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Input-Output Analysis of Various Elements of an Energy-Agro-Waste Complex

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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INPUT-OUTPUT ANALYSIS OF VARIOUS ELEMENTS
OF AN ENERGY-AGRO-WASTE COMPLEX

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for

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Washington, D.C. 20545

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FOREWORD

It has been recognized that, because of power cycle operating conditions, nuclear power plants reject more waste heat per unit of electricity produced than comparable fossil stations. Because the waste heat problem is more severe for nuclear power stations, research in the area of beneficial uses of waste heat has been sponsored for a number of years by the Advanced Nuclear Systems and Projects Division of DOE (formerly Nuclear Research and Applications Division of ERDA).

These studies have considered various uses for power plant reject heat and have centered on agricultural applications. Some of this agricultural work has been carried out in a cooperative program with the Tennessee Valley Authority (TVA). This work is continuing with a 0.5 acre demonstration greenhouse being constructed by TVA at the Browns Ferry Nuclear Station. This greenhouse is based on a DOE-supplied design, and a combined DOE-TVA report concerning this project will be issued after the greenhouse has been in operation for a growing season.

During the course of the beneficial uses investigations, it became evident that multiple-use facilities (i.e. incorporating more than one utilization technology) would be extremely important if waste heat utilization is to be implemented on a significant scale. It was also clear that the potential existed for a number of mass as well as energy interactions between the individual subsystems of such a complex. A few existing studies had examined the relative sizes of the subsystems by merely accounting for their energy consumption. However, no existing studies sought to analyze a highly integrated facility. This study was,

therefore, initiated to provide a comprehensive data base and develop a methodology for designing and analyzing highly integrated waste heat utilization complexes. As a first step, the analysis concentrated on possible mass interactions between components of the complex.

This work was carried out under contract with Oak Ridge National Laboratory, Contract No. 11Y-13549V.

This study was conducted under the direction of Dr. Luis F. Diaz and Dr. Clarence G. Golueke. Data collection and analysis were performed by Mr. Stephen Blumenkranz and Dr. John C. Glaub. Drs. Diaz, Golueke, and Glaub are the principal authors of this report. The manuscript was typed and edited by Mrs. Linda Eggerth and Mrs. Janice Hirshfield.

The Project Officer was Dr. Mitchell Olszewski.

ABSTRACT

The mass input and output streams of various agricultural and waste treatment processes were quantified and models developed to serve in the engineering analysis of potential waste heat utilization schemes. The unit process models can be integrated into energy-agro-waste complexes, in which waste heat from power plants is used by certain processes and the wastes of some processes are used as inputs to others. The models provide a means of determining the sizing of subsystems, the compatibility of subsystems, and the overall feasibility of an integrated complex. Ten potential complexes were qualitatively discussed and the considerations involved in forming such complexes explained. A mass balance analysis was performed on four integrated complexes demonstrating the engineering value of the analytical models developed.

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INTRODUCTION

Background

The growing urgency of the conservation of materials and energy provides the motivation and underlying direction for making an in-depth examination of the means traditionally used in the supply of the nation's food, energy, and services. In a simplistic but functionally descriptive sense, the population center or community requires energy, food, and various goods; and as a result of these produces a host of wastes in the form of solids, liquids, gases, and energy (principally as heat). Currently, the needs are supplied by individual, usually self-contained entities. The majority of these entities require primary ("virgin") materials and generate wastes and pollutants in the course of producing their products or providing their service. Systems have been identified, however, in which waste heat from a power plant can be used in concert with other "waste" streams to produce valuable products. The use of secondary sewage effluent in a waste heat aquaculture system is an example of the food production capability that can be realized when waste heat is combined with one or more organic waste streams. Using waste heat to enhance methane production from sewage sludge digesters is but one example of the energy production possibilities when such waste streams are combined.

The concept of the combined utilization of waste heat and of the plant nutrients in wastes is not a novel one. It was in fact discussed as early as 1956. As interest in the subject developed, the realization

came to many researchers that the most efficient approach to the combined utilization would be one that included a diversity in the nature of the constituent unit processes, so that the variety and amount of wastes capable of being used would be magnified.

Thus far, the majority of activity in modeling energy-agro-waste systems has been concentrated on the analysis of condenser cooling water utilization systems. The concentration stemmed from the fact that the input-output characteristics of the thermal elements are fairly well defined, whereas the nonthermal elements in the system either have not been defined or are only beginning to be characterized.

The proper identification of the input-output characteristics of the energy-agro-waste complex subsystems would make it possible to: 1. further develop and quantify predictive techniques that are of use in determining the compatibility of various waste processing and low-grade heat utilization systems from a material and energy resource viewpoint; 2. provide quantitative insights into the various aspects of siting goods and service and energy production facilities; and 3. allow for the planning of possibilities for retrofitting existing facilities with recovered materials and energy forms.

Thus far, few attempts have been made to arrive at a suitable relative sizing of the operations that would be used. In the present study, the establishment of the sizing is advanced to a point at which hopefully a choice of relative sizing and estimate of feasibility can be made on a more rigorously quantitative basis than could be done heretofore. The advance was made in part by establishing as far as possible the pathways of the primary nutrients, namely, nitrogen, phosphorus, and potassium (N,P,K).

Objectives

The objectives of this study were to define and catalog the input-output streams of major subsystems that could be included in an integrated energy-agro-waste complex and to develop models of candidate complexes. The objectives also included the identification of techniques to process waste streams into energy or product forms compatible with the various components of a complex. Thus, a primary purpose of the study was to explore physical possibilities of integrating various systems for optimizing energy and waste utilization. In so doing, the waste systems and processing techniques that were considered were those compatible with various techniques for the utilization of power plant waste heat that could be included as an input in a complex (i.e., organic wastes and biological treatment).

Procedure

Subsystems that had potential for inclusion in energy-agro-waste complexes were selected, and their input-output streams were identified and characterized. The characterization of input-output streams required information crossing the lines of many branches of science. Thus, an extensive multi-disciplinary literature search was conducted and quantitative information gathered on the various energy, agricultural, biological and waste processes under consideration. This literature search was conducted in several stages, with increasing extensiveness as the project progressed. The nature of the data which included wide ranges of reported values, as well as a lack of data on certain parameters, directed the course of these efforts. Private communication with researchers around the country was frequently required.

Analysis of the data was also influenced by the nature of the data, and consequently several assumptions had to be made. These were as follows: 1. Waste heat is available in sufficient quantity and is transferable at a price that permits all processes to operate at optimum temperature. 2. It is valid to use average values for variables in many processes despite seasonal, geographical, life cycle, and observable differences. 3. Biological processes can be adequately characterized by only a few of their grossest inputs and outputs. 4. Published data can be reasonably adjusted within limits of reported ranges to reconcile inputs and outputs without significantly affecting the validity of the overall model. 5. All processes are at steady-state conditions, and therefore for any given process, input and output should agree.

Early in the study it became apparent that total solids, nitrogen, phosphorus, and potassium should be accounted for in all calculations, i.e. whenever it was possible to do so. Although other elements, such as calcium, magnesium, and sulfur may occur in significant quantities, they are less likely to be limiting. In the present study it is assumed that all required trace elements are present, either by way of the input wastes or through maintenance additions. Where the inclusion of a water balance was essential, one was made.

The subsystems were first analyzed as unit processes and their mass and energy inputs and outputs identified accordingly. Applying block diagrams (from control theory) to these unit processes served as a convenient means of both expressing and analyzing the inputs and outputs. Limitations in data for certain parameters were also exposed, although with a combination of parameters most gaps in the data can be abridged.

After the unit processes were developed, they were integrated into complexes accounting for the magnitudes of the compatible mass and energy flows. The integrated complexes were then analyzed to determine their utility in estimating relative sizes and feasibility.

UNIT PROCESS MODELS

Various unit processes were selected that would lend themselves to a variety of integrated energy-agro-waste complexes. They were chicken rearing, cattle rearing, swine rearing, aquaculture (fish and algae), crop production (greenhouse and open field), wastewater treatment, and anaerobic digestion (methane production). The criteria used in their selection were their having been demonstrated technically feasible and their being either actually or potentially economically feasible.

A first step in characterizing a unit process is to identify inputs to and outputs from the system. Having identified the input-outputs, the next step is to quantify them, so as to be able to arrive at mass and energy balances. Typical inputs are: 1. radiated and converted heat energy applied to maintain a desired temperature level; 2. electrical and mechanical energy; 3. nutrients (either in the form of waste or of a primary material and in a usable form); 4. drinking water and process water; and 5. oxygen and carbon dioxide. Typical outputs are: 1. heat loss (conductive-convective, evaporative, radiated); 2. water loss (throughput, evaporated, transpiration (leafy plants, blowdown); 3. waste solids (vegetation slash, manure, slaughterhouse wastes, etc.); 4. dissolved solids (BOD, COD, salts); 5. gases (O_2 , CH_4 , CO_2 , N); and 6. food products (amount/area or volume).

Among items not mentioned in the preceding paragraph, but which would require attention with certain unit processes are: 1. optimal temperature;

2. stock or growth density; 3. length of growth-harvest-restock cycle; and
4. feed-to-growth and waste-to-food ratios.

To facilitate the collection of data on the various inputs and outputs and making mass balances, a model of a unit process is an important first step. The model serves as a guide in selecting representative or reasonable values from a reported range of values and for interrelating the collection of input-outputs. It also provides a guide for the collection of data. To make valid mass balances and to develop a comprehensive model, it is necessary to have some unit of process volume to which each input and output could be related. Such a unit could be expressed as per animal, per areal unit, or per heat dissipation unit.

A useful generalized diagram showing an arrangement of inputs and outputs is presented in Figure 1. Each input is expressed in terms of mass (M_{i1} , M_{i2} , etc.) and of energy (E_{i1} , E_{i2} , etc.). Correspondingly, each output is expressed in terms of mass (M_{o1} , M_{o2} , etc.) and of energy (E_{o1} , E_{o2} , etc.). Mass balances are expressed as $\Sigma M_i = \Sigma M_o$, and energy balances as $\Sigma E_i = \Sigma E_o$. On-site grain and food processing are assumed for certain cases, such that wastes and crops may be available as inputs to other processes.

Unit Processes for Animal Production

For the unit processes pertaining to animal production (poultry, cattle, swine, and fish), a procedure was established with which it was possible to reconcile or to rationally select values from the reported data, especially in those instances in which a wide range of values is given. The procedure is outlined in Table 1. The statements in the table are based on the usual manner of tabulating nutritional information. Tables

Figure 1. Generalized diagram of typical inputs and outputs of a unit process.

Table 1

Procedure for Determination of Input and
Output Data for Animal Production

1. Find final weight and life span. These data will be subsequently used to determine lifetime average values for various parameters.
2. Find feed conversion ratio.
3. Find daily consumption of feed.
4. Characterize solid fraction of feed and metabolizable energy content of feed.
5. Find total metabolizable energy content in feed.
6. Find water intake.
7. Find tissue storage (weight increase) per day.
8. Characterize solid and liquid fractions of tissue.
9. Find energy content of tissue and determine energy stored per day.
10. Determine O_2 consumption and CO_2 production.
11. Find solid waste production per day.
12. Characterize waste composition.
13. Perform mass balance on solids.
14. Find water losses by various processes.
15. Perform mass balance on water.
16. Find heat losses.
17. Find environmental requirements.

containing the values for the input and output parameters of various unit processes are located in Appendix A.

CHICKEN PRODUCTION

The first of the animal groups for which mass balances were made was the chicken. Chicken raising, whether it be for egg or for meat production, has been developed to become a very systematic process geared to a factory-style operation. Thus, relatively sound data are available on optimum temperatures, on the temperature dependence of latent vs. sensible heat loss, and on defined feed, manure, and water characteristics.

A representative mass balance diagram for the mass production of chickens is given in Figure 2. In developing the model, averages were made for an age-distributed flock of broilers that mature (in 75 days, average) at 1.36 kg (3 lbs) per bird, and have a feed conversion ratio of 2.6:1 on feed that has an energy content of 12.6 MJ/kg. The values in Figure 2 apply to an operation maintaining the temperature in the chicken house at 25⁰ C. The body temperature of the individual birds was 41⁰ C. Data from which the values given in the figures were derived are presented in Tables A1 and A2. Table A1 deals with input amounts and rates into the subsystem, while Table A2 lists outputs. The data in the two tables confirm the statement made in the previous section concerning the wide range of values reported in the literature on animal production.

