calculated from the measurements was used in the computer simulation program, for it was felt that it more closely approximated reality than did the value calculated from the data by Taiganides and Stroshine (1971).

VSS Concentration of the Produced Wastewater

An analysis of the VSS data from the Botkins Plant for the period February 6, 1973, through September 11, 1973, indicated an average value for the total effluent from the production unit of 5200 mg/l, and 2880 mg/l for the flush water. Using the volume measurements made between August 7, 1973, and September 13, 1973, that were discussed previously, the contribution of the flush water to the VSS concentration of the total effluent was determined to be $14.59 \times 10^7$ mg/day. Similarly the VSS in the total effluent from the production unit was determined to be $30.38 \times 10^7$ mg/day. The difference between these two numbers indicate that the waste produced in the animal production unit contributed approximately $14.89 \times 10^7$ mg of VSS each day, which when combined with the volume of produced waste indicates a VSS concentration of the produced waste of 69751 mg/l.

A calculation of VSS concentration from literature data, similar to
that described previously for COD, produced a value of 68993 mg/l. Due to the close agreement of the values calculated from measured and published data, a rounded value of 69000 mg/l was chosen for use in the program.

**Liquid-Solid Separator Efficiency**

Another factor which influences the quantity of wastewater that will have to be treated by the reactor is the liquid-solid separator efficiency. Shutt (1973) and Mote (1973) reported on a series of tests in which a stationary sieve and a vibrating screen were evaluated for removing solids from swine manure slurries. The separators were evaluated under various loading rates and various size openings in the sieve and screen. The two reports indicate that the separation efficiency of a liquid-solid separator depends on the type of separator, size of openings in the sieve or screen, slurry application rate, and solid content of the slurry.

The data from the two reports, a summary of which is presented in Table 3, illustrate that the percentage of COD, VSS, and total volume in the separator influent that can be diverted to the solids storage tank can vary over wide ranges depending on the exact type of separator and the manner in which it is operated. For general numbers to use in the computer simulation program, it was assumed that 25 percent of the COD and VSS and 1 percent of the total volume in the separator influent would be diverted into the solids storage tank. Data in Table 3 indicate that some efficiencies were much higher, while many were much lower.
Table 3. Summary of Separator Efficiencies for Two Types of Separators and Various Operating Conditions$^a$

<table>
<thead>
<tr>
<th>SEPARATOR TYPE</th>
<th>SIZE OF OPENINGS IN SIEVE OR SCREEN (in.)</th>
<th>APPLICATION RATE (gpm)</th>
<th>PERCENT DIVERTED TO SOLID STORAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>COD</td>
</tr>
<tr>
<td>18 in. Stationary</td>
<td>0.040</td>
<td>81.7</td>
<td>51.6</td>
</tr>
<tr>
<td>Sieve</td>
<td></td>
<td>60.2</td>
<td>79.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48.2</td>
<td>65.8</td>
</tr>
<tr>
<td>0.060</td>
<td></td>
<td>83.5</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>64.1</td>
<td>24.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48.6</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.9</td>
<td>11.4</td>
</tr>
<tr>
<td>18 in. Dia. Vibrating Screen</td>
<td>0.0065</td>
<td>28.8</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.1</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.8</td>
<td>3.3</td>
</tr>
<tr>
<td>0.0084</td>
<td></td>
<td>27.2</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.0</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.1</td>
<td>16.3</td>
</tr>
<tr>
<td>0.0153</td>
<td></td>
<td>30.4</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18.0</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

$^a$Data from Shutt (1973), and Mote (1973).
Design of Biological Reactor

The relationship used for the design of and the development of operational guidelines for the biological reactor are based on a consideration of the kinetics of the microorganisms that occupy the reactor. A discussion of the theory of biological treatment and the development of relationships that describe the process is presented in the section on subroutine TMT.

Design of Clarifiers

Settling tests were made with the mixed liquor from the oxidation ditch of the Botkins Plant to obtain information needed in the design of clarifiers for removing biological sludge from the treated effluent in plants treating swine wastes. Tests were made on two occasions, August 7, and October 31, 1973. On the date of each test a quantity of the mixed liquor was collected, transported to Columbus, and placed into settling columns as soon as possible after getting it into the laboratory. One liter graduated cylinders, which had a depth of about 1.15 feet (35 cm) were used for settling columns.

One cylinder was filled with mixed liquor as it came from the ditch. Two others were filled with mixed liquor that had been diluted by 25 percent and 50 percent, respectively, with distilled water. The purpose of the dilutions was to provide settling data on mixed liquors with different suspended solids concentrations. Samples were taken of the material in each cylinder for suspended solids determination.

Once the cylinders were filled, a record was made of the position of the liquid-sludge interface as time elapsed. The data thus obtained
are plotted in Figure 6. The top three curves in Figure 6 are from the August 7, 1973, test, and the bottom one from the October 31, 1973, test. Only one of the October 31, 1973, cylinders produced information different from that gained by the tests on August 7, 1973. For this reason only one curve was plotted from the October 31, 1973, data.

The curves in Figure 6 show that as the suspended solids concentration of the mixed liquor increases the rate of sludge settling declines. It also appears from Figure 6 that the sludge initially settles at a slow rate and then after a while at a faster rate, and that as the suspended solids concentration increases the length of the initial slow settling period increases.

Settling occurs at such a slow rate in mixed liquor with an initial suspended solids concentration of 7875 mg/l that it is probably not practical to design systems to operate with suspended solids concentrations above 8000 mg/l. This criteria is also supported by Okey, et al. (1969), who report that 8000 mg/l is about the maximum permissible mixed liquor suspended solids concentration for systems utilizing sedimentation clarifiers.

In order to stay below suspended solids concentrations of 8000 mg/l and still not restrict the allowable suspended solids to a severely low concentration the computer simulation program will design the clarifiers on the basis of the average of the curves for 7875 mg/l and 5302 mg/l suspended solids concentration. This is roughly equivalent to designing for a mixed liquor suspended solids concentration of 6600 mg/l. The reactor is designed for a nominal suspended solids concentration of 6000 mg/l, in order to allow for some fluctuation without overloading the
Figure 6: Mixed Liquor Interface Settling Curves for Four Suspended Solids (SS) Concentration.
clarifiers. The curves for suspended solids concentrations of 7875 mg/l and 5302 mg/l have been redrawn as Figure 7 and 8, respectively to facilitate their use in determining design information.

The prime consideration for the design of clarifiers for the sole purpose of providing a clarified effluent (as opposed to concentrating the sludge), is the rate at which the sludge interface settles and leaves clear water behind. From Figures 7 and 8 it can be seen that the initial settling rate is many times (4 to 9) slower than the secondary settling rate. Thus, for purposes of a conservative design, it will be assumed that the settling velocity is zero for the time period equivalent to the initial settling phase. This means that the surface area of the clarifier will be designed on the basis of the second stage settling velocity, and when the clarifier is built provisions should be made for the clarifier to have a detention time equal to or greater than the length of time the initial settling phase exists. Providing the required detention time should be of little concern, for more than ample detention time is usually built into the clarifier as sufficient depth is provided to accommodate sludge collection and removal.

The required surface area for clarification can be determined by dividing the clarifier effluent rate by the settling velocity (Metcalf and Eddy, 1972, p. 294). The average of the settling velocities of 2.1 cm/hour from Figure 7 and 9 cm/hour from Figure 8 is 0.18 feet/hour (5.6 cm/hr). Thus the required surface area for clarification can be expressed as

$$A = \frac{Q}{0.18 \text{ ft/hr}}$$

where $A = \text{surface area of clarifier for clarification, ft}^2$
Figure 7: Interface Settling Curve for a Mixed Liquor with a Suspended Solids Content of 7875 mg/l.
Figure 8: Interface Settling Curve for a Mixed Liquor with a Suspended Solids Content of 5302 mg/l.
\[ Q = \text{clarifier effluent rate, ft}^3/\text{hr} \]

The prime consideration for the design of clarifiers for the concentration of sludge is the time \( t_u \) required to reach the desired concentration. Metcalf and Eddy (1972, p. 292-293) present a graphical method for determining \( t_u \) using settling curves such as the average curve of Figure 9 obtained by interpolating between the curves of Figure 7 and 8. The procedure calls for locating the point of critical concentration by extending the tangents to the free-settling and compression regions of the interface settling curve to the point of intersection and bisecting the angle thus formed. The time, \( t_u \), is then the time corresponding to the intersection of a line tangent to the settling curve at point of critical concentration and a horizontal line that corresponds to the depth at which the sludge is at the desired concentration.

The maximum concentration possible will exist when the interface is at its minimum height. The degree of concentration will be the ratio of the initial interface height to the final height of the interface \( (H_0/H_u) \). Thus for the estimated settling curve in Figure 9 it can be seen that the minimum height is 0.26 feet (7.8 cm) which indicates a maximum possible increase in the sludge concentration of 4.5 with a time requirement \( (t_u) \) of 25.6 hours.

The required surface area for sludge concentration can be expressed as (Metcalf and Eddy, 1972, p. 292)

\[
A_s = \frac{(Q_w)(t_u)}{H_0} \tag{3}
\]

where

\( A_s = \) surface area of clarifier used for sludge concentration, \( \text{ft}^2 \)
\( Q_w = \) flow rate into clarifier, \( \text{ft}^3/\text{hr} \)
Figure 9: Estimated Interface Settling Curve for a Mixed Liquor with a Suspended Solids Content of 6600 mg/l. (Developed from Interpolation between Curves of Figures 7 and 8).
\[ t_u = \text{time desired to reach desired concentration} = 25.6 \text{ hr} \]
\[ H_0 = \text{initial height of interface} = 1.15 \text{ ft (35 cm)} \]

Substituting the values of \( t_u \) and \( H_0 \) provides that

\[ A_s = 22.25 \text{ Qw} \quad (4) \]

In the program, the clarifier settling tank will be designed according to Equation 2, and the sludge thickener (concentrator) tank according to Equation 3.

At this point an example can be given that will illustrate that thickening the sludge, as can be accomplished by providing a second settling tank for this purpose, can reduce the total tank volume required in a treatment plant. Assume:

1. The sludge from 5000 gallons of mixed liquor is to be wasted each day.
2. The wasted sludge is to be stored for 90 days.
3. The settling tank is to have a depth of 4 feet.
4. Case A - sludge to be concentrated by factor of 2.
   Case B - sludge to be concentrated by factor of 3.
5. The settling time, \( t_u \), is to be read from the curve in Figure 9.

From Figure 9, \( t_u \) for case A is 3.2 hours. Thus Equation 3 yields a surface area of 77 ft\(^2\) for the settling tank. The volume of the settling tank is thus 2317 gallons, and the required volume of the storage tank to store 2500 gallons of sludge per day for 90 days is 225,000 gallons.

In case B, \( t_u \) is 16.4 hours, which results in a surface of 397 ft\(^2\) from Equation 3. The volume of the settling tank in Case B is thus 11,878 gallons, and the storage volume to hold 1,667 gallons of sludge per day for 90 days is 150,000 gallons.
It can thus be seen that increasing the sludge concentration from a factor of 2 to a factor of 3 decreased the required storage volume by 75,000 gallons while increasing the settling tank volume by only 9,561 gallons. Providing the extra settling tank volume produced a net reduction in tank volume of 65,439 gallons.

Sizing of Aeration Equipment

Sizing of aeration equipment requires knowledge of the equipment and the quantity of oxygen that is required by the biomass in the reactor. Both topics are discussed in this section.

Aeration Capacity

Several different types of aeration equipment are used in biological waste treatment plants. The most common types are rotors, floating aerators, turbines, and compressed air diffusers. The aeration capacity of an aerator is dependent upon the type and particular design. Because of this, there may be considerable variation between the aeration capacities of similar equipment from different manufacturers. For this reason it is not possible to make specific design calculations without knowledge of the specific equipment to be used. There are, however, general data available that will suffice for preliminary or functional type design calculations.

Rotors are usually rated in terms of their oxygen transfer rate as pounds of oxygen per foot of rotor per hour (lb \( O_2/\text{ft-hr} \)). Lakeside Equipment Corporation (undated) provides data which indicate that rotors operated at 6 inch immersion and between 70 and 100 rpm will transfer an average of 1.1 lb \( O_2/\text{ft-hr} \). Taiganides (1973, p. 25) indicates that
rotors designed to operate at 6 inch immersion and 70 rpm can be expected to transfer 1.4 pounds O₂/ft-hr. Jones, et al. (1969) report that several different types of rotors were evaluated and that the oxygen transfer rate varied from 1.0 to 1.6 lb O₂/ft-hr. An average of the data summarized here indicates that an oxygen transfer rate of 1.3 lb O₂/ft-hr (1.9 kg O₂/m-hr) may be a reasonable value to use for approximate design calculations.

Aeration equipment is also frequently rated in terms of its oxygen transfer rate in terms of pounds of oxygen per horsepower-hour (lb O₂/hp-hr). Metcalf and Eddy (1972, p. 518) report that commercial size surface and turbine aerators range in efficiency from 2 to 4 lb O₂/hp-hr. Taiganides (1973, p. 25) states that aeration systems other than rotors have an approximate efficiency of 4.4 lb O₂/hp-hr. Taiganides (1968) has also reported that floating aerators and compressed air diffusers have an efficiency in the range 1.5 lb O₂/hp-hr to 2.3 lb O₂/hp-hr. An average of the data just summarized indicates that the approximate efficiency value of 3 lb O₂/hp-hr (5.1 x 10⁻⁷ kg O₂/Joule) may be satisfactory for use in approximate design calculations.

In the computer simulation program two aerator sizing calculations are made. One provides an estimate of the length of rotor required and the other estimates the horsepower rating of the aeration equipment. The efficiencies of 1.3 lb O₂/ft-hr and 3 lb O₂/hp-hr are used in the computer simulation program.

**Oxygen Requirement**

A rule of thumb exists which states that oxygen should be added to
a reactor at a rate equal to twice the BOD$_5$ of the animal waste being treated (Taiganides, 1968). Use of this value in the computer simulation program for estimating the size of the aeration equipment would have been satisfactory. However, since the biological treatment process is simulated, it is possible to estimate the theoretical oxygen requirement on the basis of cell growth and substrate consumption. The latter method was used in the computer simulation program because of its compatibility with the simulation of the biological treatment process.

Determination of the theoretical oxygen demand, as explained by Metcalf and Eddy (1972, p. 490), is from a consideration of the substrate that enters the reactor, the substrate that leaves the reactor, and the mass of microbial cells that are produced. Consumption of the substrate that enters the reactor occurs in two ways. Part of the substrate is oxidized for the generation of energy, and part is assimilated into new cell material. The oxidation or conversion of the substrate into energy requires oxygen, whereas incorporation of the substrate into cell material does not. Therefore the theoretical oxygen demand can be obtained by determining the difference between the amount of substrate that enters the reactor and the amount that leaves the reactor, and subtracting from this difference the oxygen equivalent of the substrate converted to cell material. The oxygen equivalent of the cell material can be calculated by multiplying the mass of the cell material by 1.42.

In the computer simulation program a substrate balance and microbial growth calculation are made on a continuous basis. Initial values for these calculation procedures are determined in the main program and are used to estimate the oxygen requirement on which the aeration equipment
sizing calculations are made.