BEEF PRODUCTION

As with chicken production, data pertaining to steer production are abundant and quite reliable. Another similarity is in the concentration of the animals in confined quarters during a part of their lifespan (steers) or during the entire lifespan (chickens). In practice, feeder

Figure 2. Mass balance diagram for chicken production.

cattle typically are brought to feedlots when they attain a weight of 340 kg (750 lbs). They are then fed over a 5-month period and then slaughtered, at which time their weight averages 500 kgs (1100 lbs).

A mass balance diagram for beef production is presented in Figure 3. The internal flow lines describe the redistribution of certain input elements. The input data used are listed in Table A3, and output data used are presented in Table A4.

PORK PRODUCTION

A considerable diversity exists between values reported for specific inputs and outputs involved in pork production. This is partially due to the wide variety of diets suitable to swine. The diagram for mass balances as presented in Figure 4 represents an average of (or perhaps compromise between) these reports. Input data used in arriving at the balances are listed in Table A5 and output data in Table A6.

FISH PRODUCTION

Aquaculture in the form of fish production is an old practice in the Orient and is receiving increasing attention in this country. While carp constitute the favorite subjects for fish farming in the Orient, in the U.S., the two types of fish most widely grown are the catfish and trout. Catfish is a favorite because it is a "warm water" fish and is fairly tolerant of adverse conditions, and yet its meat is considered to be quite delectable.

Trout are more fastidious in their requirements, but the difficulties encountered in their culture are compensated by the high quality of the fish meat and hence an assured demand for the product.

Figure 3. Mass balance diagram for beef production.

Figure 4. Mass balance diagram for pork production.

The favorite of designers of "closed" food production complexes, however, is the group of fish known as tilapia. Inasmuch as the favorable aspects of tilapia culture are well-known, there is no need to dwell upon them here. Suffice it to point out that tilapia have the advantage of being able to use almost any waste as a source of nutrient and are tolerant of adverse conditions. Moreover, the pond water may consist of 60 to 70 percent seawater (20.2-25.0 percent salinity) without adversely affecting production. The maximum salinity at which they can survive is 53.5 percent, and they reproduce only up to a maximum of 30 percent.⁽¹⁾

Despite being a practice of long standing, precise data founded on scientific observation on fish farming are extremely scarce in the literature. However, sufficient data are on hand to permit the development of plausible systems (especially for catfish, tilapia, and trout). Because of the availability of data on the latter three types, they were selected for attention in the present investigation. Although it was realized at the start the chances of advantageously fitting in trout farming in waste heat utilization schemes are slim, sufficient data were collected to confirm that conviction.

The principal inputs to be considered in tilapia, or for any fish culture, are water, feeds, oxygen, heat, and electric power for the pond operation. The type of feed required varies with the fish being raised. For instance, in tilapia culture, the range may be from manures to algae or protein pellets. Oxygen demand ranges from 22-38 mg/100 g body weight for tilapia (a "warm water" fish) to 49-80 mg/100 g body weight for trout (a "cold water" fish).⁽²⁾ Heat input, of course, depends upon the temperature requirements of the fish. Trout require relatively low temperatures in that their optimum is from 12 to 16° C.^(3,4) On the other

hand, those temperatures are practically lethal for tilapia.⁽⁵⁾ Their optimum is within a range of 22 to 35° C.⁽⁶⁾ Power requirements will also vary sharply according to the type of fish. Thus, because of the high O₂ demand of trout, their culture involves a far higher degree of pond circulation and agitation than does that of warm water fish.

The principal outputs are fish meat, proteinaceous wastes, and body and metabolic wastes (e.g. manure and CO₂).

Catfish Production

A mass balance diagram for catfish farming is presented in Figure 5. This model is based upon raceway culture. No estimated value is given to the NPK output. In this case, the absence is due to the inability to reconcile the small amount of available data. The input data used in making the balances are listed in Table A7, and output data in Table A8.

Tilapia Production

In the tropics, tilapia culture often is carried out with the use of cages. Several advantages accrue from this practice. The fish remain quiescent instead of being engaged in territorial competition, as occurs when they are crowded in extreme confinement. Moreover the practice simplifies harvesting, since the fish already are segregated according to age. In those cases in which a high mortality rate occurs, the cages must be serviced frequently to protect the surviving fish.

The lower production rates in tilapia culture in the U.S. indicate that this country lags behind other countries, especially the tropics. However, if U.S. researchers were to adopt a more systematic and quantitative approach, the lag would soon disappear. Unfortunately, some of the work being done on tilapia culture seems to be guided by the practices followed in intensive catfish and trout culture. Intensive methods

Notes:

Calculations based on 1 Raceway

1.2 m x 1.2 m x 15 m,

7000 fish at 0.25 kg/fish

$T_{H_2O} = 30^{\circ}C$, $T_{air} = 20^{\circ}C$

* Biological Oxygen Demand

Figure 5. Mass balance diagram for catfish production.

are more dependent upon energy than is the case with commercial fishing, despite the higher concentrations of fish characteristic of intensive culture.

A block diagram of a tilapia-algae production pond showing relations of inputs and outputs based on a report by Olszewski⁽⁷⁾ is shown in Figures 6 and 7; a mass balance for tilapia culture is presented in Figure 7. The balances in the figure are based on reasonable assumptions which could be made from information reported in the literature. No numbers are given for water throughput, because they vary with the conditions under which the pond is operated. A 2:1 food to meat conversion was assumed; such a ratio should be easily attained under optimum conditions. The feed is assumed to be of algae and to have a protein content of 50 percent with an energy value of 18.0 MJ/kg protein, plus a limited amount of complex carbohydrate and lipids. The meat analysis is taken from the generalized analysis given by Spector⁽⁸⁾ for fish. Fecal solids were determined by subtracting meat solids plus oxidized solids from input solids.

Various input and output data related to tilapia culture are listed in Tables A9 and A10 respectively. The wide range of yields listed under that heading in Table A10 is an excellent illustration of the importance of environmental conditions in tilapia production as well as of the intensiveness of the culture techniques used.

Trout Production

Although for reasons stated earlier no mass balances were made with respect to trout production, a moderate amount of data were collected on the subject. The information is recorded in Tables A11 and A12. A perusal of Table A11 furnished evidence for the unsuitability of trout

Figure 6. Diagram of inputs and outputs for a tilapia-algae pond.

Note:

Calculations based on

0.05 ha pond culture

1000 fish at 0.1 kg/fish

$T_{H_2O} = 30^{\circ}C$, $T_{air} = 20^{\circ}C$

Figure 7. Mass balance diagram for tilapia production.

farming in an energy-agro-waste complex. The requisite low water temperature, the high oxygen demand, and the inability to use common wastes as a nutrient source are not reconcilable with the conditions of such a complex. The highest value (2.8 kg/l/min) listed for yield in Table A12 is taken from Bardach.⁽⁹⁾ The estimate is based on reported yields obtained in a trout farming district in the Idaho-Snake River valley. According to Bardach, a more accurate description of high yields is to report them in terms of flow rate rather than of area of volume because they are functions of effective flushing of growth inhibiting wastes from the trout raceways. However, since fish farming involves a given area or volume devoted to that purpose, reporting in yield per volume or area is equally useful.

Unit Processes for Plant Production

Both open field and greenhouse growing play valuable roles in agriculture around the world. Similarly, both of these agricultural techniques can serve in valuable and different roles in an energy-agro-waste complex. Several unit process models were consequently developed for different methods of plant production as well as different crops.

GREENHOUSE PLANT PRODUCTION

The primary advantages of greenhouse growing lie in the ability to control the plant environment and in efficient land utilization. These features also make greenhouses well-suited to utilization in an energy-agro-waste complex. Waste heat from the power plant can be used to heat the greenhouse providing the required air temperature for the plants. Heating is currently the major expense for greenhouse growers. Efficient land utilization is achieved both through high crop yields and use of

land unsuited to open field growth. Consequently, greenhouses can be more conveniently sited in a complex than an open field process.

A generalized diagram showing major inputs and outputs of a greenhouse unit process is presented in Figure 8.

Tomato production is an excellent example of the use of the greenhouse in crop production, because tomatoes are the most widely grown greenhouse crop in the world. There are two good reasons for the latter, namely, the existence of a steady high consumer demand for tomato fruit and the high yielding capability of the tomato plant.

A mass balance diagram of a tomato greenhouse is presented in Figure 9, and the data used in arriving at the mass balances are listed in Table B1. A collection of yields reported in the literature is given in Table B2. Another vegetable commonly grown in greenhouses is the cucumber. Reported yields of cucumbers range from 325 tonnes fruit/ha/yr to 739 tonnes fruit/ha/yr,^(10,11) and average at 525 tonnes fruit/ha/yr. In terms of biomass production, the yield in vines is about 13.5 percent that of the fruit. The average of fruit and vine would then be 596 tonnes/ha/yr.

Roses and carnations are two flower crops most commonly grown in greenhouses. Yields reported for roses range from 1.73×10^6 stems/ha/yr to 1.67×10^6 blossoms/ha/yr.

Reported temperature requirements for tomatoes range from 14° C to 20° C for the night time, and from 21° C to 24° C for the daytime. Cucumbers prefer somewhat higher temperatures. Thus, the reported night time temperatures range from 18 to 21°C. Estimates of the heating requirements to maintain the vines at the appropriate levels under various conditions are listed in Table B3.⁽¹²⁾

Figure 8. Generalized diagram of a greenhouse unit process.

Figure 9. Mass balance diagram of a tomato greenhouse unit process.

Data on electrical requirements as collected from a variety of reports indicate an electrical requirement of 75 to 100 kW/ha.⁽¹³⁻¹⁵⁾

OPEN FIELD PLANT PRODUCTION

Open field growing can serve in several compatible functions for an energy-agro-waste complex. It can utilize various nutrients in waste-streams for fertilizer. Grain can be grown to feed livestock in the complex. Crop productivity can be enhanced by under-soil heating and hence serve as a cooling source for recirculating condensor cooling water. Or condensor cooling water can be used for spray irrigation of fields for once-through systems, also serving to reduce warm water discharge into natural bodies of water. A complex within an urban area would probably be restricted in its available land area, and thus open field growing would correspondingly be restricted. However, in complexes located outside urban areas open field growing offers unique potential.

The nitrogen, phosphorous and potassium (NPK) requirements of several grain crops are depicted in Figures 10 through 14. The numbers in the balances are based on annual inputs and outputs per hectare. In making the balances for corn and sorghum, it was assumed that field residues would be equal to 0.85 of that of the grain, both on a dry weight basis. This number is rather conservative in view of the fact that the reported values range from 0.85 to 1.35. The latter value is that reported for corn residue in California.⁽¹⁶⁾ A reason for using the conservative estimate is that it allows for some residue to remain in the field and there serve to promote soil conditioning. Additional data pertinent to forage crops are given in Table B4 along with total NPK percentages of various grains. A further discussion of nutrient uptake is contained in Appendix B.

Figure 10. NPK mass balance diagram for rice production.

Figure 11. NPK mass balance diagram for corn production.

Figure 12. NPK mass balance diagram for sorghum production.

Figure 13. NPK mass balance diagram for wheat production.

Figure 14. NPK mass balance diagram for oat production.

WATER HYACINTH PRODUCTION

Within the past few years, and especially as spurred on by reports from the NASA group, the water hyacinth again has begun to attract attention as a means of wastewater treatment. Reported results indicate that the plant is effective in cleaning up waters containing organic wastes, and to some extent in the removal of heavy metals. The role of the plant in upgrading wastewaters is twofold, namely oxygenation and assimilation of bacterial breakdown products in the wastewaters. The oxygen is released into the water medium from the submerged green portion of the plant. Inasmuch as a substantial part of the plant is emergent and the submerged portion is shaded, the extent of oxygenation is much less than that with completely submerged aquatic plants. The removal of heavy metals is primarily a function of assimilation, absorption, and adsorption by the plant; and secondarily of alterations in the suspending medium (water) brought about by the metabolic activities of the plant.