Storage Tank Capacity

The capacity of the storage tank is a function of the rate of inflow to the storage tank and the amount of time that it is desired to store the material. The desired number of days of storage capacity is a trial design condition to be selected by the program user. The rate of inflow to the tank is a function of such things as animal waste production rates, screen efficiencies, and biological sludge waste rates, all of which are discussed elsewhere.

Investment Cost of Waste Treatment and Disposal System

Investment costs are estimated for three segments of the waste treatment and disposal system; treatment plant, storage tank and hauling wagons. For cost estimating purposes the treatment plant is considered to consist of the reactor, clarifiers, separators, aerators, and pumps. The hauling wagons are assumed to be the vacuum type and thus require no extra pump for loading. No investment cost is included for a tractor to pull the wagon. However, an operating cost for the tractor is estimated in the net annual cost of the system as will be seen later.

From bids made by contractors in 1970 to construct and provide the process equipment for the waste treatment facility at the Botkins Plant it was estimated that all the plant except the storage tank and digester could have been built for $30,000. The volume of the reactor (oxidation ditch) in the Botkins Plant is approximately 27,700 gallons (105,000 liters). Estimates of treatment plant investment costs are thus made in the computer program by substituting the known cost of $30,000 for a
27,700 gallon capacity reactor into the cost-capacity relationship of
Equation 1 and using the "six-tenths factor rule."

The cost-capacity relationship of Equation 1 is also used to estimate the investment cost for the storage tank, except, instead of using the six-tenths factor rule, a value for the cost-capacity factor was calculated from some known cost data. In 1970, in connection with the building of the Botkins treatment plant, a bid was made by a fiberglass tank supplier. In the bid the price of five tanks ranging in size from 6000 gallons (21,230 liters) to 24000 gallons (84920 liters) was quoted. The prices ranged from $1295 for the 6000 gallon tank to $4145 for the 24000 gallon tank. By substituting these values into Equation 1 a cost-capacity factor of 0.84 was obtained. The storage tank investment cost is thus estimated in the computer simulation program by substituting the known cost of $1295 for a 6000 gallon (21,230 liter) tank and the cost-capacity factor of 0.84 into Equation 1.

A similar approach is used to estimate the hauling wagon investment cost. From manufacturers price list data for vacuum tank wagons, it was found that the cost per gallon for wagons of various capacities could be estimated from the following relationship

\[ l = 2.36 \left( \frac{800}{Q} \right)^{0.27} \]  \hspace{1cm} (5)

where \( l = \) cost per gallon of a tank wagon with capacity of \( Q \) gallons.

The hauling wagon investment cost is thus estimated in the computer simulation program by multiplying the value from Equation 5 by the capacity and number of the wagons being used.

In the case of each of the investment cost estimations, the values are in terms of 1970 dollars. The estimates are converted to current
levels by the use of a cost index as discussed previously.

Annual Cost of Waste Treatment and Disposal System

The total annual cost of the waste treatment and disposal system estimated by the computer program attempts to include depreciation, interest on the investment, maintenance, taxes, repairs, insurance, and labor cost for daily operation of the treatment plant. At the end of the simulated operation of the system, the cost of the hauling operation is added to the annual cost and the estimated fertilizer value of the animal waste applied to the cropland is subtracted to provide an estimate of the net annual cost of the system. The calculation of the net annual cost is further discussed in the section on subroutine ENDSM.

The annual cost of waste treatment and disposal systems estimated by Kesler (1966) varied from 14 to 20 percent of the initial investment. Morris' (1966 and 1971) estimates ranged from 17.5 to 20 percent and Shuyler, et al. (1973) used 15 to 20 percent of the initial investment as an estimate of annual cost. In each of the above cases the percentage factors were selected so as to account for depreciation, interest, maintenance, taxes, insurance, etc. On the basis of the above information a factor of 20 percent of the initial investment was chosen for use in the computer program.

Estimates made by the computer simulation program of the labor cost for daily operation of the treatment plant are based on data collected at the Botkins Plant. For a four month period in 1973 daily records were kept of the time devoted to the running of the treatment plant at Botkins. The records indicate a range from 4 hours to 10 minutes, with
an average of 20 minutes per day spent in operation of the treatment plant. This time was spent doing such things as cleaning the liquid-solid separator screen, changing valves for sludge wasting, checking the operation of all equipment, and general maintenance.

At a labor wage rate of $2.50 per hour, the 20 minutes per day operating time amounts to an annual cost of $303. This wage does not include any overhead or fringe benefits for such things as insurance or vacations, the magnitude of which would vary from operation to operation. It represents only the direct cost of the wage paid to the worker.

It seems reasonable that the labor required to operate a treatment plant will depend somewhat on the size of the plant. In order to incorporate some affect for plant capacity, the "six-tenths factor rule" is used and the $303 annual labor cost is scaled by Equation 1 on the basis of reactor volume.
DEVELOPMENT OF THE SUBROUTINES

As pointed out in the section, "The Approach to the Computer Simulation Program," the computer simulation program contains eight subroutines, one for each of the events defined for simulating the real system, plus two that are needed by GASP to keep things going properly and to end the simulation in a desired fashion. A presentation of the information and computational procedures incorporated into each of the subroutines is included in this section.

Subroutine EVENTS

The objective of the subroutine EVENTS is to insure that GASP processes the correct system event at the proper time during the simulation. GASP sees the system events only as code numbers. Subroutine EVENTS translates the code numbers into the proper system event and calls the subroutine that simulates the particular event. The particular functioning of subroutine EVENTS may be seen from the flow chart and Fortran listing presented as Figures 10 and 11 respectively.

Subroutine WETHR

The objective of subroutine WETHR is to simulate the trafficability of farm land throughout the year. A flow chart and FORTRAN listing of subroutine WETHR, which show how the objective of simulating soil trafficability is accomplished by the computer simulation program are presented
Event Code =

Return

Call P O P

Call E H A U L

Call W E T H R

Call SO L I D

Call ENDSM

Subroutine EVENTS

Figure 10: Flow Chart of Subroutine EVENTS
Figure 11: FORTRAN Listing of Subroutine EVENTS
as Figure 12 and Figure 13 respectively. A discussion of the information and computational procedures built into subroutine WETHR follows.

**Factors Affecting Soil Trafficability**

Soil type (plastic or non-plastic) and soil moisture content are the two major factors that determine the trafficability of soils (Thornthwaite, et al. 1958). As the moisture content of plastic soils increase, their trafficability declines. However, as the moisture content of non-plastic soils (sandy soils) increases, their trafficability improves.

Thornthwaite, et al. (1958) defined five tractionability classes based on the moisture content of the surface two feet of soil. Plastic soils within the "moist" tractionability class become non-trafficable to wheeled vehicles. Soils with moisture contents in the two-foot layer between 75 and 115 percent of field capacity are in the "moist" class. Since 100 percent was near the middle of the moisture content range for the "moist" class, a moisture content in the surface two feet of soil of 100 percent of field capacity was chosen for use in the computer simulation program as the non-trafficable criteria for plastic soils. In other words plastic soils above 100 percent field capacity moisture content are non-trafficable.

On the other hand, sandy soils in the "dry" tractionability class are non-trafficable. Soils with moisture contents in the two-foot layer between 33 and 75 percent of field capacity are in the "dry" class. The middle of the moisture content range of 54 percent of field capacity was chosen for use in the computer simulation program as the non-trafficable criteria for sandy soils. Sandy soils with moisture contents less than
Subroutine WETHR

Update Calendar and Schedule Next WETHR Event

Calculate the Amount of Water in the Soil

Collect Statistics on Soil Conditions

Is Soil Too Dry For Hauling? Yes No

Is Soil Plastic? Yes

Is Soil Too Wet For Hauling? Yes No

Specify Soil As Trafficable

Specify Soil As Not Trafficable

Store Soil Trafficability For Output

Will It Rain Today? Yes No

Set Precipitation to Zero

Determine Amount of Precipitation

Store Monthly Cumulative Precipitation for Output

Calculate Actual Evapotranspiration for Today

Calculate Capillary Storage at End of Day

Is Capillary Storage Above Field Capacity? Yes No

Available Gravity Storage Equals Gravity Storage From Previous Day

Add Excess to Available Gravity Storage and Set Capillary Storage Equal To Field Capacity

Calculate Actual Gravity Storage At End of Today

Return

Figure 12: Flow Chart of Subroutine WETHR
Figure 13: FORTRAN Listing of Subroutine WETHR
Figure 13: (Continued)
54 percent of field capacity are non-trafficable.

The simulation procedure requires that the soil type (plastic or non-plastic) and field capacity (inches of water) be specified. A plastic soil with a field capacity of 9.3 inches of water has been used during the development of the computer simulation program. Field capacity and soil type data for prominent Ohio soils are presented in Appendix C, Table 11.

Soil Moisture Content

Soil moisture can be broken into two categories, that portion that is controlled by capillary forces, and that portion that responds to gravitational forces. When a soil is at its field capacity, all the capillary pore spaces are filled with water and there is no water in the larger pores that drain as the result of gravitational forces (Thornthwaite, et al., 1958, and Baver, 1966, p. 285).

The quantity of water in the soil is increased by precipitation. As water enters the soil, the capillary pore spaces are filled first. Water in excess of the capillary storage capacity enters the larger pores and is considered to be in gravitational storage.

Depletion of capillary water occurs as the result of evaporation and transpiration by plants, or evapotranspiration. The rate of evapotranspiration is primarily a function of temperature, length of day (extent of exposure to solar energy), and the quantity of capillary water present (Thornthwaite, et al., 1958).

Gravitational water is depleted by downward percolation. The rate of downward percolation depends on the soils depth, permeability and the
amount of gravitational water present (Thornthwaite, et al., 1958).

**Soil Moisture Simulation**

Simulation of the occurrence of precipitation events is based on probabilities developed from many years of weather data that defines the likelihood that a given day will be dry. Feyerherm, et al. (1966) have tabulated such data for many locations across Ohio. Similar publications are available for other states.

Each day of the simulation period, a random number is selected from a uniform distribution on the interval 0 to 1. The random number is compared with the probability that the current day will be dry. If the random number is greater than the probability, a precipitation event will occur during the current day.

The amount of rain that falls during each precipitation event is determined from the average monthly precipitation and average number of precipitation events occurring during each month. Such data have been published by the U. S. Department of Commerce (1972) for many locations across the United States. The monthly average rainfall for each month is divided by the average number of days that precipitation occurred during the month, thus producing an average rainfall quantity for each occurrence during a given month. This information is stored in the computer and is called upon by the program each time a precipitation event occurs.

Thornthwaite, et al. (1958) provide data for determining the monthly potential evapotranspiration that will occur at a given location as a function of the monthly mean temperature and the latitude of the location.
By dividing the monthly value by the number of days in the month, a value for the average daily potential evapotranspiration is obtained. Values of average daily potential evapotranspiration thus determined are stored in the computer for ready reference by the program.

Potential evapotranspiration occurs only when all the capillary storage capacity is filled (soil at field capacity). At lower moisture contents, the actual evapotranspiration is proportional to the amount of water remaining in the soil (Thornthwaite, et al., 1958). For simulation purposes, the actual daily evapotranspiration is determined by multiplying the potential evapotranspiration by the ratio of the existing quantity of capillary storage to field capacity.

Water held in gravitational storage is retained in the soil only briefly prior to being lost by downward percolation. The length of detention time depends on the soil's depth and permeability, and the amount of gravitational water present. It has been empirically found that in a 40-inch thickness of loam about 90 percent of the gravitational water present on a given day is retained until the next day (Thornthwaite, et al., 1958). This percentage will become less as the depth of soil decreases and the sand content increases. The 90 percent value has been used in the development of the computer program.

Moisture Balance and Trafficability Determination

The amount of water in the soil at the beginning of a given day is equal to the amount of water that was in the soil at the beginning of the previous day, plus any precipitation that occurred during the previous day, and minus the evapotranspiration and percolation that occurred during
the previous day. A comparison of the amount of water in the soil with the trafficability criteria presented earlier determines whether or not the soil will support the traffic of farm machinery.

Subroutine TMT

The primary objective of the biological treatment event, subroutine TMT, is to simulate the activity of the microorganisms in an aerobic biological waste treatment reactor and determine the resulting substrate concentration of the effluent. Subroutine TMT also provides a continuous record of the concentration of solids in the reactor and the oxygen requirement of the microorganisms. An optional provision exists for the calculation of the required sludge waste rate to maintain a particular effluent substrate concentration. The details of subroutine TMT are presented in the flow chart and FORTRAN listing of Figure 14 and Figure 15 respectively.

Development of a routine to meet the objectives of TMT required that the theory of biological waste treatment be examined for the relationships that adequately describe a biological reactor. Once this was done, data necessary for the utilization of the relationships had to be provided.

Biological Waste Treatment Theory

An aerobic waste treatment system generally consists of a population of microorganisms suspended in a volume of water that is contained in a fixed volume vessel (a reactor) which is equipped with facilities for agitating and aerating its contents. The stream of liquified waste to
Subroutine TMT

Update Calendar

Calculate Mass of Substrate, VSS, and Viable Organisms in the Reactor

Calculate and Collect Statistics on Oxygen Requirement

Calculate Substrate, Organism, and VSS Concentrations

Is Waste Rate To Be Varied So As To Maintain Effluent Substrate Constant?

Yes: Set Effluent Substrate Conc. Equal to Effluent Goal

No: Collect Statistics on S and X

Determine Kinetic Constant Temperature Correction Factor

Calculate Kinetic Constants

Calculate Kinetic Rates

Determine Mixed Liquor Waste Rate

Store Monthly Avg. QW and S For Output

Figure 14: Flow Chart of Subroutine TMT
Is Waste Rate To Be Varied So As To Maintain Effluent Substrate Constant

Yes

Collect Statistics on QW

No

Schedule Next TMT Event

Figure 14: Continued
Figure 15: FORTRAN Listing of Subroutine TMT
Figure 15: (Continued)
be treated flows into the reactor. The organisms in the reactor convert the organic matter in the waste stream into energy and new microorganisms. The effluent from the reactor flows into a sedimentation clarifier where the organisms are removed from the treated water and returned to the reactor. In order to control the operation of the reactor some of the organisms from the sedimentation tank are not returned to the reactor, but are placed into a storage tank to await disposal. A schematic of such a waste treatment system is presented in Figure 16.

Computer simulation of the waste treatment system requires that the operation of the system be expressed in the form of equations that can be solved by the computer. Such equations were developed for the system in Figure 16 by performing mass balances on the system with respect to soluble substrate \( S_s \), mixed liquor VSS \( X \), biomass \( X_0 \), and influent VSS \( X_i \). These parameters were selected because the soluble substrate \( S_s \) is the portion of the waste stream that can be removed by the biomass, the concentration of VSS in the mixed liquor \( X \) is important to the functioning of the clarifiers, and the concentration of influent VSS \( X_i \) that remains in the reactor needs to be known so that the microorganism concentration \( X_0 \) can be differentiated from the total mixed liquor VSS.