While the utilization of water hyacinth culture in wastewater treatment has many advantages, it also is attended by substantial difficulties. Advantages are in the form of the rapid growth of the plant, which in turn ensures a rapid and effective upgrading of the wastewater. Another, but debatable, advantage is the possibility of utilizing the hyacinth crop as a feedstuff for livestock. Its characteristics as a feedstuff are indicated by the data in Table B6. Disadvantages are: (1) an essential limitation to frost-free geographical areas; (2) danger of plants escaping into waterways; and (3) difficulty in harvesting. The major problem in terms of utilization as a feedstuff is the magnitude of the water content. The plant typically has a 95 percent water content.

Unfortunately, water expressed from the plant contains a sizeable proportion of the animal nutrient content of the plant.

A mass balance diagram for water hyacinth production is shown in Figure 15. The input nutrient elements may exist in an assimilable form in the sewage at the time of introduction into the system, or after introduction is converted into such forms by bacteria indigenous to the sewage and the pond culture. Potential limiting factors are visible light energy, CO_2 , nutrient concentration and balance, and temperature.

Algae Production

Research and experimentation on the use of algae culture in wastewater treatment and production of an animal feedstuff has a long history that extends back to the early 1950's and early 1960's.

The basic principles involved are not unlike those pertinent to water hyacinth culture. The differences are in the nature of the plants involved, the degree and extent of the basic process activities and results, and of course, in the operation of the two systems.

Generally, the planktonic algal genera (e.g. *Chlorella*, *Scenedesmus*, *Euglena*) are used. Reasons are ease of culture, rapidity of growth, and distribution throughout the water being treated. In terms of food production, the light energy fixation efficiency far surpasses that by the macro-forms. A major disadvantage is the monetary and energy expenditure involved in harvesting planktonic algae. However, recent work done at the University of California (Berkeley) indicates that by manipulating natural processes, a drastic reduction of these expenditures becomes possible.

The rapidity of growth and more or less general distribution of the algal cells throughout the pond water ensures an effective oxygenation of

Typical U.S. Raw Sewage Feed ($25^{\circ}\text{C} - 29^{\circ}\text{C}$)

Figure 15. Mass balance diagram for water hyacinth production.

the wastewater. As a generalization, it may be assumed that for every gram of new cellular material synthesized during photosynthesis, 1-6 grams of O_2 are released into the aqueous medium.

The algal product has been demonstrated through animal (chickens, swine, sheep) feeding experiments conducted at the University of California (Davis) to have a nutrient quality comparable to soybean oilmeal. In especially designed ponds, production can range from 44 tonnes (dry wt.) to 110 tonnes/hectare/yr.

The principal types of ponds involving the use of algae may be either facultative or high-rate. While anaerobic ponds are used for treating heavily concentrated wastes (e.g. rendering plant effluent), algae play a very minor role in their functions. Facultative ponds are so named because they involve both aerobic and anaerobic breakdown, i.e. aerobic in the upper strata, and anaerobic in the lower strata. They normally are (i.e. they should be) at least 1.5 m deep, and preferably 2.5 m or more. High-rate ponds may be one of two types, namely, high-rate treatment or algae production. The high-rate treatment pond is on the order of 1.2 m deep and is mixed periodically throughout the day. The algae production pond is from 12 to 35 cm deep and is mixed once or twice a day in the non-daylight hours.

A typical mass balance diagram for an algae production pond is presented in Figure 16. As with water hyacinth culture, the input nutrients come from the bacterial decomposition of the organic wastes in the water. Ammonium-nitrogen is the principal nitrogen source for algae, although most forms can utilize certain of the amino acids as nitrogen sources and a few can assimilate urea-nitrogen. Excepting for tolerance of much lower temperatures, the limiting environmental factors are much

Figure 16. Mass balance diagram for algae production.

like those for water hyacinth culture. Pertinent data for an algal culture system are presented in Table C4. It should be noted that the data are mainly indicative.

Anaerobic Digestion

An important unit process considered in this section is anaerobic digestion, or as it has come to be popularly known, "biogas production." The reasons for the great surge of interest in biogas production are well documented in the scientific and the popular literatures and need not receive detailed attention in this report. Suffice it to state here that the anaerobic digestion process can be made to serve in an agro-waste complex as a means of converting residues in part to energy and in part to sources of fertilizer elements and soil amendments. Moreover, since the process is well described in the literature, a discussion of the various operational and design parameters is not given. To do justice to either of the two subjects would entail an undue expenditure as far as the present report is concerned.

A mass diagram of pertinent inputs and outputs of the anaerobic digestion process that are of significance to the present study is given in Figure 17. The balances are based on values reported by Boersma for the anaerobic digestion of swine wastes.⁽¹⁷⁾

Sewage Treatment Processes

The development of a primary-secondary treatment model was made a part of the section on unit processes because sewage, whether raw or treated, can serve as an important input in an energy-agro-waste complex. Sewage can serve as a liquid medium in aquaculture both as a suspending medium and as a source of fertilizer elements to plants in

Figure 17. Mass balance diagram for anaerobic digestion process.

systems involving the production of aquatic plants or as source of nutrients to micro and macrofauna in the systems. With respect to land crops, it again is a source of plant nutrients and of water for irrigation. It can serve as a source of heat in both land and aquaculture.

An idea of the fertilizer value of raw and treated (secondary) sewage may be gained from the data listed in Table C1. The compositions of raw activated and digested sludges as based on a sampling of reported data are given in Table C2. The data in Table C3 collectively are indicative of the efficiencies of primary and secondary sewage treatments. Balances in terms of composition and of mass showing the combined effects of primary and secondary treatment are diagrammed in Figures 18 and 19. In the compositional diagram (Figure 18), total solids are given the value 1.0. The values in Figure 19 are based on 10^6 liters of raw sewage. It goes without saying that the numerical values in both figures would vary according to the nature of the influent raw sewage and the efficiency of the primary and secondary settling chambers. The solids content of the sludges would increase with an increase in efficiency of the settling chambers; and, conversely, that of the effluents would decrease. All in all, however, the numerical values as given in the two figures are fairly typical. A typical flow pattern of incoming solids in a representative sewage treatment plant (Hyperion, Cal.) is indicated by the diagram in Figure 20. As the figure indicates, the plant provides for primary and secondary treatment of the sewage and for the anaerobic digestion of the settleable primary solids and wasted activated sludge.

Figure 18. Compositional balance diagram of the combined effects of primary and secondary sewage treatment.

Legend:

T.S.	N
D.S.	P
S.S.	K
V.S.	H ₂ O

Note:

1. Based on 10⁶ liters of sewage.
2. Values given in kilograms dry weight (except H₂O).

Figure 19. Mass balance diagram of the combined effects of primary and secondary sewage treatment.

Figure 20. Flow pattern of suspended solids in a sewage treatment plant (kg/day).

POTENTIAL INTEGRATED SYSTEMS

Having completed mass and, to some extent, energy balances for a number of likely candidate unit processes, the next logical step in the overall investigation was to integrate selected processes into what were deemed potentially useful and feasible systems or complexes. Table 2 demonstrates the potential roles of various unit processes in the integrated complexes. In the conduct of this phase of the work, the mass balances provided the information as to the nature and amounts of inputs and outputs of individual processes needed in selecting and positioning those deemed suitable to a given system. Ten potential systems were developed.

While the diagrams of the systems as presented in this section of the report are qualitative in nature, they do show interrelationships and provide sufficient information for sound assumptions regarding their practicality. The order in which they are discussed has no bearing on their comparative feasibilities.

Refeeding of Wastes

Although refeeding of animal wastes to livestock is still unconventional, a considerable amount of work has demonstrated the feasibility of a variety of refeeding schemes.⁽¹⁸⁾ Animal waste contains protein and other required nutrients which can be reclaimed to supplement livestock feed. It is essential, however, to control the passage of contaminants contained in wastes such as disease-producing organisms, parasites,

Table 2
Potential Roles of Unit Processes in Integrated Complexes

<u>Unit Process</u>	<u>Primary Role in System</u>	<u>Use of Waste Heat</u>	<u>Possible Recycled Inputs</u>	<u>Possible Recycled Outputs</u>
Chicken	Meat Production	Housing	Cattle Manure, CH ₄ for Heating, Slaughter Wastes Crop Residues, Algae	Manure, Slaughter Wastes, Litter
Cattle	Meat Production	Housing	Chicken Manure and Bedding, Water Hyacinths, Crop Residues, Algae	Manure, Slaughter Wastes
Swine	Meat Production	Housing	Cattle Manure, Water Hyacinths, Crop Residues, Algae	Manure, Slaughter Wastes
Catfish	Fish Production	Water Warming	Feedlot Manure, Algae	Slaughter Wastes, Fish Wastes
Tilapia	Fish Production	Water Warming	Algae, Slaughter Wastes	Slaughter Wastes Fish Wastes
Greenhouses	Plant Production (Vege., Flowers)	Maintenance of Optimum Temp.	CH ₄ for Heating, CO ₂ Enrichment, Composted Sludge and Crop Residues	Crop Residues
Open Field Agriculture	Plant Production (Grain, Vege.)	Soil Warming, Grain Drying	Sludge, Supernatants, Composted Crop Residues	Crop Residues, Grain
Water Hyacinths	Water Treatment	Maintenance of Optimum Temp.	Organic Wastewater, CO ₂	Feed for Livestock or Fish
Algae	Water Treatment	Maintenance of Optimum Temp.	All Types of Organic Wastes, CO ₂	Feed for Livestock or Fish
Anaerobic Digestion	Water Treatment, Methane Produc.	Maintenance of Optimum Temp.	All Types of Organic Wastes	CH ₄ , CO ₂ , Supernatant, Sludge
Sewage Treatment	Water Treatment	Maintenance of Optimum Temp.	All Wastes	Supernatant, Sludge

residues of drugs and drug metabolites, as well as other contaminants of natural and industrial origin. Thus, manure refeeding processes generally incorporate techniques to prevent contamination problems. These techniques include drying (natural and heated air), ensiling, chemical treatment, and biological treatment.⁽¹⁹⁻²²⁾ Waste heat can also be used to sterilize the manure.

Cattle manure has been used in feeds for cattle, sheep, swine, chickens and catfish.^(18,23-25) Both the large fecal output and poor feed conversion ratio of cattle have led to many efforts to utilize cattle manure for refeeding. Usually the manure is mixed with grains or hay. Ruminants have unique digestive capabilities and are particularly well-suited to refeeding of wastes.

Poultry manure and litter have also been used as feed to ruminants.^(18,26-29) Feed rations often contain 60 percent or more poultry litter. Its digestible crude protein content is approximately 25 percent, and the metabolizable energy content averages about 5600 kJ/kg.^(27,29) These values represent about 85 percent of that of good quality barley.

Another unconventional livestock feeding involves the feeding of anaerobic digester sludge to swine.⁽³⁰⁾ The use of various animal manures to grow algae which in turn is used as fish or livestock feed also has been demonstrated.⁽³¹⁾

Refeeding schemes have been incorporated into the energy-agro-waste complexes studied in this project because of their inherent suitability to such systems, demonstrated feasibility, and great potential for maximizing waste utilization.

Chicken-Cattle-Algae-Digester Complex

The first system to be developed constituted a chicken-cattle-algae-digester complex. A diagrammatic sketch of the solids and energy interrelationships of the complex is presented in Figure 21. As the figure indicates, the three major continuing solids inputs to the system are the supplemented feeds to the chickens and the cattle, and fuel to the power plant. The extent of the feed input, of course, is partly a function of the amount of the wastes generated in the complex and of their suitability as feedstuff to the animals. Note that an egg production operation may be substituted for a broiler production operation with only minor overall effects on the complex. The yield of algae from the algae pond also is a determinant of the amount of feed input that would be needed. In practice, algae could constitute only about ten percent of the chicken's total diet without having an adverse effect on egg and meat production. The algae would serve as a protein supplement for both feeds.

Economic and energetic feasibility dictate that sunlight be used as the source of the visible light energy required for algae production.