**Development of System Equations.** A mass balance on the system shown in Figure 16 with respect to soluble organic matter (soluble substrate) results in the following expression:
Figure 16: Schematic of the Biological Waste Treatment System Simulated in this Study

\[ \begin{align*}
Q & = \text{Influent rate to reactor (l/day)} \\
X_i & = \text{Volatile suspended solids concentration of influent (mg/l)} \\
S_{iS} & = \text{Soluble substrate concentration of influent (mg COD/l)} \\
S_{it} & = \text{Total substrate concentration of influent (mg COD/l)} \\
V & = \text{Volume of the reactor (l)} \\
X & = \text{Volatile suspended solids concentration in the reactor (mg/l)} \\
S_S & = \text{Soluble substrate concentration in reactor mixed liquor (mg COD/l)} \\
Q_W & = \text{Effluent rate from reactor to clarifier from which sludge is wasted (l/day)} \\
C & = \text{Sludge concentration factor} \\
X_0 & = \text{Concentration of organisms in the reactor (mg/l)}
\end{align*} \]
\[
\frac{dS_s}{dt} = QS_{is} + Q(S_{it} - S_{is})(1-T) - QS_s - V \frac{UX_0}{Y} - VMX_0
\]

which is the same as:

\[
\frac{dS_s}{dt} = V \left( S_{is} + Q(S_{it} - S_{is})(1-T) - QS_s \right)
\]

where

\(V\) = volume of the reactor (l)

\(Q\) = influent rate to reactor (l/day)

\(S_s\) = soluble substrate concentration in reactor and effluent (mg COD/l)

\(S_{is}\) = soluble substrate concentration of influent waste stream (mg COD/l)

\(S_{it}\) = total substrate concentration of influent waste stream (mg COD/l)

\(T\) = fraction of influent volatile suspended solids (VSS) which are not hydrolyzed

\(X_0\) = concentration of organisms in the reactor (mg/l)

\(U\) = microorganism specific growth rate, cells formed per unit time per number of cells present (day \(^{-1}\))

\(Y\) = yield coefficient, quantity of cells formed per quantity of
substrate consumed

\[ M = \text{maintenance energy constant, quantity of substrate consumed per unit time per quantity of cells present (day}^{-1}) \]
\[ t = \text{time (day)} \]

A similar analysis of the system in Figure 16 with respect to total volatile suspended solids indicates that:

\[
\text{Change in Mass of VSS} = \text{Input + Produced - Hydrolyzed - Effluent VSS} \tag{8}
\]

which is the same as:

\[
V \frac{dX}{dt} = QX_i + U X_0 V - (1-T)(X_i)(Q) - \frac{Q_w}{C} CX \tag{9}
\]

where

\[ X = \text{VSS concentration in the reactor (mg/l)} \]
\[ X_i = \text{VSS concentration of the influent waste stream (mg/l)} \]
\[ Q_w = \text{effluent rate from reactor to clarifier from which organisms are wasted (l/day)} \]

Other terms are as in Equation 7.

A mass balance on the system in Figure 16 with respect to biomass (organisms) indicates that:

\[
\text{Change in Mass of Organisms} = \text{Input + Produced - Effluent Organisms} \tag{10}
\]

which is the same as:

\[
V \frac{dX_o}{dt} = 0 + UX_0V - \frac{Q_w}{C} CX_0 \tag{11}
\]

where all the terms are the same as in Equation 7 and 9.
A similar analysis of the system in Figure 16 with respect to influent volatile suspended solids indicates that:

\[
\begin{align*}
\text{Change in Mass Input Produced Hydrolyzed} \\
\text{of influent} & = VSS + VSS - VSS \\
\text{- Effluent} & \\
\text{VSS} & \\
\end{align*}
\]

which is the same as:

\[
V \frac{dX_i}{dt} = QX_i + O - (1-T) QX_i - Q_w(X-X_0)
\]

where all the terms are the same as in Equations 7 and 9.

Equations 7, 9, 11 and 13 can be used to indicate the substrate concentration in the effluent, the concentration of VSS in the reactor, and the concentration of organisms in the reactor for various waste loading rates and concentrations. Thus equations 7, 9, 11, and 13 meet the basic requirements for the development of a computer simulation for the biological waste treatment system used in this study. Also as will be shown in following developments, these equations provide the basis for the system design and operating criteria.

By assuming that the system will operate in a steady state condition, the left side of Equation 7 becomes zero, (i.e. \( V \frac{dS_s}{dt} = 0 \)). Solving Equation 7 under these conditions for \( V \) indicates that:

\[
V = \frac{Q \ Y \ (S_{it} - S_s + T(S_{is} - S_{it}))}{(U + MY)(X_0)}
\]

Thus for a given waste stream everything in Equation 14 but \( V, S_s \) and \( X_0 \) will be fixed, so the required volume of the reactor to produce a given effluent quality can be calculated as a function of the organism concentration \( (X_0) \) in the reactor. However, as will be shown later, \( X_0 \) can be expressed as a function of the VSS concentration in the reactor.
(X), and the optimum VSS concentration is pretty well defined by limitations for adequate clarification, i.e., maximum of 8000 mg/1 suspended solids (see the discussion of clarifier design in the previous section on the main program) so Equation 14 is adequate for indicating the required volume of the reactor.

The physical operating procedures to be followed to produce an effluent of desired quality can be developed from Equation 11. However, to see this point more clearly, the significance of specific growth rate (U) needs to be more fully developed.

**Microorganism Specific Growth Rate (U).** For microorganism cultures growing in a controlled environment, the rate of growth of the microorganisms is a function of the nutrient concentration in the growth media (Metcalf and Eddy, 1972, p. 392). For mixed microbial cultures in activated sludge plants under continuous flow conditions, there is a direct relationship between substrate concentration and specific growth rate up to a limiting concentration above which the growth rate is constant (Garret and Sawyer, 1952). The relationship may be expressed as:

$$U = K S_s \approx U$$  \hspace{1cm} (15)

where

- $K$ = specific growth rate constant (1/mg-day)
- $U$ = maximum specific growth rate (day$^{-1}$)
- $S_s$ = soluble substrate concentration in the reactor (mg COD/1)

Equation 15 indicates that when the growth rate is low, the concentration of substrate in the effluent will also be low; and if the growth rate is increased, the substrate concentration in the effluent will also
go up. Thus the level of treatment achieved by a biological waste treatment plant may be controlled by regulating the specific growth rate of the microorganisms.

From Equation 11 it can be seen that the specific growth rate may be regulated by controlling the rate at which organisms are wasted from the reactor. By assuming that the system is operating in a steady state condition, the left side of Equation 11 is equal to zero (i.e., \( V \frac{dx_0}{dt} = 0 \)). Solving Equation 11 under these conditions for \( U \) gives:

\[
U = \frac{Q_w}{V}
\]

(16)

Therefore, for a fixed volume reactor, \( Q_w \) is the only means of controlling the growth rate and thus the level of treatment achieved by the plant.

In the discussion up to this point little has been said of the parameters \( T, K, M, \) and \( Y \). It is obvious that if values are not available for these parameters, neither the simulation nor any of the other computations discussed may be performed. Evaluation of the parameter \( T \) in the computer simulation program is based on published data, while \( K, M, \) and \( Y \) were experimentally determined.

**Evaluation of the Parameter \( T \)**

By assuming that the mass of volatile suspended solids injected into the reactor are hydrolyzed according to a first order reaction, the following equation results:

\[
V \frac{dx_m}{dt} = -K_v V x_m
\]

(17)

where

\( K_v = \) rate constant for the hydrolyzation of VSS in the reactor

\((\text{day}^{-1})\)
\( X_m \) = concentration of volatile suspended solids in the reactor originating in the influent waste stream (mg/l)

Integration of Equation 17 over the period of time, \( G \), that the sludge remains in the reactor indicates that:

\[
\frac{(X_m)G}{(X_m)_o} = e^{-K_vG}
\]  

(18)

where

\( G = \text{sludge age} = \text{the time necessary to remove all the sludge in the system at the existing removal rate (day).} \)

However, \( T \) has been defined as the fraction of influent VSS that are not hydrolyzed, thus:

\[
\frac{(X_m)G}{(X_m)_o} = T
\]  

(19)

and

\[ T = e^{-K_vG} \]  

(20)

Schmidt and Eckenfelder (1970) attempted to evaluate the rate constant, \( K_v \), during their investigation of the effects of influent VSS on the activated sludge process treating municipal sewage. They set up four batch reactors loaded with various amounts of VSS and monitored the VSS content of the reactors as \( G \) increased. The data on the decline in total VSS from their experiments indicate a value for \( K_v \) of approximately 0.1.

Vickers and Genetelli (1969) conducted tests on the stabilization of manure slurries by aeration. They reported the percent suspended solids destruction for various sludge ages. Their data were analyzed according to the procedure used for the data of Schmidt and Eckenfelder (1970), and a value for \( K_v \) of 0.05 was obtained.
Of the two values indicated for the constant $K_v$, the one from the study by Schmidt and Eckenfelder (1970), (i.e., $K_v = 0.1$) was used in the computer simulation program, for it was developed from data collected specifically for evaluating $K_v$. Therefore, the parameter $T$ is evaluated in the computer simulation program by substituting the value $K_v = 0.1$ into Equation 20.

Methodology for Evaluating the Parameters $K$, $Y$, and $M$

The other parameters, $K$, $Y$, and $M$, can be experimentally determined from a treatment system operating at several levels of substrate removal. The type of data that needs to be collected is the various influent and effluent flow rates, substrate concentrations, and VSS concentrations.

It can be seen from Equation 9 that if such data is available, $U$, can be calculated. To see this, assume a steady state condition and solve Equation 9 for $U$. Since at steady state $V \frac{dX}{dt} = 0$, solution for $U$ in Equation 9 gives:

$$U = \frac{Q_wX - TQX_j}{VX_0} \quad (21)$$

Now, all that is necessary to show that $U$ can be calculated from data collected from an operating system is to show that $X_0$ can be expressed as a function of measurable parameters. To see that $X_0$ is a function of measurable parameters, again assume a steady state condition and solve Equation 13 for $X_0$. Since at steady state $V \frac{dX_j}{dt} = 0$, solution of Equation 13 for $X_0$ gives:

$$X_0 = X - TX_i \frac{Q}{Q_w} \quad (22)$$

Since $U$ is a function of $S_s$ as given by Equation 15, a plot of $U$ as determined by Equation 21 against corresponding values of measured $S_s$ should produce a straight line with slope $K$. 
In order to see how to determine Y and M, Equation 14 is solved for \( X_0 \) as:

\[
X_0 = \frac{QY}{V(U+MY)} (S_{it} - S_s + T(S_{is} - S_{it}))
\]

(23)

and the term \( Y_0 \) is defined as

\[
Y_0 = \frac{QY}{V(U+MY)}
\]

(24)

and substituted into Equation 23. This substitution produces:

\[
X_0 = Y_0 (S_{it} - S_s + T(S_{is} - S_{it}))
\]

(25)

From Equation 25 it can be seen that

\[
Y_0 = \frac{X_0}{(S_{it} - S_s + T(S_{is} - S_{it}))}
\]

(26)

It has already been shown that the parameters \( T \) and \( X_0 \) can be evaluated from measured data by Equation 20 and Equation 22 respectively. Thus, \( Y_0 \), as defined by Equation 26, can also be determined from data collected from an operating system.

If Equation 24 is rewritten in the following form:

\[
\frac{Q}{VY_0} = \frac{1}{Y} U + M
\]

(27)

it is obvious that a plot of \( \frac{Q}{VY_0} \) versus \( U \) as determined from Equation 21 will yield a straight line with slope \( 1/Y \) and intercept \( M \).

**Evaluation of the Parameters K, Y, and M**

No published reports of experiments to determine the kinetic parameters \( K \), \( Y \), and \( M \) for the biological treatment of livestock manure have been found. However, in a paper dealing with the design of biological systems for treating cattle manure Okey, et al. (1969) assigned the values of 0.35 and 0.286 day\(^{-1}\) to \( Y \) and \( M \) respectively. A value for \( K \) was not given, but it was stated that a specific growth rate, \( U \), of 0.029 day\(^{-1}\)
would exist for the system. From this value of \( U \) an estimate of \( K \) can be made by applying Equation 15 if the substrate level of the treatment system effluent is known.

Okey, et al. (1969) did not state in their paper what they anticipated the magnitude of the effluent substrate to be, but they did indicate that a "high degree" of treatment was anticipated. Thus, if it is assumed that a "high degree" of treatment implies an effluent substrate concentration in the range of 10 to 100 mg/l, Equation 15 in turn indicates that \( K \) might range from 0.0029 to 0.00029 l/mg-day.

Because of the lack of specific, experimentally determined information, an experimental determination of the kinetic parameters applicable to the bio-treatment of swine waste was undertaken. A bench scale biological treatment system was used to determine the kinetic parameters, \( K \), \( Y \), and \( M \) for the aerobic stabilization of swine manure slurries. A schematic of the bench scale system is shown in Figure 17. A description of the bench scale system, the test procedures, and results follows.

**Description of the Bench Scale System.** The volume of liquid in the vessel (reactor and clarifier, see Figure 17) was maintained constant throughout the experiment at 5.3 l. Feed was injected into the reactor every 18 minutes by a variable speed pump that was controlled by a timer. The pump speed and the length of time it was on each 18 minutes was regulated to produce an influent rate that would displace the volume of the reactor in 1.7 days.

Mixed liquor was wasted once every hour from the reactor by a variable speed pump that was actuated by a time switch. The speed of
Figure 17: Bench Scale Biological Treatment Apparatus Used in the Determination of the Kinetic Parameters $K$, $Y$, and $M$
the waste pump was changed at intervals throughout the experiment so as to establish different levels of organism growth rate.

An aspirator functioned continuously to draw the treated effluent off the clarifier section of the system.

Compressed air was supplied to the diffuser stones through a filter-regulator and rotometer. Prior to the start of data collection, the air flow rate was varied to determine the rate that produced the best agitation. It was found that a minimum flow rate of 2200 cc/minute was necessary to prevent excessive settling of solids in the bottom of the reactor. The air flow rate was maintained at 2200 cc/minute throughout the experiment.

The 2000 cc/minute air flow rate was adequate for maintaining an aerobic condition in the reactor. The dissolved oxygen in the mixed liquor was always observed to be greater than 1 mg/l.

Data Collection. The daily volume of feed material that was pumped into the reactor (Q), the daily volume of treated effluent (Q_e), and the daily volume of wasted mixed liquor (Q_w) was determined and recorded. This was accomplished by weighing each of the respective containers at the beginning and end of each day and converting the weight difference to an equivalent volume using a specific gravity of 1.0.

A 100 ml sample of the influent, mixed liquor, and effluent were taken five days per week for analysis of COD and VSS. The samples were stored in a refrigerator at 4°C until laboratory analysis could be completed. Analysis of the samples was usually completed within two days, and no sample was ever stored more than four days before being analyzed.
Each of the samples was analyzed for VSS in order to determine the influent VSS concentration \( (X_i) \), the mixed liquor VSS concentration \( (X) \), and the effluent VSS concentration \( (X_e) \). A COD analysis was run on the feed sample in order to determine the total substrate concentration of the influent waste stream \( (S_{it}) \). The feed sample and the effluent sample were then centrifuged and a COD analysis was run on the centrate in order to determine soluble substrate concentration of the influent waste stream \( (S_{is}) \) and the soluble substrate concentration of the effluent \( (S_s) \). The procedures used for the COD and VSS determinations are presented in Appendix D.