The water needed to set up the system would be that required to serve as an algal culture medium, to dilute the cattle manure to the desired solids level (10 to 15 percent solids), for initial sanitation of the animal quarters, and for drinking water for the livestock. Conceivably, once supplied, an amount equal to only a fraction of that initially supplied would have to be added as makeup water on a continuing basis since the water would be reclaimed and recycled within the system. For example, effluent from the algae production pond could be used for sanitizing the animals' quarters. The water thus used would be returned to the pond. The wastes picked up in sanitizing would serve as a source of

Figure 21. Diagrammatic sketch showing mass and energy interrelationships for a Chicken-Cattle-Algae-Digester Complex.

nutrients for the algae. Of course, the water components of the system could not be completely closed, both because of loss of water through evaporation and spillage and also because of a salt buildup from the animal wastes and the concentrating effect of evaporation. Although, theoretically, water could be rendered suitable for use as drinking water, in practice it would be better to bring in external drinking water. Drinking water in excess of that imbibed by the animals could be directed to the algae pond, where it could serve as makeup water. Probably, it would not be advisable to have cooling water from the power plant come into direct contact with the algae, mainly because in conventional practice cooling water is dosed with phytocidal agents to inhibit slime buildup. If no such substances were added to the cooling water, it could be passed through the pond. Another limitation to the introduction of cooling water might be temperature. The algae usually cultured for high-rate yields have an upper temperature limit of 35-38° C.

Fish-Chicken-Cattle-Algae-Hyacinth-Digester Complex

In the second system, two additional processes are introduced, namely, fish farming and water hyacinth culture. A diagram of the complex is shown in Figure 22. Aside from the fuel to the power plant, the major continuing solids inputs are feedstuffs to the livestock to compensate for deficiencies in the plant products grown within the system. For example, the hyacinths may lack the carbohydrates and fibrous content required by the cattle and the amino acid complement essential to the chickens. The algae serve as a feedstuff to the tilapia.

The water requirements are much the same as those for the first complex, although in the present system the initial input would be larger to account for the hyacinth pond. Of course, the algae, hyacinths, and

Figure 22. Diagrammatic sketch showing mass and energy interrelationships of a Fish-Chicken-Cattle-Algae-Hyacinth-Digester Complex.

fish could be cultured together in one pond. The chances are, however, that by so doing, algae production would be adversely affected due to the shading brought about by the hyacinths. However, the tilapia could be successfully grown with either type of plant (i.e. algae or hyacinth). The constraints on the use of cooling water also apply here.

The anaerobic digester is used to "treat" the manure from the cattle with a subsequent production of methane. The methane is used for heating the chickens, while the sludge can be applied on open fields to recover the nutrients.

The proliferation of subsystems in the complex may have the disadvantage of increasing the chances of toxic intermediate products being generated, i.e., toxic to members of the complex. On the other hand, the introduction of fish culture provides a reliable and effective means of harvesting and simultaneously utilizing the algae. It should be noted that the hyacinths are not the sole agents in "cleaning up" the water, inasmuch as algae also are very effective in that regard.

Fish-Chicken-Cattle-Swine-Algae-Hyacinth Complex

The complex is diagrammed in Figure 23. As the figure indicates, the differences between the preceding complex and the present complex is that the latter calls for swine production in addition to beef production and eliminates the digester. Although the design diagram for the present complex indicates a common unit for the algae, fish, and hyacinth culture, the three could be separated as in the preceding complex. The same arguments, pro and con, hold for both arrangements. An added feed input to the present system would be one to the swine. While it has been demonstrated that algae can serve as a sole protein source for swine, they (algae) are not utilized as efficiently as is fish meal or other animal

Figure 23. Diagrammatic sketch showing mass and energy interrelationships of a Fish-Chicken-Cattle-Swine-Algae-Hyacinth Complex.

protein. Nevertheless, the complex as diagrammed in Figure 23 provides for the algae to be utilized by tilapia. Another variation could be the return of a portion of the slaughter wastes as feed to the swine. In fact, the wastes could provide the protein required by the animals (swine).

With the combined input of wastes from the swine and cattle subsystems, the danger of overloading the algae-fish-hyacinth subsystem could be a very real one. Swine wastes are especially "strong." On the other hand, the fertilizer elements are correspondingly abundant for algae and hyacinth production.

Greenhouse-Open Field-Chicken-Cattle-Digester Complex

Crop production is expanded from an intra-supporting role within the complex to one as an output in the present system, as is shown by the diagrammatic sketch of the complex presented in Figure 24. This is done by incorporating a greenhouse and an open field subsystem into a complex, although according to the figure the open field subsystem is, strictly speaking, an "intra-supporting" system since its output goes to the cattle. The water input/output situation is complicated by the inclusion of the open field. The latter brings in uncertainties related to climate, i.e., rainfall, evaporation, wind velocity, etc. The net result is that the external input of water would significantly exceed that with the preceding systems. While the presence of the open field may have brought with it an increase in need for external water, it does eliminate the need for an input of feed for the cattle. However, another external input may be required, namely chemical fertilizer elements to make up for an insufficiency of the elements in the sludge, if an insufficiency should exist.

Figure 24. Diagrammatic sketch showing mass and energy interrelationships of a Greenhouse-Open Field-Chicken-Cattle-Digester Complex.

The advantages accruing from the insertion of an anaerobic digester into the system are: 1. It serves as a conversion system for crop residues and the wastes from beef production. 2. It is an indirect source of heat energy through its production of the combustible gas, CH_4 . 3. It also is a source of CO_2 . Enriching the atmospheric CO_2 is demonstrated in daily practice as being beneficial to plant production in greenhouses. Theoretically, it would be advantageous in crop production if the CO_2 in the stack gases from the power plant could be diverted to the greenhouse. However, the practical difficulties in so doing would rule out the step for the time being.

Open Field-Cattle-Chicken-Digester Complex

In this complex, as diagrammed in Figure 25, the greenhouse has been eliminated and its (greenhouse) inputs and outputs are diverted to open field crop production. The open field components differ from that in the preceding section in that a sprinkler irrigation system is introduced. The sprinkler irrigation system serves as a partial heat sink for the waste heat from the power plant and the chicken and beef production components. The term "warm" is a more appropriate term for the waters from the latter two components than would be "hot", inasmuch as the temperatures of the waters would be only slightly above that of the ambient temperatures during warm seasons, and more so during the cold season. Of course in addition to its role in heat transport, the water supplies the needed moisture in crop production.

As in the preceding complex, the digester serves as a treatment device for the wastes from beef production; and its residue, as a source of nutrients for crop production in the open field. The differences between the two complexes are: (1) The CO_2 from the digester is simply

Figure 25. Diagrammatic sketch showing mass and energy interrelationships of an Open Field-Cattle-Chicken-Digester Complex.

wasted to the atmosphere in the present complex, whereas in the preceding complex it was diverted to a greenhouse. (2) The methane is diverted to the power plant, there to be used as a fuel. It should be pointed out that this contribution would be very minute in proportion to the total fuel input to the power plant. Perhaps a better use for the CH_4 would be as an energy source for the operation of the beef, chicken, and slaughter facilities. To meet the operational requirements of the power plant, the digester gas would have to be upgraded, i.e. remove the CO_2 and objectionable trace gases.

Tree Farm-Cattle-Digester Complex

The tree farm-cattle-digester complex is diagrammed in Figure 26. In this complex a switch from the agricultural crop production in the preceding complexes is made to forest products production. The inputs to the tree farm are much the same as those to the open field in the preceding complex. For example, the hot water from the power plant serves the dual purpose of heat transport and irrigation with respect to the tree farm.

The digester serves as a treatment device for the wastes from the cattle production, the milling, and the slaughter components. Because of the high C/N ratio characteristic of lumbermill wastes, nitrogen normally would have to be added to them before introduction into the digester. However, in the present complex, the nitrogen deficiency of the milling wastes could be made up to an appreciable extent by the nitrogen in the wastes from the beef production and slaughter components. Any remaining nitrogen deficiency would have to be eliminated through the addition of a chemical source, e.g. urea. Ammonia could be added, but only with great caution, since free ammonia is extremely toxic to bacteria.

Figure 26. Diagrammatic sketch showing mass and energy interrelationships of a Tree Farm-Cattle-Digester Complex.

With some modification of the tree farm component, the complex could be used in converting solar energy to biomass. The latter would be digested anerobically to produce methane. With such a modification, the milling component would be eliminated, whereas the chipping component (minus the drying) would be retained. The entire output of methane could be sent to the power plant, or a part could be diverted to other uses.

Greenhouse-Fish-Digester-Recreational Water Complex

The greenhouse-fish-digester-recreational water complex is diagrammed in Figure 27. The present complex is best adapted to the U.S. southeast. The reason is that in the southeastern tier of states, rainfall is of such a magnitude and frequency as to eliminate evapotranspiration as a major means of water removal. Consequently, an effluent is to be expected from the fish production component. Inasmuch as the effluent would be heavily contaminated with fish wastes, it must be treated prior to discharge into the environment. Settleable solids are produced in the primary treatment step (settling basins). Secondary treatment of the wastewaters is accomplished through the establishment of a recreational lake. The extent of the recreational use of the lake depends upon the degree of contamination of the raceways effluent, i.e. of the potential incidence of pathogens. The lake also serves, at least in part, as a source of cooling water for the power plant.

The remaining components of the complex are the greenhouse and the digester. The settled solids from the settling basins are used as a source of plant nutrient and as a component of the soil medium of the greenhouse. Plant debris from the greenhouse serve as input to the anaerobic digester. It is highly problematical that enough residue would be produced to enable a methane production sufficiently great to

Figure 27. Diagrammatic sketch showing mass and energy interrelationships of a Greenhouse-Fish-Digester-Recreational Water Complex.

constitute a substantial contribution to the fuel requirements of the power plant.

Sewage-Hyacinth-Digester-Swine-Composting-Open Field Complex

A rather involved complex is diagrammed in Figure 28. Its principal elements are sewage treatment, hyacinth production, anaerobic digestion, pork production, a compost operation and open field production of grain. The principal output is pork. Probably, the major feature that distinguishes this complex from others proposed in the present report is the provision for composting the organic fraction of municipal refuse along with the sludge produced in the system's digester. Therefore, its inputs include two major municipal wastes, namely, refuse (garbage and organic rubbish) and sewage. Another important feature is the provision for feeding slaughterhouse wastes and digested sludge to the swine. These characteristics combined with the extensive use of waste heat make this complex a potentially valuable implement for use in resource recovery.

Hyacinth-Cattle Complex

The water hyacinth-cattle complex diagrammed in Figure 29 is another comparatively simple complex in that it consists of only three major components, namely, the ever-present power plant, a cattle production component, and a hyacinth production lagoon.

Plant biomass production in the complex is in the form of water hyacinths. The hyacinth component is the recipient of wastes from the cattle production and slaughter components. Wastes from the latter two must be processed before being introduced into the hyacinth lagoon, mainly to reduce them to a particle size small enough not to interfere with the successful functioning of the lagoon. This processing also calls for the

Figure 28. Diagrammatic sketch showing mass and energy interrelationships of a Sewage-Hyacinth-Digester-Swine-Composting-Open Field Complex.

Figure 29. Diagrammatic sketch showing mass and energy interrelationships of a Hyacinth-Cattle Complex.

suspension of the solids. The fertilizer elements in the wastes serve as nutrients for the hyacinth. By the same token, the hyacinth pond acts as a waste treatment device for the waste output of the two components. Waste heat and electricity from the power plant are used to power the shredder and supply heat to the dryer. The cooling water from the power plant eventually finds its way to the lagoon via the dryer, shredder component. This water serves as makeup water for the lagoon.

The hyacinth production from the lagoon may or may not be great enough to satisfy the nutritional requirements of the livestock. Chances are that it will not. More study is needed on nutritional requirements before firm conclusions on the matter are warranted.

Fish-Open Field Complex

The fish-open field complex is the simplest of the complexes discussed in the present report. According to the diagram in Figure 30, its main components, in addition to the power plant, are a catfish production facility, a fish-feed factory, and open field grain and soybean production. The end products of the complex are fish, grain, and electricity.

The effluent from the fish production component serve both as a water source for irrigating the grain fields and as a source of nutrient for the grain crops. It is most likely that an external input to the open fields in the form of a chemical fertilizer would be needed to augment the plant nutrients content in the fish raceways effluent.

It should be noted that no provision is made for recycling crop residues within the complex.

Those fish processing wastes not found suitable for use in fish production could be used as a source of plant nutrients in the open field production.

Figure 30. Diagrammatic sketch showing mass and energy interrelationships of a Fish-Open Field Complex.

Summary Statements on the Potential Complexes

In the course of perusing the preceding descriptions and discussions, the reader may have noticed the absence of a critical discussion on the advantages and disadvantages of the individual complexes. The reason for the failure to include such a discussion is that it would be presumptuous without having first arrived at a collective complete material and energy balance of the individual complex as a whole. While it is true that in the preceding section material and to some extent energy balances were made of a number of unit processes, arriving at a collective balance for a complex necessitates integrating and, if necessary, adjusting the balances of its constituent individual components.