**Experimental Procedure.** Feed for the bench scale system was wastewater produced by flushing, with fresh water, the gutters in the swine production unit at Ohio State University's Don Scott Farm. The wastewater from the gutters was discharged through a stationary screen. The liquid discharge from the screen was collected and used in the experiment.

In order to eliminate as much variation as possible in the day to day feed going into the system, as much as a 49 day feed supply was collected at one time and stored in a freezer. A one day feed supply was removed from the freezer and thawed each day. In spite of this precaution, however, there was variation in the COD and VSS of the feed from day to day. For feed supplies collected on the same day the COD varied from 1802 mg/l to 7955 mg/l, and the VSS varied from 530 mg/l to 1560 mg/l.

Data was collected during two separate test periods. The first period was 28 days long and ran from September 3 through September 30,
1973. During the first test period the mixed liquor waste rate was set for two different levels. For the 17 day period from September 3 through September 19 the mixed liquor waste pump was set for a rate of 0.54 l/day, and for the 11 day period from September 20 through September 30 the waste pump was set for a rate of 1.1 l/day.

The second test period was 44 days long and ran from October 9 through November 23, 1973. During the second test period the mixed liquor waste rate was set at three levels. The waste pump was set for a rate of 1.1 l/day for 12 days, 0.65 l/day for 11 days, and 1.64 l/day for 21 days.

The intent of the experimental procedure was to operate the system for several days at each of the mixed liquor waste rates so that a steady state condition would be approached. The data indicates, however, that the system did not operate under steady state conditions. One reason for this may be the variations from day to day in the COD and VSS content of the feed. Another contributing factor is that the concentration of solids in the effluent varied significantly. During some periods of operation, there were so many solids in the effluent that the effluent rate had more effect on determining the organism growth rate than did the mixed liquor waste rate, but during other periods there were few solids in the effluent. The VSS concentration of the effluent varied during the experiment from a minimum of 20 mg/l to a maximum of 4568 mg/l and averaged 679 mg/l.

Data Analysis. The daily flow rate determinations, COD, and VSS data were averaged by utilizing the method of "Weighted Averages" as presented by
Fair and Geyer (1954, p. 94-96) before any calculations were made. This procedure helped to reduce the significance of irregularities introduced by the sampling techniques and the small size of the system.

The "Weight Averaged" data was used to calculate $T$ according to Equation 20, $Y_0$ according to Equation 26, $X_0$ according to Equation 22, and $U$ according to Equation 21. The weight averaged data and the calculated values are included in Appendix E.

Once the calculations were made, all the data points were grouped on the basis of the specific growth rates. Data for each day that had a specific growth rate between 0.12 and 0.14, 0.14 and 0.16, etc. were averaged and recorded as in Table 4. Data from each test period was grouped separately.

The values in Table 4 were plotted as $U$ versus $S_s$ and $Q/(VY_0)$ versus $U$ in Figure 18 and Figure 19 respectively. In each plot a straight line was statistically fitted to the data points according to the procedure described by Harshbarger (1971, p. 367-368). In Figure 19 the data points corresponding to the growth rate ranges of 0.16 to 0.18 and 0.24 to 0.26 for the first test period (see Table 4) were so far removed from the other data points that they were not included in the fitting of the line. Because of this, the data points corresponding to the same growth rates were not used in the fitting of the line in Figure 18 either. When fitting the line in Figure 18, the intercept was forced to go through the origin in accordance with the theoretical relationship described in Equation 15.

From the lines fitted to the data points in Figure 18 and 19 it was deduced that
Table 4: Averaged Experimental Kinetic Data

<table>
<thead>
<tr>
<th>U Specific Growth Rate Grouping (DAY⁻¹)</th>
<th>U Average Specific Growth Rate (DAY⁻¹)</th>
<th>Sₘ Average Effluent Soluble Substrate (mg/l)</th>
<th>Q/(VY₀) Average Ratio of Dilution Rate to Observed Yield Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DATA FROM FIRST TEST PERIOD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.120 to 0.140</td>
<td>0.132</td>
<td>378.2</td>
<td>1.534</td>
</tr>
<tr>
<td>0.140 to 0.160</td>
<td>-----</td>
<td>No Observation</td>
<td>-----</td>
</tr>
<tr>
<td>0.160 to 0.180</td>
<td>0.172</td>
<td>463.0</td>
<td>3.064</td>
</tr>
<tr>
<td>0.180 to 0.200</td>
<td>0.198</td>
<td>439.9</td>
<td>0.989</td>
</tr>
<tr>
<td>0.200 to 0.220</td>
<td>-----</td>
<td>No Observation</td>
<td>-----</td>
</tr>
<tr>
<td>0.220 to 0.240</td>
<td>-----</td>
<td>No Observation</td>
<td>-----</td>
</tr>
<tr>
<td>0.240 to 0.260</td>
<td>0.248</td>
<td>478.2</td>
<td>7.303</td>
</tr>
<tr>
<td>DATA FROM SECOND TEST PERIOD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.180 to 0.200</td>
<td>0.184</td>
<td>402.7</td>
<td>1.001</td>
</tr>
<tr>
<td>0.200 to 0.220</td>
<td>0.208</td>
<td>631.3</td>
<td>0.864</td>
</tr>
<tr>
<td>0.220 to 0.240</td>
<td>-----</td>
<td>No Observations</td>
<td>-----</td>
</tr>
<tr>
<td>0.240 to 0.260</td>
<td>-----</td>
<td>No Observations</td>
<td>-----</td>
</tr>
<tr>
<td>0.260 to 0.280</td>
<td>-----</td>
<td>No Observations</td>
<td>-----</td>
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<tr>
<td>0.280 to 0.300</td>
<td>0.296</td>
<td>580</td>
<td>1.760</td>
</tr>
<tr>
<td>0.300 to 0.320</td>
<td>0.305</td>
<td>330</td>
<td>1.217</td>
</tr>
<tr>
<td>0.320 to 0.340</td>
<td>0.330</td>
<td>481</td>
<td>2.158</td>
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</tbody>
</table>
Figure 18: Experimentally Determined Relationship Between Specific Growth Rate ($U$) and Soluble Substrate Concentration ($S_s$)
Figure 19: Experimentally Determined Relationship Between the Ratio of Dilution Rate to Observed Yield Coefficient \( \left( \frac{Q}{V_Y} \right) \) and Specific Growth Rate \( (U) \) Calculated from Data taken From Bench Scale Treatment Plant (day\(^{-1}\)).

Note: Points designated as \( \& \) were not used in fitting line.

Specific Growth Rate \( (U) \) Calculated from Data taken From Bench Scale Treatment Plant (day\(^{-1}\))

Graph showing the relationship between \( \frac{Q}{V_Y} \) and \( U \) with data points and a linear trend line. The slope of the trend line is indicated as 0.19.
\[ K = 0.00051 \, \text{l/mg-day} \]
\[ Y = 0.19 \]
\[ M = 0.10 \, \text{day}^{-1} \]

**Discussion of Experimental Results.** The relationships used to determine the kinetic parameters from the experimental data were based on the assumption of steady state conditions in the treatment system. The bench scale system used did not operate under steady state conditions for any appreciable period of time during the course of the experiment. Thus the values determined for the parameters are subject to some question. However, as will be shown in a following section, when the parameters determined from the experimental data are substituted into Equation 14, a reactor volume is calculated that is similar to reactor volumes calculated from more conventional design recommendations published by Day, et al. (1971). Therefore, it is felt that the experimental results should serve as reasonable estimates for the three parameters.

**Effect of Temperature Changes on the Kinetic Parameters**

Friedman and Schroeder (1972) used a bench scale system similar to the one used in the experiment described above to measure the effect of temperature on growth rates and yield coefficients of activated sludge organisms. They determined that the kinetic parameters increased as temperature increased from 3.7°C to 20°C and declined as the temperature was further increased from 20°C to 41.2°C.

The modified Arrhenius equation is often used to characterize temperature effects on biological treatment system reaction rates (Fried-
man and Schroeder, 1972). The modified Arrhenius equation is

\[ \frac{K}{K_r} = \phi T - T_r \]  

(28)

where

\( K \) = unknown reaction rate at temperature, \( T \)

\( K_r \) = known reaction rate at temperature, \( T_r \)

\( \phi \) = a constant called the temperature coefficient

The Arrhenius equation temperature coefficient, \( \phi \), obtained by Friedman and Schroeder (1972) is 1.047 for temperatures between 3.7°C and 20°C, and 0.970 between 20°C and 41.2°C.

The temperature of the mixed liquor during the experimental determination of the kinetic parameters varied between 18.5°C and 25.8°C and averaged 23.1°C. Correcting the experimentally determined values for the kinetic parameters from 23.1°C to 20°C by the above coefficients results in the following values:

\[ K = 5.6 \times 10^{-4} \text{ l/mg-day} \]

\[ y = 0.21 \]

\[ M = 0.11 \text{ day}^{-1} \]

The 20°C values for the kinetic parameters may be converted to any other temperature condition by applying the correction factor provided by the following equations:

\[ \text{CORRECTION FACTOR} = (1.047)^{T-20.0}, \text{ for } 3.7°C \leq T \leq 20°C \]

(29)

\[ \text{CORRECTION FACTOR} = (0.971)^{T-20.0}, \text{ for } 20°C \leq T \leq 41.2°C \]

(30)

Observations of temperature charts for air and oxidation ditch mixed...
liquor temperatures from the Botkins Plant indicated that ditch mixed liquor temperature was approximately equal to the average daily air temperature. On the basis of these observations the temperature of the mixed liquor in the reactor is assumed in the computer simulation program to be equal to the normal monthly average ambient temperature except during the Winter months when the average temperature would be below freezing. The temperature for the Winter months is fixed at 10°C, for it was observed at the Botkins Plant that with proper insulation and aeration procedures the Winter temperature of the mixed liquor can be prevented from falling below 10°C.

Normal monthly average ambient temperature data is available for many locations across the country from the U. S. Department of Commerce (1972) publications.

**Influent Soluble COD as a Percentage of Influent Total COD**

During the period of laboratory tests for determining the values of the kinetic parameters, 47 observations were made of the total COD and the corresponding soluble COD of the swine waste used as feed for the bench scale system. The soluble COD was determined by centrifuging samples of the wastewater and determining the COD of the centrate. For these 47 observations, the soluble COD averaged 31 percent of the total COD and ranged from a maximum of 55 percent to a minimum of 11 percent. Since the material fed to the bench scale system was the same material that would be introduced into the reactor of an actual system, it was decided to use the 31 percent factor in the computer simulation program to distinguish between the portion of the system influent COD that is
Subroutine SOLID

The objective of the solid storage event, subroutine SOLID, is to monitor the level of material in the storage tank and schedule a haul event when the level reaches some point pre-set by the program user (HFLG). If a haul event does not occur in time, subroutine SOLID keeps a record of the volume of material that overflows, or more accurately, the volume of material produced for storage in excess of the storage capacity.

The objective of subroutine SOLID is accomplished quite simply. The sources of inflow to the storage tank are the solids discharged from the liquid-solid separator and the wasted biological sludge from the reactor. The solids discharge rate (SOLIN) from the separator is calculated by subroutine POP as a function of the number of animals in the production unit and the separation efficiencies of the liquid-solid separator discussed previously. The sludge waste rate is calculated as a constant fraction of the mixed liquor waste rate. In the previous discussion on clarifier designs it was noted that the sludge concentration in the sludge thickener would be 4.5 times the original concentration of the mixed liquor if the detention time was 25.6 hours. For use in the computer simulation program, however, a factor of 4 was chosen.

The manner in which the routine has been constructed to meet the objectives of subroutine SOLID can be seen from the flowchart and Fortran listing of subroutine SOLID presented in Figures 20 and 21 respectively.
Subroutine SOLID

Update Calendar

Calculate the Volume of Solids in Storage Tank

Yes

Is Storage Tank Overflowing

No

Store Quantity of Overflow for Output

Set Volume of Solids Equal to Storage Capacity

Collect Statistics on Time Tank Overflowed and Specify Tank as Overflow

Record Time That Overflow Began

No

Are Hauling Operations in Progress?

Yes

Is Storage Tank Full to Haul Out Level?

No

Yes

Schedule Haul Event

Schedule Next SOLID Event

Return

Figure 20: Flow Chart of Subroutine SOLID
Figure 21: FORTRAN Listing of Subroutine SOLID
Figure 21: (Continued)
Subroutine POP

The population event, subroutine POP, has two main objectives. One is to simulate the changes in the number of pigs in the production unit as finished hogs are sold and new pigs are moved into the unit. The other is to determine the waste flow rate from the production unit corresponding to the size of the population.

In an effort to define the manner in which the animal population varies in a swine production unit, Dr. Marvin Nelson, the Director of Research for Botkins Grain and Feed Company, Botkins, Ohio, was consulted. Dr. Nelson stated that their operation was set up so that 19 hogs, or 3.8 percent of their unit capacity of 500, were sold each week and 130 pigs, or 26 percent of unit capacity, were moved into the unit every 6 weeks. Dr. Nelson felt that this was a fairly typical operating scheme for most confinement operations.

The simulation procedure in the computer simulation program is thus set up to decrease the population by an amount calculated as 3.8 percent of the production unit capacity, plus or minus 5 percent of the value thus calculated, every 7 days, and to increase the population by 26 percent of the unit capacity, plus or minus 5 percent, every 42.0001 days. The small fraction was added to the time for moving in the pigs to insure that the finished hogs scheduled for market would have already been removed, thus reducing the probability of overcrowding the production unit. The plus or minus 5 percent variation in the number of animals moved in or out was put into the simulation to represent a small degree of uncertainty in the farrowing and growing of animals. The degree of uncertainty is produced in the simulation by selecting a random number between 0.0 and 1.0,
subtracting 0.5 from it, dividing the result by 10.0, and adding one. The resulting factor is then multiplied by the standard number of animals to be moved in or out. For example, the number of animals to be moved in on the 42nd day would be

\[(0.26)\text{(UNIT CAPACITY)} \left[1.0 + \frac{\text{RANDOM NO. -0.5}}{10.0}\right].\]

The waste flow rate from the production unit is calculated on the basis of population size using the waste production rate, flush water requirements, etc. discussed in the previous section on the main program.

The manner in which the information and relationships discussed above are incorporated into a routine that will meet the objectives of subroutine POP can be seen from the flowchart and Fortran listing of subroutine POP presented in Figures 22 and 23 respectively.

Subroutine HAUL

The objective of the haul event, subroutine HAUL, is to simulate the transportation of material from the storage tank and its application to the cropland. In performance of this task consideration must be given to such details as the trafficability of the soil, crop production cycles, and previous application history. Therefore, several specific tasks must be performed by subroutine HAUL. They may be enumerated as follows:

1. Set volume of sludge applied to land to zero at the end of each growing season.
2. Check soil conditions to determine if it is possible to haul. If soil conditions are unsuitable, HAUL terminates without reducing the volume in storage.
Subroutine POP

Update Calendar

Are Pigs Being Moved Into Or Out Of The Production Unit?

Schedule Next Event For Moving in Pigs

Collect Statistics On The Size Of The Population

Increase The Population

Is Production Unit Over Populated?