Another point to be made is that it is highly likely that a provision for auxiliary cooling for the power plant would have to be made in all of the complexes described herein. It also should be emphasized that only the major components and inputs and outputs are included in these diagrams.

MASS BALANCE ANALYSIS OF INTEGRATED COMPLEXES

With the completion of a qualitative study of potential integrated systems, several complexes were formed and their mass balances quantitatively analyzed. This was achieved by coupling the unit process models and iterating through the calculations between the different unit processes until acceptable balances were reached. Iterative modifications involved variation in sizing of the unit process operations (e.g., 200 cattle to 100 cattle), addition or depletion of unit processes from the complex being assembled, as well as adjustment of parameter values (within reported ranges). The complexes for which mass balances are presented here thus may vary somewhat from the complexes qualitatively discussed in the previous chapter.

Due to time and budgetary constraints of this project, four complexes were chosen for detailed analysis with emphasis on mass balances. The four complexes chosen were:

1. Chicken Manure-Digester-Algae-Tilapia Complex
2. Greenhouse-Cattle-Digester-Open Field Complex
3. Chicken-Cattle-Digester-Open Field Complex
4. Sewage-Digester-Hyacinth-Swine-Open Field Complex

A key for explaining the values represented is given for each figure describing the complex. The symbol "TS" stands for total solids, and the symbol "VS" stands for volatile solids. The chemical elements nitrogen, phosphorous, and potassium are denoted by their conventional symbols N,

P, and K, respectively. Inputs and outputs are given in units of kg per day. Due to the lack of information on certain parameters, some gaps exist in the figures and some figures vary from others in format. Appendix D contains details concerning the integration of each complex.

Chicken-Digester-Algae-Tilapia Complex

This system is based in large part upon experiments reported by Dugan, et al.⁽³²⁻³⁴⁾ The principal additional feature in the proposed scheme is the introduction of tilapia to feed upon the algae. The introduction of the fish removes the need for resorting to mechanical or chemical means to remove the algae as is required when the algae are to serve as a feedstuff for livestock.

Conservative estimates based upon feed-to-fish conversion and the experimental production of algae in a suspension of chicken manure indicate that the overall conversion of manure solids to fish is on a modest scale. However, the conversion to fish is not the only productive factor, methane also is produced and recoverable phosphate is precipitated. Although nitrogen recovery should figure strongly in the scheme, a recovery of only about three percent of the manure-N seems likely. A prime reason for the low efficiency in nitrogen recovery is a substantial loss of the element by way of gases evolved from the pond. Most likely, the nitrogen is lost in the form of ammonia.

In the system, chickens are reared as in any large-scale egg production operation, i.e. in cages suspended over a manure trough, but modified somewhat in the manner described by Dugan. Wash-down water for the chicken cages as well as drinking water for the hens are a part of the "closed" system.

The integrated mass balance for this complex is presented in Figure E1. Some parameter values were adjusted from the unit process models to provide compatibility with other processes. Most of the values used were taken from Dugan, et al.⁽³²⁻³⁴⁾ A 2:1 feed conversion ratio was used for tilapia on an algae diet.

The operation of the process begins with the removal of the suspended solids from the flushings from the manure troughs by passing the flushings through a settling tank. The supernatant from the tank is discharged directly into the algae pond. The settled solids are subjected to anaerobic digestion with a consequent production of CH_4 . The effluent slurry from the digester is passed on to the algae pond. (No settled solids are recovered from the digester.) Thus the algae derive their nutrients from two sources, settling tank supernatant and digester effluent. Pond temperature is maintained at an optimum level ($25^{\circ}\text{--}30^{\circ}\text{C}$) during cold weather through the use of waste heat. Light is assumed not to be a limiting factor. Algal suspension is discharged continuously from the algae pond into the fish production pond (optimum temp. $30^{\circ}\text{--}32^{\circ}\text{C}$). Fish wastes are sent to the algae pond by way of discharging into the pond the effluent released from the fish pond.

Not taken into consideration in the development of the mass balances were a water balance for bulk correction, metabolic and biochemical water balances, and the eventual fate of phosphorus. Also, salinity buildup would have to be kept down to an acceptable level through the provision of a blowdown.

While not as yet demonstrated experimentally, conceivably phosphate could be recovered by taking advantage of the diurnal rise in pH level characteristic of algae production ponds. The high pH level triggers the

precipitation of phosphate complexes. By passing the algal suspension through a special chamber during the time of high pH levels, the rapidly precipitating phosphate could be localized for mechanical recovery. However, no technology for such a recovery presently exists, and the obstacles to the development of one are formidable.

An overall analysis of the complex shows that 1 kilogram of chicken manure input ends up producing 0.074 kilograms of fish meat (wet weight), 0.119 kilograms of methane, and 0.148 kilograms of $\text{Ca}_3(\text{PO}_4)_2$. These figures correspond to about 300 chickens and 335 tilapia, roughly 1:1.

Greenhouse-Cattle-Digester-Open Field Complex

The principal input to this system is fertilizer to the greenhouse; and the outputs are vegetables, beef, and methane. Feed for the cattle comes from the open field crops and to a limited extent from cannery wastes and bone meal supplement. The digester serves not only as a source of fertilizer for crop production and of CH_4 , but also as a treatment device for the animal wastes.

Greenhouse and digester temperatures are maintained throughout the year at an optimum level with waste heat. The open fields are unheated and are sufficiently spacious to accommodate the storage need throughout the year. The tomato cropping is phased such that uniform vine and fruit output continues throughout the year.

The integrated mass balance for this complex is presented in Figure E2. The inputs to the greenhouse are 5.2 tonnes of nitrogen per year, 0.73 tonnes of phosphorus per year, 8.4 tonnes of potassium per year and an unspecified amount of water. Water is also supplied to the digester, the cattle, and the feed crops. Bone meal is supplemented to the cattle

diet at the rate of 4.6 tonnes per year. The outputs of the complex are 1240 tonnes of tomatoes per year, 38.3 tonnes of beef per year, and 24.8 tonnes of methane per year.

The edible tomato products account for about 67 percent of the influent nitrogen, which leaves only 33 percent to be recovered in the remainder of the complex. The beef production element accounts for 17 percent of the total nitrogen input, although after slaughter, this is reduced to 10 percent. Alfalfa, however, fixes additional nitrogen from the air. Loss of plant nutrients by way of leaching is minimal if the amount of nitrogen is adjusted to that of the nitrogen required by the crop. Phosphorus tends to be immobilized in the top 15 centimeter layer. The soil thus forms a reservoir for phosphorus, the availability of which is quite sensitive to pH. Digester effluent in excess of that required in the open-field crop production can be directed to the greenhouse.

While the integration of the various elements of which it consists is a novel concept, the actual functioning of the individual unit processes as part of the complex does not differ from that in conventional agriculture. The principal exception might be the almost exclusive use of organic wastes to fertilize the open field crops.

The final results of the analysis and calculations lead to the conclusion that a 100-steer (mixed ages) operation would entail the need for a 4-ha greenhouse, a 140m³ digester, 8.3 ha alfalfa and 13 ha corn. The total area that would be involved in establishing the complex (excluding the power plant) is approximately 26 hectares.

Chicken-Cattle-Digester-Open Field Complex

The flow patterns of this complex is completed by the use of chicken manure as supplementary feedstuff for the cattle, the use of slaughter wastes as supplementary feedstuff for both chickens and cattle, the use of digester effluent to irrigate open field crops, running the digester on animal and crop wastes, and feeding both the chickens and cattle with the field grown grain. The slaughter wastes are a source of protein as well as calcium phosphate. Principal inputs to the complex are fertilizer to the fields, water for the animals and irrigation and bone meal supplement for the animals. Principal outputs are chicken and beef products and methane.

Waste heat can be used to heat the livestock quarters and to maintain the digester at optimum temperature. Undersoil heating is not used here but also offers potential, particularly in cool or cloudy climates.

Silage would of course be required to distribute the grain supply evenly over the year.

The integrated mass balance for this complex is presented in Figure E3. The fertilizer input to the system is 4.8 tonnes of nitrogen per year, 0.66 tonnes of phosphorus per year, and 3.5 tonnes of potassium per year. Total crop production would be 122 tonnes of corn (grain) per year, 91 tonnes of alfalfa hay per year, and 9.0 tonnes of sorghum (grain) per year. The corresponding field areas for these crops are 14.4 hectares of corn, 6.7 hectares of alfalfa, and 1.0 hectare of sorghum.

The total meat production of the complex would amount to 13.1 tonnes of chicken per year and 14.4 tonnes of beef per year. (These are post-slaughter figures.) The livestock operations would involve 2750 chickens and 100 cattle. Feed to the chickens amounts to 116 kilograms per day

(42.3 tonnes per year). This daily ration consists of 6 kilograms of slaughter wastes (5 percent), 87 kilograms of corn (75 percent) and 23 kilograms of sorghum (20 percent). The total weight of rations for the cattle herd is 620 kilograms per day (226 tonnes per year), of which 124 kilograms is in the form of slaughter wastes (20 percent) and 248 kilograms (40 percent) each of corn and hay.

The digester volume of 92 m^3 is based on an input of 440 kg solids/day at a 13:1 dilution. Supplemental nitrogen requirements in the digester could be met by diverting a portion of the slaughter wastes into the digester. The determination of the amount of digester effluent required for fertilizing the sorghum and the corn fields is accomplished by assuming a nitrogen loss of 20 percent of the total assimilated by the crop. (This loss indicates the advisability of crop rotation, i.e. with alfalfa.) A summary of data used in arriving at NPK mass balances for the open field crops is given in Tables B4 and B5.

The fact of losing nitrogen in the soil by leaching is indicative of an accompanying excess of phosphorus and potassium, since the NPK is in a fixed ratio in the digester effluent. The excess phosphorus tends to accumulate in the soil. This phosphorus can be recovered by rotating corn and sorghum with alfalfa. Alfalfa tends to fix nitrogen and thereby paves the way for a further utilization of the phosphorus, at the expense of the accumulated phosphorus. Nutrients not supplied directly in the open field operations may be present as dissolved minerals naturally present in the water used to irrigate the fields. For example, the corn crop would require an addition only of 8 ppm in the irrigation water to compensate for the nitrogen deficit. The amount of potassium to be added would only be 3 ppm.

Relying upon a dilution of 13:1 of the feed to the digester (i.e. $4.81 \text{ kg/m}^3/\text{day}$) leads to a digester effluent production equivalent to irrigating at the amount of 0.01 m^3 water/year. Additional irrigation would be required in most locations.

The amount of the nitrogen output by way of meat is much smaller than that in the nitrogen input; all nitrogen values for meat are based on the assumption that $N = 0.035$ of the total mass or 0.10 of the total solids. The phosphorus content of the meat equals that of the phosphorus input. The concentration of phosphorus for chicken and beef bodies and meat are based on a bone content of 14 percent phosphorus, and that bones constitute 5 percent of chicken carcass and 10 percent of the beef carcass. The value 5 percent is an estimate. The potassium content of the meat is slightly less than the potassium input.

The final results of this analysis leads to the conclusion that a 2750 chicken brood would be compatible with a 100 steer herd, a 92 m^3 digester, a 14.4 hectare corn field, a 6.7 hectare alfalfa field, and a 1.0 hectare sorghum field. The total area that would be involved in establishing this complex (excluding the power plant) would be approximately 24 hectares.

Sewage-Digester-Hyacinth-Swine-Open Field Complex

The interrelationships comprising the Sewage-Digester-Hyacinth-Open Field Complex include the use of sewage treatment effluent for field fertilization and water hyacinth production, the anaerobic digestion of sewage sludge, crop wastes and swine manure, and the feeding of field-grown grain, water hyacinths, slaughter wastes and digested sludge to the swine. The principal input to the complex is raw sewage. The principal outputs are pork and methane.

Waste heat is used to heat the swine housing and maintain the optimum temperature in the sewage treatment and anaerobic digestion processes. Again, underoil heating is not used here but does offer added potential use of waste heat.