Set Population Equal to Capacity of Prod. Unit

Schedule Next Event For Moving Out Pigs

Collect Statistics on The Size of the Population

Decrease the Population

Collect Statistics on Total Waste Flow Rate

Calculate The Waste Prod. and Waste Flow Rates

Return

Figure 22: Flow Chart of Subroutine POP
Figure 23: FORTRAN Listing of Subroutine POP
Figure 23: (Continued)
3. Check the stage of the crop production cycle and select the cropland available for hauling onto. If no cropland is available for hauling, HAUL terminates without reducing the volume in storage.

4. Compare the amount previously hauled onto the land during the current cropping cycle against the maximum quantity that can be utilized by the crop. If the maximum has been reached, no more will be hauled until the next season.

5. Determine the amount of time required to haul a load and schedule an end of haul event (EHAUL).

6. Reduce the volume in the storage tank by the volume hauled per load.

7. Determine if the storage tank has been overflowing. If so, the overflow period is terminated and statistics are collected on the length of the overflow period.

A flow chart and Fortran listing of subroutine HAUL, which show how the objective is met in the computer simulation program are presented as Figure 24 and Figure 25 respectively. A discussion follows of the basic information and procedures integrated into this subroutine to enable each task to be performed.

Soil Trafficability Condition

Subroutine WETHR simulates the trafficability of the soil with respect to moisture content. HAUL merely checks the condition specified by WETHR to determine if the cropland is suitable for hauling. However, if the ground is frozen, it is assumed that hauling operations can be
Subroutine HAUL

Update Calendar

Zero Applied Sludge Volume at End of Growing Season

- Is It Winter?
  - Yes
  - Is the Ground Frozen?
    - Yes
    - Schedule end of Haul Event to Corn Land
  - No
  - Is any Corn Being Grown?
    - Yes
    - Is Corn Land Available For Hauling Onto?
      - Yes
      - Has Maximum Application Been Attained?
        - Yes
        - Schedule end of Haul Event to Corn Land
        - No
      - No
    - No
  - No
  - Is any Wheat Being Grown?
    - Yes
    - Is Wheat Land Available for Hauling Onto?
      - Yes
      - Has Maximum Application Been Attained?
        - Yes
        - Schedule end of Haul Event to Wheat Land
        - No
      - No
      - Schedule end of Haul Event to Wheat Land
      - No
    - No
  - No
  - Is the Soil Trafficable?
    - Yes
    - Schedule end of Haul Event to Wheat Land
    - No
  - No
  - Is it Winter?
    - Yes
    - Is the Ground Frozen?
      - Yes
      - Schedule end of Haul Event to Corn Land
      - No
    - No
    - Is any Corn Being Grown?
      - Yes
      - Is Corn Land Available For Hauling Onto?
        - Yes
        - Has Maximum Application Been Attained?
          - Yes
          - Schedule end of Haul Event to Corn Land
          - No
        - No
      - No
      - Is any Wheat Being Grown?
        - Yes
        - Is Wheat Land Available for Hauling Onto?
          - Yes
          - Has Maximum Application Been Attained?
            - Yes
            - Schedule end of Haul Event to Wheat Land
            - No
          - No
        - No
        - Schedule end of Haul Event to Wheat Land
        - No
      - No
    - No
    - Is any Corn Being Grown?
      - Yes
      - Is Corn Land Available For Hauling Onto?
        - Yes
        - Has Maximum Application Been Attained?
          - Yes
          - Schedule end of Haul Event to Corn Land
          - No
        - No
      - No
      - Is any Wheat Being Grown?
        - Yes
        - Is Wheat Land Available for Hauling Onto?
          - Yes
          - Has Maximum Application Been Attained?
            - Yes
            - Schedule end of Haul Event to Wheat Land
            - No
          - No
        - No
        - Schedule end of Haul Event to Wheat Land
        - No
      - No
      - Is any Corn Being Grown?
        - Yes
        - Is Corn Land Available For Hauling Onto?
          - Yes
          - Has Maximum Application Been Attained?
            - Yes
            - Schedule end of Haul Event to Corn Land
            - No
          - No
        - No
        - Is any Wheat Being Grown?
          - Yes
          - Is Wheat Land Available for Hauling Onto?
            - Yes
            - Has Maximum Application Been Attained?
              - Yes
              - Schedule end of Haul Event to Wheat Land
              - No
            - No
          - No
          - Schedule end of Haul Event to Wheat Land
          - No
1. Schedule End of Haul Event to Soybean Land

2. Schedule End of Haul Event to Forage Land

3. Is there any Uncultivated land?
   - Yes
     - Has Maximum Application Been Attained?
       - Yes
       - No
         - Schedule end of Haul Event to Uncultivated Land

   - No
     - Specify no Hauling Operations in Progress and Collect Statistics on Time Devoted to Hauling

   - Specify Hauling Operations in Progress
     - Reduce Volume of Sludge in Storage
       - Was Storage Tank Overflowing?
         - Yes
           - Calculate and collect statistics on the Time the Storage Tank Overflowed.
           - Specify storage tank as not Overflowing and Collect Statistics on Overflow Status.
         - No
           - Return

Figure 24: Continued
Figure 25: FORTRAN Listing of Subroutine Haul
Figure 25: (Continued)
Figure 25: (Continued)
Figure 25: (Continued)
carried out regardless of the soil moisture content. So during the Winter months, HAUL also determines whether or not the ground is frozen before determining that the soil conditions are unsuitable for hauling.

In climates such as that of Ohio, the soil is not always frozen in Winter. Some days it isn't frozen at all, some days it is frozen a full 24 hours, and some days it is frozen only during the early part of the day. As a means of approximating the frozen soil conditions, it is assumed that during the months of December, January and February the soil will always be frozen between midnight and noon, and unfrozen the rest of the time.

**Crop Production Cycles**

Land devoted to the production of crops will be available for hauling onto only during stages of the cropping system when the crops will not be damaged by the traffic. The simulation is set up to handle farming operations producing some or all of the following crops; corn, soybeans, wheat, and forage (hay and/or pasture). A provision is also made for specifying that a certain amount of land is kept out of cultivation each year so that some land will always be available for hauling onto. It is assumed that in actual practice, the uncultivated acreage will be rotated so that a high nitrogen demand crop will be grown on the land the following year.

The number of acres devoted to each crop are initially input to the computer simulation program, and it is assumed that the acreage allocations remain constant each year. If one or more of the crops is not grown in a particular operation, its acreage is specified as zero.

According to the Ohio State University Cooperative Extension Service
(1972), the recommended early planting date for corn in Ohio varies from April 24 at Portsmouth to May 7 at Wooster. Maturity time for corn varies from 95 to 130 days, depending on the variety (OSU Cooperative Extension Service, 1972). Therefore, for simulation purposes it was assumed that land devoted to the growing of corn is not available for hauling onto between May 1 and October 1 of each year.

Wheat is planted in Ohio in late September and early October, and is harvested in late June and early July (OSU Cooperative Extension Service, 1972). By December the plants are well enough established so as not to be damaged by traffic of hauling equipment if the soil is dry or frozen. In order to insure that the crop is not damaged after it begins to grow and mature in the Spring, it was assumed that no hauling onto wheat should occur after April 1. Therefore, for simulation purposes it was assumed that land devoted to production of wheat is not available for hauling onto from April 1 to July 15, and October 1 to December 1.

The planting dates and time required for maturity of soybeans is very similar to that of corn (OSU Cooperative Extension Service, 1972). Thus, the same land availability schedule was used for corn and soybeans.

The first cutting of hay and silage is usually made in mid-May. Each succeeding cutting is made after 40 days. Pastures are usually grazed heavily during the early Spring and rotationally throughout the Summer and early Fall (OSU Cooperative Extension Service, 1972). It was assumed that no manure should be applied to the crop for a period of four weeks before harvesting or grazing, and that hay or silage and pasture land will have the same availability schedule. For simulation purposes
It was thus assumed that land devoted to the production of forage crops is not available for hauling onto from April 15 to May 15, June 1 to July 1, July 15 to August 15, and September 1 to October 1.

It was assumed that uncultivated land is always available for hauling onto. The schedule of available periods for hauling that is used by HAUL is shown schematically in Figure 26 for each crop.

Zeroing Applied Volume

Since it has been assumed that no more waste material will be applied to the land than that amount which will not exceed the annual nitrogen requirement for the crop growing there (see previous section on the main program), at the end of each growing season all the fertilizer elements in the material that has been previously applied has been utilized. Thus the quantity applied to each type of cropland should be set to zero and the application cycle begun anew.

The cycle for wheat ends at the end of harvest on day 196 or about July 15. Since corn and soybeans are in the middle of their growth stage at this time, no more waste material can be applied for the benefit of the current crop. Thus the quantity applied to wheat, corn, and soybeans can be zeroed at the same time.

After July 15 there is only one more short period available for applying sludge to forage cropland before the end of the current crop year. Thus for simplicity the quantity applied to forage cropland will also be zeroed at the same time as the other crops.

Subroutine HAUL therefore zeros all cumulative application registers the first time it is called after day 196 of each year.
Figure 26: Schedule of Available Hauling Periods
Hauling Time

The amount of time required to haul a load of waste material and spread it onto cropland can be broken down into travel time to and from the field, loading time, and unloading time. Observations of hauling at the Botkins Plant indicate that approximately 8 minutes are required to position the wagon, connect the hose and load 1000 gallons. It was also ascertained that approximately 6 minutes are required to spread 1000 gallons once the load has been transported to the field. Thus the time required for loading and unloading can be expressed as \(9.72 \times 10^{-6}\) day/gallon (2.57 \(\times 10^{-6}\) day/l). 

The maximum one way travel time is equal to the maximum one way travel distance divided by the travel speed. (See previous section on main program for travel distance.) It is assumed that the travel speed is 10 mph both to and from the field. Thus the maximum travel time per load can be estimated by dividing the maximum travel distance by 10 mph.

It is assumed that sludge will be hauled to all parts of the farm. Thus the travel distance will vary from zero to maximum. In order to simulate the variation in travel distance, a random number uniformly distributed on the interval 0 to 1 will be selected for each load and multiplied by the maximum travel distance to determine the actual travel distance for the load.

The total time required to haul a load is estimated in the computer simulation program by adding the load time and unload time to the travel time.
Contents of Storage Tank and Overflow Period Record Keeping

Once subroutine H A U L has determined that a load can be hauled and has scheduled an end of H A U L event, it is considered that the wagons are loaded and are on their way to the field. Thus the volume of the contents of the storage tank can be reduced by the amount taken out, which is equal to the number of wagons being used times their capacity.

If the storage tank has been overflowing, it stops as soon as the wagons begin to be loaded. Thus the length of the overflow period may now be determined by subtracting the time that the tank began to overflow from the current time.

Subroutine EHAUL

The objective of subroutine EHAUL is to keep the books for the hauling operation and end the hauling operation when the storage tank is empty. The bookkeeping includes an account of the quantity of waste material applied to the land for each crop as well as monthly, annual, and total simulation period field application totals.

The manner in which the bookkeeping and haul event scheduling tasks are accomplished may be seen from the flow chart and Fortran listing of subroutine EHAUL presented as Figures 27 and 28 respectively.

Subroutine ENDSM

The objective of subroutine ENDSM is to end the simulation phase of the computer program, calculate the net annual cost of the system, and print out the desired information that has been determined by all phases of the computer program. The only function of subroutine ENDSM
Subroutine EHAUL

Update Calendar

Determine Onto Which Cropland The Load Was Hauled (ATRIB(4) = ?)

1. Increase Application on Corn Land
2. Increase Application on Uncultivated Land
3. Increase Application on Wheat Land
4. Increase Application on Soybean Land
5. Store Quantity Applied to Uncultivated Land for Output

Are There More Solids to be Hauled?

No
Specify No Hauling Operations In Progress and Collect Statistics on Time Devoted to Hauling

Yes
Schedule Haul Event

Return

Figure 27: Flow Chart of Subroutine EHAUL
Figure 28: FORTRAN Listing of Subroutine EHAUL
Figure 28: (Continued)
that requires explanation is the calculation of the net annual cost of the waste treatment and disposal system.

As pointed out during the discussion of the main program the net annual cost is the annual cost plus the hauling cost less the fertilizer value of the waste material applied to the cropland. At the end of the simulation period the number of days devoted annually to the hauling operation and the quantity of waste applied annually to the cropland are known. All that remains is to apply the daily cost of hauling and the unit fertilizer value of the waste.

Morris (1966 and 1971) used a cost of $4.00 per hour for hauling manure slurries and applying them to cropland with trailer type wagons. This value includes wages for the operator and cost of operating the tractor. The $4.00 per hour or $96.00 per 24 hour day value was adopted for use in the computer program.

The fertilizer value of animal waste can be estimated by calculating, on the basis of the cost of chemical fertilizer the value that can be realized from the fertilizer elements in the animal waste. Taiganides and Stroshine (1971) report that fertilizer elements are present in raw swine manure in the following proportions expressed as percent of total solids; N-5.6 percent, P₂O₅-2.5 percent, and K₂O-1.4 percent. Previously in the discussion of the functions of the main program, it was pointed out that waste from systems with biological treatment has a nitrogen content of 0.00212 pound/liter and that waste from systems with no treatment has a nitrogen content of 0.0031 pound/liter. If it is assumed that the fertilizer elements in the waste from treatment and disposal systems are present in the same proportions as in the raw manure,
it follows that waste from systems with biological treatment has a \( \text{P}_2\text{O}_5 \) and \( \text{K}_2\text{O} \) content of 0.00094 pound/liter and 0.00052 pound/liter respectively, and that waste from systems without treatment has a \( \text{P}_2\text{O}_5 \) and \( \text{K}_2\text{O} \) content of 0.00138 pound/liter and 0.00077 pound/liter respectively.

In January, 1973, a fertilizer company stated that the factory price of fertilizer elements in Central Ohio was $0.16 per pound for N, $0.13 per pound for \( \text{P}_2\text{O}_5 \), and $0.05 per pound for \( \text{K}_2\text{O} \). These prices and the above fertilizer element concentrations indicate that waste from a system with biological treatment has a potential value of $0.00049 per liter, and that waste from a system with no treatment has a potential value of $0.00072 per liter.

Research has indicated however that the fertilizer elements in animal waste are not as effective as chemical fertilizers. Morris (1966) reviewed the literature on the recovery efficiency of fertilizer elements in animal waste and decided that for waste applied throughout the year the efficiency of N was 50 percent that of chemical fertilizer, \( \text{P}_2\text{O}_5 \) was 67 percent, and \( \text{K}_2\text{O} \) was 75 percent. If these efficiencies are weight averaged on the basis of the amount of each nutrient present in the waste, an overall efficiency of 58 percent is obtained.

Applying the 58 percent efficiency, the actual value of the waste from systems with biological treatment becomes $0.00028 per liter, and waste from systems with no treatment has a value of $0.00042 per liter.

The particular manner in which the net annual cost is calculated as well as the manner in which the other objectives of subroutine ENDSM are met may be seen from the Fortran listing presented in Figure 29.
Figure 29: FORTRAN Listing of Subroutine ENDSM
F O R T R A N  IV  C l R E L E A S E  2 .0  E N 0 5 *  O A T F  ■  7071 lO /3 ® /2 3  P A G F  0 0 0 3

Figure 29:  (Continued)
GENERAL INSTRUCTIONS FOR
USING THE COMPUTER PROGRAM

Proper use of the computer simulation program requires an understanding of the data cards and the ability to interpret the output. There are eleven data card types which are described in detail in Appendix A. Data card types one through nine are for specifying values of non-GASP variables and may be altered by the user as new situations are defined. Data card types ten and eleven initialize GASP variables and should be set up exactly as described in Appendix A unless the user is familiar with GASP and is aware of the effect a change will have on the operation of the program.