In the sewage treatment element of the complex, primary and secondary treatment are accomplished. Sludges (raw sludge and activated sludge) are discharged to the digester as in conventional sewage treatment practice. The supernatant (secondary effluent) is discharged in part to a pond to support a water hyacinth crop, and in part to open fields to serve in irrigation. The hyacinth crop serves as a feed supplement in the swine production element. Effluent from the hyacinth pond is used to irrigate the open field. Wastes produced in rearing the swine are discharged into the digester, and the animals eventually are slaughtered. Wastes from the slaughter operation are discharged in part to the animal rearing element for use as a feed supplement, and in part to the digester. A connection could also be made between the slaughter element and the sewage treatment facility to indicate the discharge of processing wastewaters to the latter for treatment (i.e. "cleaning up"). The open field receives effluents from the hyacinth pond and the digester. Its output (grain) is fed to the swine in the swine rearing element. Crop residue (stover) is discharged into the digester. From the preceding description, it becomes apparent that the digester is an important element in the waste conversion function of the complex. It has an input from all of the elements with the exception of the water hyacinth pond. Its principal outputs are gases and digested sludge. The gas of importance is methane. Methane would have a greater place of significance in a diagram showing energy relationships. Digester residue (settled solids

and supernatant) is an important source of plant nutrient for the crops in the open field element.

The integrated mass balance for this complex is presented in Figure E4. It should be noted that in constructing the diagram, not all of the inputs and outputs are included. For example, neither the gas exchange (CO_2 , O_2) at the hyacinth pond/atmosphere interface nor the water losses from the open field by way of evaporation and run-off are indicated, but instead, only those inputs and outputs essential to the continued functioning of the complex.

The raw sewage input into the complex is 1000 cubic meters per day. Crop production amounts to 1720 kilograms of grain per day (628 tonnes per year) and 4410 kilograms of water hyacinths per day (1610 tonnes per year), although the latter is composed of 95 percent water. Post-slaughter pork yield is 425 kilograms per day (155 tonnes per year).

On a dry weight basis, the daily feed ration to the 1000 swine operation is 2000 kilograms per day. The composition of this ration is 65 kilograms of slaughter wastes per day (3 percent), 210 kilograms of digested sludge per day (11 percent), 210 kilograms of water hyacinths per day (11 percent) and equal parts of corn and sorghum, each 760 kilograms per day (38 percent).

Because a sizeable share of the nutrient elements (i.e. N, P, K) involved in the animal (swine) element of the complex is contained in the slaughter wastes, it is important that the latter be kept within the system. This could be done efficiently by using to the extent possible the slaughter wastes as a feed supplement for the swine. An added advantage in so doing is that the nitrogen in the wastes is in the form of amino acids and thus is more efficiently utilized by the animal than it would be in the form of grain.

The final results of this analysis leads to the conclusion that a 1000 cubic meter per day sewage treatment plant could support 1000 swine. a 36 hectare corn field, a 36 hectare sorghum field, and a 0.84 hectare water hyacinth pond. A 470 cubic meter anaerobic digester would be required in the system. The total area that would be involved in establishing this complex (excluding the power plant) would be approximately 250 hectares.

CONCLUSIONS

The primary value of the models developed in this work lies in their utility in the engineering analysis of proposed energy-agro-waste complexes. The models provide a guideline for the design of such complexes by determining the sizing of subsystems, the compatibility of subsystems, and the overall feasibility of an integrated complex. This was achieved by the quantification of mass inputs and outputs of the various unit processes and the subsequent performance of mass balances on the integrated complexes.

The inherent difficulty in applying overall mass and energy balances to biological systems is well attested to by anyone who has worked in this field. The problems are greatest when trying to apply these balances to the total body of an animal. This consideration should be kept in mind when reading and using this report. The goal here has been to present the best possible models from information currently available, as well as a useful guide to the analysis of energy-agro-waste complexes (not rigid design formulas).

The wide range of parameter values reported in the literature posed the greatest difficulty in construction of these models. This situation is due to a variety of reasons. Some data reported in the literature were not measured accurately nor under controlled conditions. Often only one parameter was measured in a study, consequently making it difficult to relate to other parameters. Most parameters involved in this analysis are functions of other parameters, not just constants or even ratios of

other parameters. For example, feed conversion efficiency is a function of type of feed, ambient temperatures, activity of the animal, and age of the animal. Manure solids content is a function of type of feed, amount of feed, feed conversion efficiency and water intake, as well as a weaker function of other parameters. These problems were reconciled as best as possible by cross-calculations to confirm the values used and preferential use of what we believed to be more reliable publications.

Some parameter values are completely lacking from the literature and thus necessitated assumptions or exclusion from the models. This was particularly common for the fish. Composition of feed, tissue, and manure were frequently unavailable parameters. Further experimental studies would be useful to establish more refined and complete data for most of the animals considered here.

The integrated mass balances were accomplished by an iterative procedure. This involved first making estimates of subsystem sizes and flows and then readjusting to achieve balance of the inputs and outputs for each subsystem. Many iterations are required, and, therefore, this becomes a tedious process by hand calculation. Computer coding of the unit process models and the integration algorithm would be very beneficial.

Several complexes proved feasible from a mass balance point of view. Other considerations also need to be taken into account, however, such as energy inputs and outputs, engineering design of material transport systems between the subsystems, and operation procedures to ensure a steady year-round distribution of inputs to the appropriate subsystems. Certain processes have a natural interruption of their operation, such as slaughter or harvest, but other dependent subsystems cannot have their

inputs cut off. Various alternatives to avoid this need to be investigated.

The next stage in development of a more comprehensive analytical model should include quantification of energy inputs and outputs to the unit processes and a computer coding of the unit process models and the integration algorithm.

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APPENDIX A

The tables concerning input and output data of animal production were constructed as follows. A general format of input and output information was used to provide ease of comparison, although the same type of information in each category varies due to applicability and availability. Input data were categorized into assumptions, feed, water intake and environmental requirements. Output data were categorized into metabolism and tissue production, solid wastes, water losses and heat losses. Values are given on a per animal basis and generally as lifetime averages. In certain cases, ranges of reported values in the literature are presented. Reference sources are indicated in the right hand column. Where reference numbers do not appear, data have been derived from calculations using other data in the table.

Figure A-1. Terminology pertaining to energy in animal nutrition.

Table A1
Input Data Regarding Chicken Production

1. Assumptions:
 - a. Growth time and weight at slaughter = 10 to 13 weeks, 1.5 to 2.0 kg (35)
 - b. Animal body temperature = 41° C
 - c. Chicken house temperature = 25° C
 - d. Data taken for White Leghorn variety
2. Feed:
 - a. Feed to weight gain ratio = 2.5 to 3:1 (35,36)
 - b. Daily consumption = 6% to 10% of body weight/day, lifetime average = 0.05 kg/day (35)
 - c. Solid fraction in feed = 0.90 (0.045 kg/day) (36)
 - d. Metabolizable water fraction in feed = 0.54 (0.027 kg/day) (36)
 - e. Metabolizable energy content of feed = 1.26×10^4 kJ/kg (7.27 Watts total) (37)
 - f. Composition: Protein = 22% to 24% (9,200 to 13,800 kJ/kg; Fats = 2% to 5% (32,300 to 36,900 kJ/kg) (37)
3. Water Intake:
 - a. Water to feed ratio = 2.4:1 (0.12 kg/day) (36)
4. Environmental Requirements:
 - a. Ambient temperature comfort zone = 35° C initially, decreasing linearly to 19° C on 32nd day. Adults maintained between 15° C and 25° C (36-38)
 - b. Relative humidity = 60% to 85% (36,39)
 - c. Heat input in cold weather (-18° C), approximately 0.15 to 0.30 kW/m² (40)
 - d. Ventilation = 0.1 to 0.3 liters/sec/kg animal (16-48 kW/ha) (36,37)
 - e. Illumination = 110 kW/ha average (36)
 - f. Space = 0.1 to 0.3 m²/animal (37)

Table A2

Output Data Regarding Chicken Production

1. Metabolism and Tissue Production:

- a. Stored tissue = 0.019 kg/day (average) (35)
- b. Moisture fraction of tissue = 0.70 (8)
- c. Stored water = 0.135 kg/day
- d. Stored solids = 0.0058 kg/day
- e. Energy content of tissue = 6280 kJ/kg (8)
- f. Stored tissue energy = 1.40 Watts
- g. Energy requirements for metabolism = 20.9 kJ/liter O_2 consumed (8)
- h. Metabolic energy = Feed energy - Stored tissue energy = 5.87 Watts
- i. O_2 consumption = 24.3 liters/day = 0.032 kg/day
- j. Respiratory quotient = 0.8 (8)
- k. CO_2 metabolic production = 19.4 liters/day = 0.036 kg/day
- l. Total broiler production = 3.0×10^5 kg/ha/year (40)

2. Solid Wastes:

- a. Total manure = (Feed + Water intake)/1.8 (0.095 kg/day) (36)
- b. Solid fraction of manure = 0.23 (0.022 kg/day) (36)
- c. Fecal solids from mass balance = Feed solids - stored solids - metabolic losses = 0.045 - 0.0058 - 0.013 = 0.026 kg/day
- d. Manure composition: (28,37,41)
 - H_2O = 57% to 80% (fresh), 16% (air-dried)
 - Protein (crude) = 25% (dry weight)
 - Nitrogen = 4% to 6% (dry weight)
 - P_2O_5 = 1.17% (at 57% moisture content)
 - K_2O = 0.62% (at 57% moisture content)

Table A2 (continued)

- e. Nitrogen loss as ammonia in air = 0.007 kg/day
(assuming 50 ppm)
- f. Litter change with each brood = 0.1 m deep = (37)
13 kg/m² saw wastes = 0.022 kg litter per
bird per day
- 3. Water Losses:
 - a. Water fraction of manure = 0.77 (36)
 - b. Water content of manure = 0.062 kg/day
 - c. Respired water to water intake ratio = 0.43:1 (36)
 - d. Respiratory losses = 0.068 kg/day
 - e. Water balance: Water intake + Metabolic water -
Stored water - Fecal water - Respired water =
0.12 + 0.027 - 0.0135 - 0.062 - 0.068 = 0.00
- 4. Heat Losses:
 - a. Body heat loss = 9.0 to 15.5 W/kg at 15° C (36)
= 7.1 to 12.9 W/kg at 27° C
 - b. Latent heat loss = 1.9 W

Table A3
Input Data Regarding Beef Production

1. Assumptions:
 - a. Growth time and weight at slaughter = 2 years, 500 kg (42,43)
 - b. Animal body temperature = 40° C (44)
 - c. Ambient temperature = 15° C
2. Feed:
 - a. Feed to weight gain ratio = 7.5:1 to 12:1, lifetime average = 9:1 (43,45,46)
 - b. Daily consumption = 1.4% to 3% of body weight/day, lifetime average = 6.2 kg/day (42,46,47)
 - c. Solid fraction in feed = 0.9 (5.58 kg/day) (42)
 - d. Metabolizable water fraction in feed = 0.54 (3.34 kg/day) (36)
 - e. Metabolizable energy content of feed = 1.00×10^4 kJ/kg (721 Watts total) (42)
3. Water Intake:
 - a. Water to feed ratio: 3:1 at 5° C and 8:1 at 32° C (average 31.0 kg/day) (42,47)
4. Environmental Requirements:
 - a. Ambient temperature comfort zone = -5° C to 25° C (assume 15° C) (44)
 - b. Ventilation (in enclosure) = 24 liters/sec/animal (44)
 - c. Space = 6 m²/animal (47)

Table A4
Output Data Regarding Beef Production

1. Metabolism and Tissue Production:
 - a. Stored tissue = 0.68 kg/day (average) (43)
 - b. Moisture fraction of tissue = 0.68 (8)
 - c. Stored water = 0.46 kg/day
 - d. Stored solids = 0.22 kg/day
 - e. Energy content of tissue = 8770 kJ/kg (8)
 - f. Stored tissue energy = 69.5 Watts
 - g. Energy requirements for metabolism = 20.1 kJ/liter O_2 consumed (8)
 - h. Metabolic energy = Feed energy - Stored tissue energy = 652 Watts
 - i. O_2 consumption = 2800 liters/day = 3.7 kg/day
 - j. Respiratory quotient = 0.8
 - k. CO_2 metabolic production = 2240 liters/day = 4.1 kg/day
2. Solid Wastes:
 - a. Total manure = 9 to 25 kg/day (47,48)
 - b. Solid fraction of manure = 0.18 (41)
 - c. Fecal solids from mass balance = Feed solids - stored solids - metabolic losses = 5.58 - 0.22 - 1.43 = 3.93 kg/day
 - d. Slaughter composition (no bones): Nitrogen = 8% to 10%; P_2O_5 = 3%; B.O.D. = 0.102% of live weight (41,49)
 - e. Bonemeal: N = 3% P_2O_5 = 20% (only 8% available) (41)
3. Water Losses:
 - a. Water fraction of manure = 0.82 (41)
 - b. Water content of manure = 17.9 kg/day

Table A4 (continued)

- c. Urine to feces ratio = 0.22:1 to 0.65:1 (assume 0.4:1) (47)
- d. Respiratory losses = 7.1 kg/day (44)
- e. Water balance: Water intake + Metabolic water -
Stored water - Fecal water - Urine - Respired water
= 31.0 + 3.3 - 0.5 - 17.9 - 8.8 - 7.1 = 0.0
- 4. Heat Losses:
 - a. Body heat loss = 2.2 W/kg at 200 kg, 1.4 W/kg at 400 kg (44)
 - b. Latent heat loss = 25% to 50% of total heat loss at 15° C to 25° C (44)
 - c. Latent heat loss = 200 W

Table A5

Input Data Regarding Pork Production

1. Assumptions:
 - a. Animal body temperature = 38°C to 39°C (8)
 - b. Ambient temperature = 15°C
2. Feed:
 - a. Feed to weight gain ratio = 2.6 to 4.2:1 (average 3.5:1) (46,50)
 - b. Daily consumption = 9% to 3.3% of body weight/day (declines with maturity), lifetime average = 2.2 kg/day (51,52)
 - c. Solid fraction in feed = 0.9 (2.0 kg/day)
 - d. Metabolizable water fraction in feed = 0.54 (1.2 kg/day)
 - e. Metabolizable energy content of feed = 12,600 kJ/kg (318 Watts total) (51)
 - f. Crude protein content = 22% to 13% (declines with maturity) (51)
 - f. Recyclable waste feed: (40,53)
 - Poultry manure = 15% of ration
 - Garbage = 6 to 9 kg/100 kg animal
3. Water Intake:
 - a. Water to feed ratio = 1.8:1 (3.96 kg/day) (52)
4. Environmental Requirements:
 - a. Ambient temperature comfort zone = 18°C to 23°C (40)
 - b. Heat input capability = 0.12 kW/m^2 (40)
 - c. Electrical input (mechanical, lighting) = 0.0014 kW/m^2 (15)
 - d. Illumination minimal
 - e. Space = $2.3\text{ m}^2/\text{animal}$ (40)

Table A6
Output Data Regarding Pork Production

1. Metabolism and Tissue Production:

- a. Stored tissue = 0.63 kg/day (lifetime average) (51)
- b. Moisture fraction of tissue = 0.65
- c. Stored water = 0.41 kg/day
- d. Stored solids = 0.22 kg/day
- e. Energy content of tissue = 10,500 kJ/kg
- f. Stored tissue energy = 76.3 Watts
- g. Energy requirements for metabolism = 20.1 kJ/liter O_2 consumed (8)
- h. Metabolic energy = Feed energy - Stored tissue energy = 242 Watts
- i. O_2 consumption = 1040 liters/day = 1.4 kg/day
- j. Respiratory quotient = 0.8
- k. CO_2 metabolic production = 832 liters/day = 1.5 kg/day

2. Solid Wastes:

- a. Total manure = 2% to 10% of body weight per day (52,54,55)
- b. Solid fraction of manure = 0.19 (41,54)
- c. Fecal solids from mass balance = Fecal solids - Stored solids - Metabolic losses = 2.0 - 0.2 - 0.5 = 1.3 kg/day
- d. Manure composition:
 - H_2O = 75% to 85% (41,54,55)
 - Organic matter = 17% (wet weight)
 - Nitrogen = 0.2% to 0.9% (dry weight) (55)
 - P_2O_5 = 0.14% to 0.83% (dry weight) (55)
 - K_2O = 0.18% to 0.52% (dry weight) (55)
- e. Slaughter composition (no bones):
 - Nitrogen = 8% to 10%; P_2O_5 = 3%; B.O.D. = 0.32% of live weight (41,49)
- f. Manure to N-fixing algae production ratio = 5.4:1, non N-fixing algae ratio = 16.3:1 (48)

Table A6 (continued)

3. Water Losses:

- a. Water fraction of manure = 0.81 (41)
- b. Water content of manure = 1.05 kg/day
- c. Urine to feces ratio = 1.2:1 (52)
- d. Urine loss = 1.26 kg/day
- e. Respiratory losses = 3.5% of body weight/day (52)
(2.4 kg/day)
- f. Water balance: Water intake + Metabolic water -
Stored water - Fecal water - Urine - Respired water =
 $4.0 + 1.2 - 0.4 - 1.1 - 1.3 - 2.4 = 0.0$

4. Heat Losses:

- a. Body heat loss for 57 kg animal, loosely confined (52)
= 117 Watts sensible, 62 Watts latent at 10° C
= 94 Watts sensible, 73 Watts latent at 20° C
= 53 Watts sensible, 94 Watts latent at 30° C
- b. Body heat loss for 57 kg animal, tightly confined (52)
= 108 Watts sensible, 67 Watts latent at 10° C
= 70 Watts sensible, 82 Watts latent at 20° C
= 6 Watts sensible, 117 Watts latent at 30° C
- c. Heat loss per unit surface area = 625 W/m² (40)

Table A7

Input Data Regarding Catfish Production

1. Assumptions:
 - a. Raceway culture
 - b. Fingerling stocking = 50 to 90 kg/m³/yr (56,57)
 - c. Average harvestable size = 0.5 kg (can be grown to 2.5 kg) (57)
2. Feed:
 - a. Feed to weight gain ratio = 1.3 to 3.3:1, best conversion rates at optimum water temperatures (49,56-59)
 - b. Daily consumption = 1.8% to 6% of body weight/day (lifetime average = 0.005 kg/day) (56,60)
 - c. Metabolizable energy in feed = 12,100 kJ/kg (0.70 Watts total) (56,61)
 - d. Feed composition (Purina Catfish Food): (56)

Protein = 36.5%	Carbohydrates = 42%
Fats = 4%	Fiber = 3%
Total nitrogen = 5.8%	Phosphorus = 1%
 - e. Terramycin = 0.0055% fish weight/day
- e. Environmental Requirements:
 - a. Water temperature comfort zone = 15° C to 35° C (57,61)
 - b. Optimum water temperature = 29° C to 30° C (59,60)
 - c. Water flow rate (raceway culture) = 0.14 to 0.50 liters/min/kg fish (56,62)

 Water flow rate (pond culture) = 1.1×10^{-4} liters/min/kg fish (62)
 - d. Dissolved oxygen = 6.3 to 7.3 ppm (56,60)
 - e. pH = 5.0 to 8.5 (optimal = 6.3 to 7.5) (9)
 - f. Stocking density = 8 to 160 kg/m³ (assume 80 kg/m³) (56,62)
 - g. Individual raceway volume = 1.2 m x 1.2 m x 15 m = 21.6 m³ (growing space = 18 m³) (56)
 - h. Electrical power required = 112 to 2500 kW/ha (56,63)

Table A8

Output Data Regarding Catfish Production

1. Metabolism and Tissue Production:

- a. Stored tissue = 0.0015 kg/day (average) (56)
- b. Moisture fraction of tissue = 0.70 (8)
- c. Stored water = 0.00105 kg/day
- d. Stored solids = 0.00045 kg/day
- e. Energy content of tissue = 6280 kJ/kg (8)
- f. Weight doubling period = 64 to 148 days (56)
- g. Total output of fish = 2.2×10^5 to 2.4×10^6 kg/ha/yr (40,56,62)

2. Solid Wastes:

- a. Total solids loss = 1.23% of body weight/day (assume 0.003 kg/day) (56)
- b. Suspended solids = 1.02% of body weight/day (56)
- c. BOD production = 0.49% of body weight/day (49,56)
- d. Nitrogen ($\text{NH}_4\text{-N}$ = 90%): 0.067% to body weight/day (56)
- e. Slaughter composition: (41)
 - Nitrogen = 4% to 10%
 - P_2O_5 = 3% to 9%
 - C/N ratio = 4 to 5:1

3. Water Losses:

- a. 5,000 to 20,000 m^3 /ha/yr depending on local weather

4. Heat Losses:

- a. Heat loss from tanks (maintaining water temperature at 30°C): (60)
 - = 1600 Watts/ m^2 at air temperature = -5°C
 - = 1200 Watts/ m^2 at air temperature = 0°C
 - = 920 Watts/ m^2 at air temperature = 10°C
 - = 540 Watts/ m^2 at air temperature = 20°C
- Note: These heat loss values are only approximate.
Heat loss is also a function of wind speed and humidity.

Table A9
Input Data Regarding Tilapia Production

1. Assumptions:
 - a. Stagnant pond
 - b. Growing time to harvest = 300 days to 0.15 kg; (6)
160 to 180 days to 0.3 kg (more intensive) (64)
 - c. Minimum marketable weight = 0.1 kg
 - d. Fingerling stocking weight = 1 to 20 grams (64)
2. Feed:
 - a. Feed to weight gain ratio = 2 to 7:1 (6,65)
 - b. Daily consumption (% of body weight/day) = (1)

<u>Age</u>	<u>Animal diet</u>	<u>Plant diet</u>
3 months	20% to 40%	30% to 60%
6 months	5% to 15%	10% to 25%
12 months	3%	3%
 - c. Types of feed:
Tilapia are omnivorous, although mainly phytophagous; will eat algae, aquatic plants and most organic wastes.
 - d. Metabolizable energy content of algae = 10,465 kJ/kg
 - e. Solid fraction of algae = 0.2 (66)
 - f. Commercial feed = 35% peanut meal; 35% soybean meal; 15% fish meal; 15% distiller's dry solubles. (65)
2. Environmental Requirements:
 - a. Water temperature comfort zone = 13° C to 38° C (6)
(temperatures outside of this range are lethal)
 - b. Optimum water temperature = 22° C to 35° C (6)
 - c. O₂ demand at 25° C = 22 to 38 mg O₂/100 grams body weight/hour (2)
 - d. Optimum pH = 7.5 to 8.5 (67)
 - e. Stocking density = 10,000 to 100,000 fish/ha (31,68)

Table A9 (continued)

f. Salinity tolerance ranges from 20% to 35%
depending on species.	(1,6)
g. Electric power required = approximately 3.1 kW/ha	(66)

Table A10

Output Data Regarding Tilapia Production

1. Metabolism and Tissue Production:

- a. Stored tissue = 1.1% to 2.0% of body weight/day (lifetime average) (1,64)
Percent gain of body weight decreases with age (6,68)
(0.002 kg/day average)
- b. Moisture fraction of tissue = 0.70 (8)
- c. Stored water = 0.0014 kg/day
- d. Stored solids = 0.0006 kg/day
- e. Energy content of tissue = 6280 kJ/kg (8)
- f. Total output of fish varies depending on culture techniques used. Reported extremes range from (1,6,64,66, 67,69,70)
200 to 18,000 kg/ha/yr. Heavier feeding, oxygenation and use of all-male hybrids result in the highest yields.

2. Solids Wastes:

- a. Lack of data; assume values for catfish (Table A8), where unavailable.
- b. Fecal solids balance (assuming algae diet):
Fecal solids = Feed solids - Stored tissue solids =
0.002 - 0.0006 = 0.0014
- c. Slaughter composition: (41)
Nitrogen = 4% to 10% P_2O_5 = 3% to 9%
C/N ratio = 4 to 5:1

3. Water Losses:

- a. 5,000 to 20,000 m³/ha/yr depending on local weather

4. Heat Losses:

- a. Heat loss from tanks (maintaining water temperature at 30° C): (60)
= 1600 Watts/m² at air temperature = -5° C
= 1200 Watts/m² at air temperature = 0° C
= 920 Watts/m² at air temperature = 10° C
= 540 Watts/m² at air temperature = 20° C
Note: These heat loss values are only approximate.
Heat loss is also a function of wind speed and humidity.