Most of the output generated by the program is sufficiently labeled so as to be self explanatory. There are, however, some statistics generated by GASP that are identified by code numbers. The code numbers and statistical reports are explained in this section.

Initializing Variables

Some of the variables will have the same value every time the computer simulation program is run, others will change only when the program is used to study a problem in a location that has different climatic or soil conditions from the last problem studied, and still others may be changed for each run of the program as the basic problem definition is modified or new trial design conditions are specified.
All the variables that can always use the same initial values are evaluated by data card types eight and nine. In some cases the values are design constants, the development of which has been discussed earlier, or they merely describe conditions that must have some initial value in order for the simulation to get started. The initial value for every variable that requires one is described along with the variable definition in Appendix B.

Precipitation, temperature, and evapotranspiration data that must be entered on data card types three, four, five, and six are presented in Appendix C for several areas of Ohio. Other variables that will require different values for various times and locations are CSTNDX, SOILTY, and FLDCAP. CSTNDX, the cost index value for the current year, is entered on data card type nine. The cost index value in May, 1973, was 143. Current values may be found in a recent issue of Chemical Engineering (Anon., 1974). Values for SOILTY and FLDCAP, which are entered on data card type 8 may be found in Appendix C where properties are listed for several Ohio soils.

Variables that must be provided by the program user, and the ones which will be modified most frequently are entered on data card types one and two. The variables on data card type one define the basic situation to be studied, and data card type two provides trial design conditions.

Running the Computer Simulation Program

Once the computer simulation program has been set up for a particular location by appropriately initializing the variables as discussed above, the design and operation of a waste treatment and disposal system can be
studied. The first step is to define the situation for which a waste system is desired. This is done by entering the capacity of the proposed production unit, acres of available cropland, acres of each crop that are grown, and the desired COD of the treatment plant effluent, if a treatment plant is to be incorporated into the system. This information is entered on data card type one.

The second step is for the program user to select the trial design conditions and enter them on data card type two. Trial design conditions are the size and number of liquid manure wagons to be used, the number of days of storage capacity to be provided, the percentage of storage capacity utilized when hauling operations are to be initiated, and the temperature for which the biological reactor should be designed. Sometimes values for the trial design conditions may be dictated by existing conditions or they may be varied from one computer run to another in order to determine the most desirable situation.

If a system that will incorporate a biological treatment plant is being considered, the next step is to set the value of TRMT to one on data card type eight and set the appropriate values of FLUSH and VALUE on data card type nine (see Appendix B for appropriate values). It is recommended that a preliminary run be made with IOP (data card type eight) equal to two. This will cause the computer to calculate the average daily mixed liquor waste rate for each month necessary to maintain the treatment plant effluent at the desired COD level as specified on data card type one. For the preliminary run, data card type eleven, cards number five and six should not be used and the time for the end of simulation on data card type ten, card number six and data card type eleven,
card number seven should be set at 730 days (two years).

After the preliminary run has been made, the calculated average mixed liquor waste rates should be examined and the desired waste rates for each month selected and entered on data card type seven. The maximum and minimum average daily waste rates should be entered on data card type two. The value for IOP should be set to three and data card type eleven, cards number five and six should be reinserted into the deck. The time for the end of simulation event should now be set for the length of simulation period desired by the user and the computer run made.

If a biological treatment plant is not to be incorporated into the waste disposal system, the preliminary run is not necessary. In this case the variable TRMT is set to zero, FLUSH and VALUE are evaluated at the appropriate level, data card type eleven, card number two is removed from the deck, and the computer run is made for the length of simulation period desired by the user.

After observing the results of the computer run, the program user may desire to investigate the change in the results by altering one or more of the design conditions. If so, it is only necessary to modify the appropriate value on data card type two and repeat the run procedure.

Output

Much information is generated during one computer processing of the program. Any or all of it can be printed out for observation. Provisions have been made for the printing out of what has been deemed some of the more significant information. An example of the type of information routinely printed out by the program is presented in Figures
through 33. Any other information generated by the program that a user might like to have printed out can be provided by modifying the program to collect the data as it is generated and providing an appropriate write statement in subroutine ENDSM.

As can be seen from Figure 30, the problem definition data (input limiting conditions) and trial design conditions are printed out for ready reference. This information is followed by a listing of the results of the design calculations and the estimated system investment and annual cost data. Results from several aspects of the simulated operation of the system are then tabulated, and the output is concluded by reports from the GASP statistical routines (see Figures 31, 32, and 33).

Most of the output is self explanatory, but the reports from the statistical routines need some explanation due to the information being identified by code number (see Figure 33). The first report labeled "Generated Data" provides the mean, minimum, maximum, and standard deviation for the daily oxygen requirement of the biomass, the treatment plant effluent COD, the reactor mixed liquor volatile suspended solids concentration, and the daily mixed liquor waste rate, which are respectively code one, two, three, and four.

The second report labeled "Time Generated Data" provides under the "mean" heading the percentage of time that the storage tank overflowed, the percentage of time that animal waste was being hauled onto the fields, and the percentage of time that the soil was not trafficable. This information is respectively code one, two, and four.
INPUT LIMITING CONDITIONS

- PADDY CAPACITY: 500.0 GROC
- FARM TYPE: 200.0 ACRE
- COTTON ACREAGE: 100.0
- WHEAT ACREAGE: 0.0
- FALLS ACREAGE: 0.0
- SUGAR ACREAGE: 0.0
- RICE ACREAGE: 10.0
- UNFERTILIZED ACREAGE: 100.0
- DESIGN REPLANT COST: 300.0 $/LITER

TOTAL DESIGN CONDITIONS

- WASTEWATER CAPACITY: 454.00 LITER
- NUMBER OF WASTEWATER TREATMENT PLANTS: 1
- PAYMENT TREATMENT: 0.0
- FRACTION OF STORAGE FULL DRY: 0.0
- DESIGN WASTEWATER TEMPERATURE: 30.0 degree Celsius

RESULTING DESIGN

- RAIN SIZE: 350.0 GROC
- VOLUME OF REACTIONS: 1,125.0 LITER
- CANOPY AREA OF PRIMARY CLASSIFIER: 173.61 FT
- SURFACE AREA OF SECONDARY CLASSIFIER: 560.27 FT
- STORED VOLUMES: 420.0 LITER
- LENGTH OF STORAGE: 6.3 FT
- LENGTH OF TREATMENT: 5.3 FT
- MILL WASTE MILL RATE: 1,716.17 LHR
- MIX MILL WASTE MILL RATE: 1,716.17 LHR
- MILL WASTE MILL RATE: 1,716.17 LHR
- MILL WASTE MILL RATE: 1,716.17 LHR
- MILL WASTE MILL RATE: 1,716.17 LHR
- FLUSH WASTE FLUSH RATE: 350.00 LITER
- TREATMENT TOTAL INFLUENT VOLUME: 1015.00 LHR

- ESTIMATED COST
  - RAIN---- 30.00,42 MILLION
  - TREATMENT PLANT---- 27.00,47 MILLION
  - STORING TANK---- 10.00,26 MILLION
  - CYCLING MACHINERY EQUIPMENT---- 10.00,26 MILLION

TOTAL INVESTMENT---- 60.01,16 MILLION

- NET ANNUAL COST OF WASTE SYSTEM
  - YEAR-- COST
  - 1  11526.67
  - 2  11526.67
  - 3  11526.67
  - 4  11526.67
  - 5  11526.67

Figure 30: Example of Computer Simulation Program Output
## ADDITIONAL SIMULATION RESULTS

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### MONTHLY AVERAGE TREATMENT PLANT EFFLUENT CONCENTRATIONS (PPM)

### MONTHLY RAINFALL IN INCHES

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### MONTHLY OVERFLOW FROM STORAGE TANK IN LITERS

### MONTHLY AVERAGE ML WASTE RATE (LITERS/MONTH)

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**Figure 31:** Example of Computer Simulation Program Output
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Figure 32: Example of Computer Simulation Program Output
The same report also provides as code three the mean, standard deviation, minimum, and maximum of the animal population in the production unit. The same information is also provided for the total waste flow rate from the production unit as code five.
VERIFICATION OF THE COMPUTER SIMULATION PROGRAM

Confidence in the computer simulation program developed in this study must be developed in large part by scrutiny of the data and computation procedures built into it and the results it produces. Adequate historical data from a real swine waste treatment and disposal system against which to compare the complete program results are not available. It is possible, however, to compare the results of some phases of the simulation program against specific real data.

In this section the results of the trafficability simulation phase of the computer simulation program are compared against real data, the results of the population simulation are compared with records of the animal population at the Botkins Plant, the reactor volume determined from the theoretical developments and experimental kinetic parameters built into the computer simulation program are compared with the reactor volume indicated by conventional design parameters, and the simulated performance of the biological treatment plant is compared in general terms with the performance of the oxidation ditch in the Botkins Plant.

Trafficability Comparisons

One aspect of the computer simulation program that can be compared with real data is the trafficability simulation.

Miller and Tucker (1970), and Davis and Tucker (1973) have tabulated the number of days suitable for field work in Ohio for each month during
the late Spring, Summer, and early Autumn for the years 1967 through 1972. Their data have been averaged and plotted in Figure 34 for the months of May through October. Also plotted in Figure 34 is the average number of days for which the program indicated the soil would be trafficable. These data were obtained for a five year simulation period.

As can be seen from the two curves in Figure 34, the simulated data follows the same trends as the real data, although the simulated number of trafficable days is usually a little greater than the number of days suitable for field work. It is reasonable to expect that the number of trafficable days would be slightly greater than the number of days suitable for field work, since there will be period of time during and after rainfall events when the soil surface would be too sticky for cultivation and the crops would be too wet for harvesting but the soil could still bear the traffic of farm machinery.

Population Comparisons

Another aspect of the computer simulation program that can be compared with real data is the animal population simulation. Figure 33 shows that during a five year simulation period, the simulated population averaged 447.8 and had a maximum of 500, minimum of 383, and a standard deviation of 33.3. Records of the animal population in the production unit at the Botkins Plant for the one year period from August, 1972, through July, 1973, indicate that the population averaged 337 and varied between a maximum of 394, and a minimum of 246 with a standard deviation of 33.8. It can thus be seen that the degree of variation in the simulated population was similar to the degree of variation in the real
Figure 34: Comparison of Number of Simulated Trafficable Soil Days with Observed Number of Days Suitable for Field Work
population. The reason for the difference in population magnitude is that, even though the production unit in the Botkins Plant has a capacity of 500 pigs, the feeding program during the year for which the data is available was such that the effective maximum population was 400, instead of 500 as used by the computer simulation program.

Reactor Volume Comparisons

Day, et al. (1971) recommend that $9 \text{ ft}^3$ of oxidation ditch volume should be provided for each finishing pig in the production unit. They also reported that a reactor designed on the basis of $9 \text{ ft}^3$/pig produced an effluent which had a soluble BOD$_5$ (BOD$_5$ of centrate of centrifuged effluent samples) of 65 mg/l. On the basis of data reported by Taiganides and Stroshine (1971) that the BOD of swine waste is 30.7 percent of the COD, the 65 mg/l soluble BOD effluent from the reactor reported by Day, et al. (1971) would be equivalent to an effluent with a soluble COD of 212 mg/l.

From Figure 36, in the next section, it can be seen that the computer simulation program indicates that the reactor volume to produce an effluent with a soluble COD concentration of 212 mg/l is 139,000 liter or 4909 ft$^3$ if the animal population is 500 pigs.

The 9 ft$^3$/pig criteria of Day, et al. (1971) indicates a 4500 ft$^3$ reactor volume for a population of 500 pigs. The reactor volume determined by the computer simulation program is thus 8.3 percent larger than the reactor volume indicated by the criteria of Day, et al. (1971).

The close comparison between the reactor volume calculated by the computer simulation program and the volume indicated by the more conven-
tional design criteria published by Day, et al. (1971) substantiates the accuracy of the experimentally determined values for the kinetic parameters and the theoretically determined design concept (see Equation 14) used by the computer simulation program.

General Performance Comparisons

The computer simulation program has the capability of maintaining the mixed liquor waste rate constant and simulating the variation in effluent substrate concentration. When the computer simulation program is operated in this mode, the resulting monthly average of the simulated effluent substrate concentration declines to a minimum in the Summer (July, August, and September) and increases to maximum in the Winter (December, January, and February), as illustrated in Figure 35.

Mixed liquor wasting at the Botkins Plant has been essentially constant year round. A plot of the monthly average treatment plant effluent COD for the period from April, 1972, through March, 1973, (see Figure 35) reveals a similar decline and increase sequence between the simulated system and the Botkins Plant. In fact the two curves in Figure 35 are essentially parallel from April through October.

On the basis of this comparison it appears that the computer simulation program does an adequate job of accounting for the effects of seasonal temperature changes on the biological treatment process.

No implication of equality of treatment plant effluent COD is intended in Figure 35. In fact, the effluent COD of the real and simulated system cannot be directly compared because no soluble COD data is
available for the Botkins Plant. Figure 35 does, however, illustrate a similar response to seasonal changes in both systems.
Figure 35: Effluent Substrate Concentration From a Simulated and a Real System
EXAMPLE APPLICATIONS OF THE COMPUTER SIMULATION PROGRAM

The computer simulation program developed in this study can be used to investigate many specific waste treatment and disposal situations. To demonstrate some of the capabilities of the computer simulation program some example situations have been investigated and are discussed in this section.

As pointed out earlier, the computer simulation program can simulate systems with and without a biological treatment plant. In order to demonstrate both methods of operation, the first series of examples analyzed are discussed primarily with respect to biological treatment plant design and operation, while the second series pertain to liquid manure storage and field disposal systems only.

Systems Incorporating Biological Treatment Plants

With respect to systems incorporating biological treatment plants, the computer simulation program has been used to examine five different relationships. These relationships are:

1. the effect of the treatment plant effluent COD goal on the required volume of the treatment reactor and the required mixed liquor waste rate;

2. the effect of the temperature at which the reactor is designed to operate on the volume of the reactor;
3. the effect of the reactor volume on the mixed liquor VSS concentration for reactors with constant effluent COD's;
4. the effect of constant and varying mixed liquor waste rates on the reactor effluent COD;
5. the effect of the production unit capacity on the net cost of the waste treatment and disposal system.

**Effluent COD Goal**

The computer simulation program has shown that as the desired COD level of the reactor effluent increases, the required volume of the reactor declines at a decreasing rate and the percentage of the mixed liquor from which the sludge must be wasted each day in order to maintain the desired COD level increases linearly. These results are illustrated in Figure 36.

Each of the data points in Figure 36 are from computer simulation program runs made for a system treating the waste from a 500 animal production unit. In each of the runs a design temperature (DESTMP) of 20.0°C was used.

The decline in the required reactor volume illustrated in Figure 36 reflects the shorter reaction or treatment time necessary to remove less of the COD. An increasing mixed liquor waste rate results from the fact that at higher substrate concentrations in the reactor, the microorganism growth rate will be greater (see Equation 15) thus providing more suspended solids which must be handled.
Figure 36: Relationship of Reactor Volume and Mixed Liquor Waste Rate to Reactor Effluent COD Goal
Design Temperature

The activity of the microorganisms in the treatment reactor is a function of temperature. Thus it stands to reason that the temperature condition at which the treatment plant is designed to operate will affect the required volume of the reactor. In fact, the computer simulation program has shown that the required volume of the reactor declines almost linearly as the design temperature increases from 10°C to 20°C. This result is illustrated in Figure 37.

The data points in Figure 37 are from computer simulation program runs made to study the effect of design temperature on the volume of the reactor required for a plant treating the waste from a 500 animal capacity production unit. In each computer run the effluent COD goal was 300 mg/l.

The decrease in reactor volume shown in Figure 37 as the design temperature increases reflects the increase in microbial activity as the temperature approaches 20°C. These results imply that the microorganisms can consume the substrate faster at 20°C than they can at 10°C. Failure of the volume decline to be exactly linear is probably the result of the exponential change in the fraction of incoming VSS that are not hydrolyzed which is integrated into the volume determination (see Equation 14 and 20).

Reactor Volume and Mixed Liquor VSS

The results of the computer runs presented in Figure 37 also show that the effluent COD was maintained at 300 mg/l by each of the reactors, even though there was considerable variation in the volume of the reactors. Since each of the reactors treated the same quantity of waste and experienced the same temperature conditions throughout the year, it may
Figure 37: Relationship of Reactor Volume and Effluent COD to the Temperature at Which the Reactor is Designed to Operate
be concluded that something had to be changing inversely to the reactor volume in order to maintain the effluent COD constant. A plot of the reactor volumes from the computer simulation runs against the corresponding simulated mixed liquor VSS concentration, as has been done in Figure 38, show that the mixed liquor VSS concentration was the parameter that increased as the reactor volume declined.

Other data presented in Figure 38 illustrate that even though the same effluent COD level can be maintained by a range of reactor volumes, too small a reactor can produce conditions that will interfere with the operation of the clarifier. Recall the settling data presented earlier that indicated very poor sludge settling for mixed liquor with suspended solids concentrations near 8000 mg/l. With this criteria it can be seen from Figure 38 that a reactor smaller than 135,000 liter will result in clarification problems at some time due to the VSS concentration approaching 8000 mg/l.

The variation in VSS concentration with reactor volume is a reflection of the fact shown in Figure 38 that the mass of VSS is always the same if the effluent COD level is held constant. Since the mass of VSS is a constant, a change in reactor volume is accompanied by a change in VSS concentration.

**Constant and Varying Mixed Liquor Waste Rates**

Results from runs of the computer simulation program have shown that a constant waste rate at the appropriate level will prevent the effluent COD from going above the goal and at the same time provide several months of operation each year during which the effluent COD will
Figure 38: Relationship of Mixed Liquor VSS Concentration, Mixed Liquor VSS Mass and Effluent COD to Reactor Volume
be considerably less than the goal. This result is illustrated in Figure 39.

The information plotted in Figure 39 is from two different runs of the computer simulation program. Each were for an animal capacity of 500 pigs and a design temperature (DESTMP) of 22.0°C. However, for the first run the waste rate was varied by the computer simulation program as necessary to keep the effluent COD level constant at 300 mg/l. During the second run the waste rate was held constant at the winter rate as determined from the first run, and the computer simulation program determined the resulting effluent COD level.

Data in Figure 39 shows that for the effluent COD to be maintained constant at 300 mg/l, the average waste rate for each month must vary by almost a factor of 2 between the Winter and Summer seasons. Whereas, if the waste rate is maintained constant at the Winter level, a similar variation in effluent COD is produced. This relationship between waste rate and effluent COD is an important consideration to the operation of a waste treatment and disposal system, since greater waste rates produce more material to be handled and disposed of, and thus increase the operating cost of the system.

**Net Cost**

Cost studies with the computer simulation program have indicated that as the capacity of the animal production unit increases the approximate net cost of owning and operating the waste treatment and disposal system per animal produced declines at a decreasing rate. This result is illustrated in Figure 40.
Figure 39: Effluent Substrate Concentrations Corresponding to Constant and Varying Mixed Liquor Waste Rates
Figure 40: Relationship of Animal Production Unit Capacity to Net Cost of Waste System and Required Reactor Volume
Data plotted in Figure 40 are from a series of computer simulation program runs made for a system located on a 600 acre farm producing 400 acres of corn and 90 acres of soybeans. One hundred and ten acres of the farm land were uncultivated each year. The effluent COD goal for the treatment plant was set at 1500 mg/l and a design temperature of 20°C was used. The sludge storage tank was required to have a 30 day storage tank capacity and an attempt to begin hauling operations was made each time the storage tank was 20 percent full. One liquid manure wagon with a capacity of 4164.0 l (1100 gal) was used to empty the sludge storage tank.

The declining net per animal cost illustrated in Figure 40 reflects the fertilizer value of the increasing amount of animal waste material applied to the fields as well as the declining per unit construction cost as the size of the system increases. A linear increase in reactor volume, as illustrated in Figure 40, is to be expected since the quantity of waste to be treated is directly related to the number of animals present.

Systems Without Biological Treatment Plants

With respect to systems that consist only of liquid manure storage and field disposal, the computer simulation program has been used to examine four different relationships. These relationships are:

1. the effect of the production unit capacity on the net cost of the disposal system;
2. the effect of the operating criteria of when to initiate hauling operations on the quantity of storage tank overflow and the number of overflow events;

3. the effect of the level of storage capacity on the quantity of storage tank overflow;

4. the effect of variations in the simulated precipitation occurrences on the results of the computer simulation program.

Runs with the computer simulation program for studying each of these relationships were made for a swine production unit located on a 200 acre farm planted to 100 acres of corn and 90 acres of soybeans, with 10 acres being uncultivated each year. Unless altered as an aspect of one of the relationships being studied, the production unit capacity was 500, one liquid manure wagon with a capacity of 4164 liters (1100 gallons) was used, and the storage tank had capacity for storing 90 days of waste production. Hauling operations were normally undertaken each time the storage tank was 80 percent full.

**Net Cost**

Results of the computer simulation program runs have shown that as the production unit capacity increases the net cost per animal produced declines at a decreasing rate. This result is illustrated in Figure 41, where the results from 5 year periods of simulated operation of the system are plotted.

The decline in net annual cost reflects the fertilizer value of the increasing quantity of animal waste that is applied to the farm land and the decline in per unit construction cost as the size of the storage
Figure 41: Relationship of Animal Production Unit Capacity to Storage Tank Volume and Net Cost of Liquid Manure System

Approximate Net Cost of Disposal System Per Animal Produced ($)

DSTOR = 90.0
HFLG = 0.80
tank increases. The linear increase in the storage tank volume illustrated in Figure 41 reflects the direct relationship between the number of animals and the quantity of waste produced.

Criteria for Initiation of Hauling Operations

Results of several five year simulation runs with the program show that storage tank overflow is reduced as the amount of material that is allowed to accumulate in the tank before hauling operations are attempted is reduced. This result is illustrated in Figure 42.

From Figure 42 it can be seen that as the percent of the storage tank that was full when a decision to haul was made increased from 20 to 100 percent, the overflow volume from the storage tank and number of overflow events increased at an increasing rate. Figure 42 also indicates that the fraction of time devoted to hauling operations declined and net annual cost of the waste handling and disposal system increased as the percent of the storage tank that was full when the decision to haul was made increased. The decline in hauling time reflects the decline in the quantity of material hauled as the overflow volume increased, since the material that overflowed was not hauled onto the fields. The increase in net annual cost is a result of the loss of fertilizer value of the material that overflowed.

Storage Capacity

In connection with the relationship discussed above, the computer simulation program has also shown that increasing the number of days of storage capacity, without altering any other operating criteria, will
Figure 42: The Effect of Hauling Initiation Criteria on Storage Overflow, Hauling Time and System Annual Net Cost
not always reduce the magnitude of storage tank overflow. In fact as shown in Figure 43, an increase in the number of days of storage capacity may increase the overflow.

The data plotted in Figure 43 was developed from 5 year simulation runs during which the criteria for initiating hauling operations was kept constant at 80 percent. In other words, no attempt to empty the tank was made until it was 80 percent filled.

The decrease in overflow followed by an increase as the number of days of storage capacity increases reflects two sets of circumstances. One is that with a short term storage facility, capacity to hold the produced waste until weather or crop conditions improve does not exist. The other is that facilities with long term storage capacities are able to hold the produced waste for long periods of time and thus miss opportunities for hauling the waste onto the cropland.

The information presented in Figure 43 also shows that the net cost per pig produced increases as the number of days of storage capacity increases. The increase in net cost reflects the increased cost to construct the larger storage tanks. An overall conclusion that may be drawn from Figure 43 is that there is an optimum number of days of storage capacity which if exceeded, produces an increase in net cost that may be accompanied by a decline in service.

Of course the specific relationships shown in Figure 45 apply only for the conditions under which the computer simulation program was run. Each set of conditions (i.e., cropping programs, size and number of hauling wagons, etc.) will probably be associated with a particular set of
Figure 43: Relationship of Days of Storage Capacity to Overflow Volume and Net Cost of Waste Disposal System
relationships. The computer simulation program can be useful in deter­
mining the various relationships.

Precipitation

In order to observe the effect of variations in rainfall occurrences
on the results of the computer simulation program, the computer runs from
which the data plotted in Figure 43 were obtained were repeated for a
different five year period that had a different precipitation history.
(The precipitation history was altered by changing the entry in columns
53 through 55 on data card type 10, card number 6.) Results from the
repeated series of computer runs and the average precipitation history
for each of the five year periods are presented in Figure 44 and 45
respectively.

As shown in Figure 44, the repeated series of computer runs also
indicate that the overflow volume may be increased by an increase in
storage capacity. However, the specific overflow volumes associated with
each storage capacity are different for the two sets of computer runs.
Since the only difference between the two sets of runs was the precipi­
tation, it can be concluded that variations in the simulated precipita­
tion events will affect the specific results produced by the computer
simulation program.

It is therefore evident that precipitation is an important variable
in the design and operation of livestock waste storage and field spread­
ing systems. The ability of the computer simulation program to readily
simulate precipitation events facilitates the performance of experiments
to investigate the effects of different precipitation sequences.
Figure 44: Relationship of Days of Storage Capacity to Overflow Volume

BRNCAP = 500.0
HFLG = 0.80
Figure 45: Precipitation History for Two Five-Year Simulation Periods
CONCLUSIONS AND RECOMMENDATIONS

This study was undertaken for the purpose of developing a computer simulation program to simulate the operation of a biological treatment and cropland disposal system for waste from a confinement swine production unit. The computer simulation program has been developed to a satisfactory degree and can now be used to study numerous swine waste treatment and disposal situations.

Specific Conclusions

1. The rainfall and soil trafficability simulation technique used in the computer simulation program functioned to provide a simulated field access schedule comparable with real field access data.

2. The animal population simulation procedure used in the computer simulation program produced population variations similar to variations observed in a real population.

3. Microbial kinetic parameters developed from the laboratory bench scale treatment system and the theoretically determined design concepts enabled the computer simulation program to calculate reactor volumes that compared favorably with volumes determined from conventional design criteria.

4. A study made with the computer simulation program indicates that, for a given waste stream, if the effluent COD is kept constant
the mass of mixed liquor VSS in the reactor remains constant for all reactor volumes. This indicates that too small a reactor will lead to a high mixed liquor suspended solids concentration that will cause plant operating difficulties.

5. Studies with the computer simulation program also indicate that it is economically feasible to empty a liquid manure storage tank of moderate volume more frequently than it is to provide larger storage volumes.

Specific Recommendations for Continuing Research

The computer simulation program developed in this study has proven to be effective in the investigation of the design and operation of treatment and disposal systems for waste from a confinement swine production unit. It is now possible to use the program to aid in the design of waste systems for numerous situations. It is recommended that as a research application the computer program be used in a comprehensive investigation to develop a series of graphs that describe the relationship between the design and operating parameters for a range of situations. Some specific recommendations for graphs are a set of curves which relate:

1. Reactor volume to maximum mixed liquor VSS for a range of effluent COD standards, and production unit capacity.

2. Production unit capacity to net annual cost for a range of effluent COD standards.

3. The percent of a storage tank that is filled when a decision to haul is made to overflow volume for a range of days of storage capacity, production unit capacity, and cropland acreage.
4. The number of liquid manure wagons to the percent of time
devoted to hauling operations for a range of wagon capacity,
storage capacity, and production unit capacity.

In addition to developing graphs for swine units as suggested above,
it is also recommended that the necessary parameter values be obtained so
that the computer program may be expanded to other types of animal units.
APPENDIX A

DESCRIPTION OF INPUT DATA CARDS
FOR THE COMPUTER PROGRAM
DESCRIPTION OF INPUT DATA CARDS
FOR THE COMPUTER PROGRAM

Each of the input data cards required by the computer program is described below. The type of information, its location on the card, and entry format is presented for each card.

Table 5. Details of Input Data Cards For Non-GASP Variables

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25-27 0.0
31-40 Time for end of simulation in F10.4 format
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48-50 567
53-55 567
15-18 0.01
25-27 1.0
35-37 0.0
15-17 7.0
25-27 4.0
55-57 2.0
14-17 30.0
25-27 4.0
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APPENDIX B

THE COMPUTER PROGRAM VARIABLES
THE COMPUTER PROGRAM VARIABLES

The computer program symbols are defined below. The meaning of any symbol that does not appear here is obvious in the computer program itself. Symbols preceded by an asterisk must be initialized, i.e., values provided by user.

*ACRE - Total quantity of cropland available for application of livestock waste (acres). Value to be provided by program user.

ACUM - Internal program variable used in calculation of monthly average mixed liquor waste rate.

*AERCAP - Aeration capacity of aerator (1.36 Kg of O₂/HP-HR).

AGST - Available gravity storage; inches of water above field capacity available for storage.

ANCST - Annual cost of system; includes depreciation, interest, maintenance, treatment plant operation labor, etc. ($/year).

AOFLO (1 YEAR, MONTH) - Storage array for monthly overflow volume.

*BRNCAP - Animal capacity of production unit. Value to be provided by program user.

BRNCST - Estimate of production unit construction cost (dollars)

BRNSIZ - Required floor space in production unit (sq. feet)

*BUS - hauling operations flag; 0 if hauling operations not in progress, 1 if hauling operations are in progress.

*CAPP - Amount of manure or sludge applied to corn land during current production cycle (liters). Initial value of 0.0 is recommended.

CHECK - Internal variable used to zero quantities applied to cropland at end of production cycle.

CLSZP - Surface area of primary clarifier (sq. ft.).
CLSZS - Surface area of waste mixed liquor clarifier (sq. ft.).

CLSZPD - Designed surface area of primary clarifier (sq. ft.).

CLSZSD - Designed surface area of waste mixed liquor clarifier (sq. ft.).

CORFCT - Temperature correction factor for biological kinetic constants.

*CORN - Acreage planted to corn (acre). Value to be provided by program user.

CMAX - Maximum amount of manure or sludge that can be applied to corn land during one production cycle (liters).

*CSTNDX - C. E. Plant cost index for current year. Value to be provided by program user.

*DAY - Elapsed time of current month (days). Initial value of 0.0 recommended.

*DESTMP - Temperature used in biological reactor design calculation (degree centigrade). Value to be provided by program user.

*DSTOR - Desired number of days for storing all sludge or manure produced (days). Value to be provided by program user.

EAT - Rate of substrate consumption by cells (Kg/day).

EM - Biomass maintenance energy constant (mg substrate consumed/mg cells present/day).

*EMD - Experimental value of biomass maintenance energy constant (0.11 mg substrate consumed/mg cells present/day).

EVAP - Daily loss of water from soil by evapotranspiration (inches).

*FALLOW - Cropland that is kept out of production for current production cycle (acre). Value to be provided by program user.

FAPP - Amount of manure or sludge applied to fallow land during current production cycle (liters).

*FLDCAP - Inches of water in top two feet of soil when soil is at field capacity (inches). Value may be found in Appendix D.

*FLUSH - Volume of flush water required; 72.6 liter/animal/day if recycle water used for flushing, 6.06 liter/animal/day if recycle water not used for flushing.
*GAPP - Amount of manure or sludge applied to forage land during current production cycle (liters). Initial value of 0.0 is recommended.

GK - Biomass specific growth rate constant (liter/day/mg).

*GKD - Experimental value of biomass specific growth rate constant (5.6 x 10^-4 liter/day/mg).

GMAX - Maximum amount of manure or sludge that can be applied to forage land during one production cycle (liters).

*GRASS - Acreage planted to forage crops (acres). Value to be provided by program user.

GROWTH - Growth rate of cells (Kg/day).

*GST - Gravity storage; inches of water above field capacity stored in soil (inches). Initial value of 0.0 recommended.

*HCAP - Capacity of liquid manure tank wagon (liters). Value to be provided by program user.

HCST - Estimated cost of liquid manure tank wagon (dollars).

*HFLG - Haul flag, percent of storage tank filled when decision to start hauling is made. Value to be provided by program user.

HLTM (I YEAR) - Storage array for annual time spent hauling sludge or manure.

*I - Integer defining current day of year (day). Initial value of 1 is recommended.

*1OP - Waste rate option; 1 if mixed liquor waste rate to be held constant at value calculated for design conditions, 2 if mixed liquor waste rate necessary to maintain a constant effluent COD is to be determined at each treatment event, 3 if monthly average mixed liquor waste rate is to be read from storage.

*IRAIN - Daily precipitation history; 1 if it did not rain, 2 if it did rain. Initial value of 1 is recommended.

*IWET - Soil trafficability condition; 1 if cannot haul, 0 if can haul. Initial value of 1 is recommended.

*IYEAR - Current year of simulation period. Initial value of 1 is recommended.
IYR - Internal variable used in calculation of monthly average effluent substrate concentration and mixed liquor waste rate.

KOUNT - Internal variable used in calculation of monthly average effluent substrate concentration and mixed liquor waste rate.

L - Twice the maximum travel distance for transporting a wagon load of sludge or manure to the cropland (ft.).

M - Internal variable used in calculation of monthly average effluent substrate concentration and mixed liquor waste rate.

*MONTH - Integer defining current month of year (month). Initial value of 1 is recommended.

*NWAG - Number of liquid manure tank wagons. Value to be provided by program user.

*OFLO - Storage tank overflow flag; 0 if storage tank will hold all the material that needs storing, 1 if an attempt has been made to store more material than the storage tank can hold. Initial value of 0 is recommended.

OXYG - Daily oxygen requirement of biomass (Kg O₂/day).

*PE(MONTH) - Storage array for average daily evapotranspiration loss of water from soil (expressed in inches). Values may be found in Appendix D.

PIG - Number of animals in the production unit.

PNTCST (IYEAR) - Array for storing estimate of net annual cost in dollars of owning and operating the treatment and disposal system.

*PRODM - Quantity of manure produced per animal per day (6.43 liter/animal/day).

QAPP (IYEAR,MONTH) - Storage array for quantity of sludge applied to cropland each month (liters)

QAPPYR(IYEAR) - Storage array for quantity of sludge applied to cropland each year (liters).

QF - Flush water flow rate (liter/day).
QFAPP - (IYEAR, MONTH) - Storage array for quantity of sludge applied to fallow land each month (liters).

QW - Daily volume of reactor mixed liquor from which the sludge is wasted (liter/day).

QWD - Design mixed liquor flow rate for sludge wasting (liter/day).

*QWMAX - Greatest average monthly mixed liquor flow rate for sludge wasting (liters/day). Value may be determined from a program run with I0P and TRMT set equal to 2 and 1 respectively.

QWMIN - Smallest average monthly mixed liquor flow rate for sludge wasting (liters/day). Value may be determined from a program run with I0P and TRMT set equal to 2 and 1 respectively.

*QWSLCT (MONTH) - Storage array of mixed liquor flow rate for sludge wasting to be used each month (liters/day). Values may be determined from a program run with I0P and TRMT set equal to 2 and 1 respectively.

QWST (IYEAR,MONTH) - Storage array for monthly average mixed liquor flow rate for sludge wasting that is calculated by program under the waste rate option, I0P = 2 (liters/day).

*RAIN (MONTH) - Array which contains the average number of inches of rainfall for a precipitation event during each month. Values may be found in Appendix D.

*RARCP - Aeration capacity of rotor (0.59 KgO2/HR - FT)

*RNPROB(I, IRAIN) - Storage array for daily rainfall probabilities. Values may be found in Appendix D.

ROTSIZ - Length of aeration rotor required (ft.).

*S - Substrate (COD) concentration of reactor mixed liquor and effluent (mg/l). Initialize at the value of the treatment plant effluent goal.

*SBAPP - Amount of manure or sludge applied to soybean cropland during current production cycle (liters). Initial value of 0.0 is recommended.

*SBEAN - Acreage planted to soybeans (acres). Value to be provided by program user.

SBMAX - Maximum amount of manure or sludge that can be applied to soybean cropland during one production cycle (liters).
\*SCSEF - Fraction of substrate (COD) in total waste stream diverted with the solids discharged from the liquid-solid separator; 0.25.

\*SCSLEF - Fraction of volatile solids in total waste stream that is diverted to storage by the liquid-solid separator; 0.25.

SCUM - Internal program variable used in calculation of monthly average substrate concentration, COD, of treatment plant effluent.

\*SCVEF - Fraction of total waste stream diverted as solids by liquid-solid separator; 0.0101.

SG - Desired substrate concentration, COD, of treatment plant effluent (mg/l).

SHYDR - Rate of soluble substrate, COD, production by hydrolyzation of solids (Kg/day).

\*SI - COD of the waste produced in the production unit (67638 mg/l).

SIN - Rate of substrate inflow to reactor (Kg/day).

SIR - COD of the influent to the reactor (mg/l).

\*SOILTY - Soil type; 0 if soil is plastic, 1 if soil is non-plastic (sandy).

\*SOL - Volume of solids in storage tank (liters). Initial value of 0.0 recommended.

SOLIN - Solids discharge rate from liquid-solid separator (liters/day).

SOUT - Substrate effluent rate from reactor (Kg/day).

\*SPACE - Space requirement in production unit for each animal (7.0 FT²/animal).

SST(IYEAR,MONTH) - Storage array for monthly average substrate concentration, COD, of treatment plant effluent (mg/l).

\*ST - Soil moisture storage; inches of water in top two feet of soil that does not flow in response to the force of gravity. Choose initial value to be less than or equal to FLDCAP.

STOR - Capacity of storage tank (liters).

STRCST - Estimated capital cost of storage tank (dollars).

SV - Quantity of substrate, COD, in reactor (Kg).
T - Temperature of reactor mixed liquor (degree centigrade), also fraction of influent volatile suspended solids that are not hydrolyzed.

*TAPP - Amount of manure or sludge applied to all cropland during the simulation period (liters). Initial value of 0.0 is recommended.

TB - Beginning time of hauling operation (day).

*TEMP(MONTH) - Storage array for inputting average monthly temperature of reactor mixed liquor (degree centigrade). Values may be found in Appendix D.

TFL0 - Flow rate of total waste stream from the production unit (liter/day).

TFLOD - Total waste flow from production unit determined from design conditions (liters/day).

*TIME - Cumulative time since beginning of current year of simulation (days). Initial value of 0.0 is recommended.

TMTCST - Estimated capital cost of treatment plant, includes reactor, clarifiers, aerator, pumps, etc. (dollars).

TOTCST - Estimated capital cost of total system (dollars).

TPRCIP (IYEAR, MONTH) - Storage array for total monthly precipitation (inches).

*TRMT - Treatment option flag; 0 if no treatment is to be used, 1 if biological treatment is to be used. (Note: When TRMT is changed, the value of FLUSH and VALUE should also be changed to be compatible with the modified system).

TRMLBR - Estimated cost of labor to operate the treatment plant (dollars/year).

TT - Time duration of overflow period (day).

TTB - Beginning time of overflow period (day).

U - Microorganism specific growth rate (day\(^{-1}\)).

V - Volume of the reactor (liter).

*VALUE - Fertilizer value of manure or sludge; $0.00028 per liter for systems with biological treatment, $0.00042 per liter for systems without biological treatment.
WAPP - Amount of manure or sludge applied to wheat land during current production cycle (liters). Initial value of 0.0 is recommended.

WASTE - Rate of biomass removal from system (Kg/day).

WET(IYEAR, I) - Array in which daily soil trafficability condition is stored.

WHEAT - Acreage planted to wheat (acres). Value to be provided by program user.

WMAX - Maximum amount of manure or sludge that can be applied to wheat land during one production cycle.

WRTBL - Moisture balance; inches of water in top two feet of soil (inches). Initial value should be less than or equal to FLDCAP.

X - Volatile suspended solids concentration of reactor mixed liquor (mg/l). Initial value should be 6000.0.

XHYDR - Rate of hydrolyzation of influent volatile suspended solids in the reactor (Kg/day).

XI - Volatile suspended solids concentration of waste produced in animal production unit (69000 mg/l).

XIN - Rate of volatile suspended solids inflow to the reactor (Kg/day).

XIR - Volatile suspended solids concentration of inflow to reactor (mg/l).

X0 - Concentration of viable organisms in the reactor mixed liquor (mg/l).

XOV - Mass of viable organisms in the reactor (Kg).

XV - Quantity of volatile suspended solids in reactor (Kg).

Y - Microorganism yield coefficient (mg cells formed/mg substrate consumed).

YD - Experimental value of microorganism yield coefficient (0.21 mg cells formed/mg substrate consumed).
APPENDIX C

REPRESENTATIVE CLIMATIC AND SOIL DATA FOR
USE IN THE COMPUTER PROGRAM
Table 7. Values of the Computer Variable RAIN(MONTH) For Three Locations in Ohio

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aInformation in this table was estimated from data in the references by Feyerhern, et al. (1966) and U. S. Department of Commerce (1972).
Table 8. Values of the Computer Variable TEMP(MONTH) For Three Locations in Ohio

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*aInformation in this table was estimated from data in the reference by the U. S. Department of Commerce (1972).*
Table 9. Values for the Computer Variable PE(MONTH) for Three Locations in Ohio

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*Information in this table was obtained from the reference by Thornthwaite, et al. (1958).*
Table 10. Values of the Computer Program Variables RNPROB(1,1) and RNPROB (1,2) For Three Locations in Ohio

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Information in this table was taken from the reference by Feyerherm, et al. (1966).
Table 11. Values of the Computer Program Variables FLDCAP and SOILTY for Ten Ohio Soils

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</tr>
<tr>
<td>Morely silt loam</td>
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*aInformation in this table was calculated from data provided by the Soil Physical Characterization Laboratory at The Ohio State University.*
APPENDIX D

PROCEDURE FOR CHEMICAL OXYGEN DEMAND AND SUSPENDED SOLIDS DETERMINATIONS
PROCEDURE FOR OXYGEN DEMAND DETERMINATION

1. Place 25 ml of oxidizing agent in a 125 ml Erlenmeyer flask. Add about 0.05 grams of silver sulfate.

2. Add appropriate ml of sample (usually between 1.0 and 5.0 ml) so that COD will be between approximately 160 and 8000 mg/l. (This assumes a depletion of at least 1 ml and no more than 10 ml).

3. Heat to 165°C within 3 to 5 minutes.

4. Transfer contents of 125 ml flask to a 500 ml Erlenmeyer flask. Rinse 125 ml flask several times with 200 ml of distilled water, transferring all rinsings to the 500 ml flask.

5. Let sample come to room temperature.

6. Add 5 drops of ferroin indicator to the flask.

7. Titrate with 0.1 N Fe \((SO_4)_2(NH_4)_2\) until light blue color changes to brick red. (Initial color after ferroin addition should be yellow).

8. Carry out steps 1 through 7 on a blank using 5 ml of distilled water as the sample.

\[
\text{COD} = \frac{(\text{Blank titer} - \text{Sample titer}) (\text{N of Fe}(SO_4)_2(NH_4)_2)(8000)}{\text{ml sample used}}
\]

REAGENTS FOR COD DETERMINATION:

1. Oxidizing agent: 500 ml of conc. sulfuric acid, 500 ml of conc. phosphoric acid, and 2.5 grams of potassium dichromate. Dissolve the dichromate in about 25 ml of water before adding the acid.

2. FERROUS Ammonium sulfate: Dissolve 39 grams of ferrous ammonium sulfate in distilled water, add 20 ml of conc. sulfuric acid, and
then make mixture up to one liter with distilled water.

3. Ferroin indicator: Dissolve 1.485 grams of 1.10 phenanthyoline monohydrate, together with .695 grams of FeSO₄·7H₂O in water and dilute to 100 ml.
PROCEDURE FOR SUSPENDED SOLIDS DETERMINATION

1. Place 40 ml of sample into a centrifuge tube and centrifuge for 10 minutes at 4200 RPM.

2. Decant centrate and wash solids from centrifuge tube into a crucible of known weight with distilled water.

3. Place crucible into 103°C oven for 12 to 16 hours.

4. Weight crucible and dry solids, and calculate total suspended solids (TSS) concentration as:

   \[
   \frac{\text{Weight of crucible and solids} - \text{Weight of crucible}}{40 \text{ ml}}
   \]

5. Place crucible into 600°C oven for 30 minutes.

6. Weigh crucible and fixed solids and calculate fixed suspended solids concentration (FSS) as:

   \[
   \frac{\text{Weight of crucible and fixed solids} - \text{Weight of crucible}}{40 \text{ ml}}
   \]

7. Calculate volatile suspended solids concentration (VSS) as:

   \[
   \text{TSS} - \text{FSS} = \text{VSS}
   \]
APPENDIX E

DATA OBTAINED FROM THE BENCH SCALE TREATMENT SYSTEM FOR DETERMINATION OF MICROBIAL KINETIC PARAMETERS
Table 12. Weight Averaged Experimental Data From Bench Scale Model Tests

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<th>Q/V (day^-1)</th>
<th>S_i (mg/l)</th>
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\(^a\)Multiply by 10.9 to convert to 1/day.
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REFERENCES CITED


Taiganides, E. Paul and Richard K. White. 1971. Automated Handling, Treatment and Recycling of Wastewater From an Animal Confinement