Table A11
Input Data Regarding Trout Production

1. Assumptions:
 - a. Raceway culture
 - b. Marketable size = 0.25 to 0.30 meters
2. Feed:
 - a. Feed to weight gain ratio = 1.25 to 2:1, more efficient conversion when small (lifetime average = 1.5:1) (4,71,72)
 - b. Daily consumption = 3% of body weight/day (4)
 - c. Metabolizable energy in feed = 10,600 kJ/kg (4,61)
 - d. Feed composition (Purina #20 and #25 marine ration): (3)

Protein = 20%	Carbohydrates = 49%
Fats = 10%	Fiber = 4%
Ash = 7%	H ₂ O = 10%
3. Environmental Requirements:
 - a. Optimum water temperature = 12° C to 16° C (3,4,9)
 - b. Water flow rate = 0.35 liters/min/kg fish (9)
 - c. O₂ demand = 49 to 80 mg O₂/100 grams body weight/hr. Water should be 95% saturated with O₂. Minimum concentration = 5 ppm. (2,4,73)
 - d. Production density = 2.8 kg/liter/min (on volume basis = 25 to 50 kg/m³, but flow rate is the criteria) (9,71,74)
 - e. Stocking density = 0.2 to 0.4 kg/liter/min (74)
 - f. Electrical power requirement = approximately 1.0 kWh/kg (74)

Table A12

Output Data Regarding Trout Production

1. Metabolism and Tissue Production:

- a. Stored tissue = 1.9% to 3.1% of body weight/day (0.0013 kg/day lifetime average) (3)
- b. Moisture fraction of tissue = 0.70 (8)
- c. Stored water = 0.00091 kg/day
- d. Stored solids = 0.00038 kg/day
- e. Energy content of tissue = 9200 kJ/kg (8)
- f. Energy required = 15,200 kJ/kg of weight gain (4)

2. Solid Wastes: (4)

<u>Parameter</u>	<u>Mass Fraction of Feed</u>	<u>Effluent Concentration</u>
Settleable Solids	0.30	4.71 ppm
B.O.D.	0.34	5.33
Nitrates	0.087	1.36
Ammonia	0.032	0.5
Phosphates	0.005	0.078
O ₂ uptake	0.25	3.9

3. Water Losses:

- a. 5,000 to 20,000 m³/ha/yr depending upon local weather

4. Heat Losses:

- a. Trout require cool water; therefore water heating is seldom required, and heat losses from the water are small.

APPENDIX B

This section contains data used for plant growing processes. Also included is a discussion on nutrient uptake by plants.

Nutrient Uptake as Related to Fertilizer Requirements

The wide variation in estimates of crop nutrient requirements indicates both that plant analyses vary with soil analyses and that plant analyses do not provide a clear definition of soil maintenance requirements. The three major nutrients (N, P, and K) react differently. Nitrogen is almost always quite soluble and may change oxidation state depending on the type of soil, soil aeration, and soil bacterial population. If the N assumes one of its volatile states, such as N_2O during reduction from NO_3^+ (N^{+5}) to NH_4^+ (N^{-3}), it will be lost. Retention of NH_4^+ depends on the percentage of clay which holds it by surface adsorption. Of the three nutrient requirements, those for nitrogen can be most closely approximated in the short-run by measurement of nitrogen removal in crops. Heavy excess applications lead to increased leaching losses, because of the mobility of NO_3^- with water movement and low storage capacity due to lack of precipitated or bound forms.

Phosphorus, by contrast, is strongly bound and quite pH sensitive. An excess of calcium and iron brings about the immobilization of large amounts of P and renders the element unavailable to the plants. It can be kept available by pH adjustment. It should be noted that P requirements can be substantially lower or higher than removal rates determined by plant analysis even over long time periods. Phosphorus is immobilized in the top 20 cm of the soil, and as such, its concentration is not

diminished by water percolation. Reserves of P in soil may be so large that even at soil pH levels of 6.5 to 7.0 and with less of the element added each year than is removed by the crop, yields may not be adversely affected. However, eventually a shortage would occur, and therefore sound practice dictates the maintenance of a reserve of the element in the soil.

As with phosphorus, potassium also is unpredictable on the basis of uptake measurements. It differs in that its compounds generally are very soluble, and hence, it is mobile. In terms of adsorption in clay soils, it resembles the NH_4^+ ion.

In the present report, adequate soil conditioning is assumed as are the existence of correct background nutrient levels and pH adjustment for nutrient availability (i.e. steady-state conditions, and therefore no transients). In the face of advice to the contrary in the soil and fertilizer literature, nutrient uptake is used herein as the prime indicator of soil needs. Modern soil management techniques justify this approach and would be applied in any high-output, optimized system such as are considered in this report. An additional assumption of a 20 percent N loss between application of the element to the soil and the harvesting of the crop is made to account for N-loss instead of attempting to deal with it as a variable.

In the case of legumes (e.g., alfalfa, clover), nitrogen requirements are drastically reduced as a result of N-fixation through a plant-soil bacteria symbiosis.

The value for soil nutrient removal as used in the analyses in the present report are those reported for grain and whole plant analyses. They do not reflect the nitrogen lost through leaching and volatilization

which, as stated in the preceding paragraphs, can vary considerably. For example, the application of $\text{NO}_3\text{-N}$ to a flooded rice paddy under reducing (anaerobic) conditions could be attended by a loss of nitrogen in the form of N_2O that would be several times greater than the total uptake of nitrogen by even the most active rice hybrids. On the other hand, under other conditions, the loss could be negligible. It was felt that the purposes of this report could be satisfactorily served by assuming a 20 percent loss of nitrogen. The decision was based upon the facts that manures and digester supernatants characteristically have an appreciable concentration of reduced $\text{N}(\text{NH}_3 \text{ or } \text{NH}_4^+)$ and the yields indicated in the input-output (mass balance) diagrams represent only moderate levels, and thus imply no overdosing with fertilizer. Furthermore, a detailed investigation of the variation in nitrogen loss with change in field and climatic conditions would be beyond the scope of the present project.

Also contained in this section are the input and output data used in the plant production unit process models.

Table B1

Data Used in the Mass Balance for a Tomato
Greenhouse Unit Process

Average Fruit Yield: 343 tonnes/ha/yr^a

Average Vine Yield: 20.4 tonnes/ha/yr^a

NPK Content of Plants: Nitrogen: Fruit - 0.971 tonnes/ha/yr^b
Vines - 0.453 tonnes/ha/yr^b

Phosphorus: Fruit - 0.137 tonnes/ha/yr^c
Vines - 0.062 tonnes/ha/yr^c

Potassium: Fruit - 1.715 tonnes/ha/yr^d
Vines - 0.567 tonnes/ha/yr^d

^a Average of yields reported in the literature

^b N = 0.28% of fruit weight
= 2.22% of vine weight

^c P = 0.04% of fruit weight
= 0.31% of vine weight

^d K = 0.50% of fruit weight
= 2.78% of vine weight

Table B2
Collection of Tomato Yields Reported in the Literature

<u>Locale</u>	<u>Yield (tonnes fruit/ha/yr)</u>	<u>Reference</u>
Southwest U.S.A.	325	(10)
Puerto Penasco	313	(10)
Puerto Penasco	257	(75)
Sherco, Minnesota	374	(14)
San Jose, California	425	(76)
TVA Muscle Shoals	336	(77)
Corvallis	368	(78)
Average	343	
Vines (avg. dry weight-tonnes/ha) ^{a,b}	20.4	

^a Based on dry wt. vines to be 1/16.8 of yield of fruit (79)

^b Vines as grown are 87% moisture (80)

Table B3

Estimated Heating Requirements for Greenhouse Operation
(Inside Temperature = 19° C)

<u>Location</u>	<u>Degree-C Days</u>	<u>Design Temp (°C)</u>	<u>Winter Design Heat Loss (MW/ha)</u>	<u>Annual Heat Loss (GW/ha)</u>
Birmingham, AL	1,417	-6	2.8	8,340
Anchorage, AK	6,035	-29	4.4	35,510
Tucson, AZ	1,000	0	2.5	5,880
Little Rock, AR	1,788	-5	2.8	10,520
Los Angeles, CA	749	3	2.2	4,410
San Francisco, CA	1,675	3	2.3	9,870
Jacksonville, FL	688	0	2.5	4,050
Atlanta, GA	1,648	-5	2.8	9,680
Chicago, IL	3,268	-18	3.6	19,220
South Bend, IN	3,577	-18	3.6	21,040
Dubuque, IA	4,098	-22	3.9	24,110
Louisville, KY	2,589	-11	3.2	10,020
Portland, ME	4,173	-18	3.6	24,550
Detroit, MI	3,462	-13	3.4	20,370
Duluth, MN	5,556	-26	4.2	32,680
Kansas City, MO	2,617	-13	3.4	15,400
Buffalo, NY	3,923	-14	3.4	23,080
Charlotte, NC	1,773	-6	2.8	10,430
Cleveland, OH	3,528	-11	3.2	20,760
Knoxville, TN	1,941	-8	3.0	11,420
Laredo, TX	443	2	2.3	2,610

Reference (12)

Table B4
NPK Content of Grains and Principal Forage Crops
(percent)

<u>Crop</u>	<u>N</u>	<u>P</u>	<u>K</u>
Alfalfa	2.3-3.1	0.2-0.4	1.8-2.1
Clover	2.0-2.8	0.2-0.4	1.7-2.5
Corn	2.8	0.3-0.5	0.9-1.8
Oats	1.5-1.6	0.3-0.4	1.8
Rice	2.2-2.4	0.4-2.0	1.8-1.9
Sorghum	3.4	0.2-0.6	2.7
Timothy	1.2-1.9	0.2-0.3	0.9-1.6
Wheat	2.9	0.4	1.8

References (8,81)

Table B5
Growth and NPK Uptake of Sorghum, Corn, and Hay

Item	Total (kg/ha-day)	Element (kg/ha-day)		
		N	P	K
SORGHUM				
grain	24.7	0.370	0.068	0.088
stover	--	0.361	0.049	0.493
uptake	--	0.732	0.115	0.581
CORN				
grain	23.3	0.370	0.063	0.088
stover	19.5	0.222	0.038	0.348
uptake		0.592	0.101	0.436
MIXED•CLOVER-ALFALFA				
hay	37.0	1.000	0.096	0.666

Table B6

Water Hyacinth Chemical Content
(whole plant percent dry weight)

Protein	9.7 - 23.4
Fat	1.6 - 2.2
Carbohydrate	36.9 - 51.6
Fiber	17.1 - 19.5
Ash	11.1 - 20.4
Total Kjeldahl Nitrogen	1.6 - 3.7
Phosphorous	0.31 - 0.89
Potassium	1.6 - 3.4
Metabolic Energy Content	2.7 - 3.1

References (82,83)

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APPENDIX C

This section contains data used for water treatment processes.
Values have been averaged from a variety of sources.

Table C1
Composition of Raw (Primary) and Treated (Secondary) Sewage
(mg/liter)

<u>Item</u>	<u>Average</u>	<u>Fraction of Total Solids</u>	<u>Variation</u>
A. <u>Raw Sewage</u>			
Total Solids	700 - 1570	1	
Dissolved Solids	500 ^a - 1030	0.69	0.2 - 0.94
Suspended Solids	200 ^b - 540	0.32	0.16 - 0.8
Volatile Solids	350 - 780	0.50	0.2 - 0.5
Nitrogen	40 ^c - 41	0.042	0.026 - 0.057
Phosphorous	5.6 - 10	0.0089	0.004 - 0.014
Potassium	24 - 25	0.0033	0.015 - 0.035
B. <u>Secondary Sewage</u>			
Dissolved Solids	920	0.91	
Nitrogen	24		
Phosphorus	13		
Potassium	20		

^a Vol. solids, 200 mg/liter

^b Vol. solids, 150 mg/liter

^c NH₃, 25 mg/liter

Table C2

Composition of Raw (Primary), Activated, and Digested Sludges
(percent of total solids)

<u>Item</u>	<u>Average</u>	<u>Range</u>	<u>Fraction of Total Solids</u>
A. <u>Raw</u>			
Total Solids	5.7 ^a	2 - 10	1
Volatile Solids	70	60 - 80	0.7
Nitrogen	3.6	1.5 - 5.0	0.036
Phosphorus	0.84	0.35 - 1.22	0.0084
Potassium	0.35	0 - 0.83	0.0035
B. <u>Activated</u>			
Total Solids	1.2 ^a	0.5 - 2.0	1
Volatile Solids	70	65 - 85	0.7
Nitrogen	5.8	2.3 - 8.0	0.058
Phosphorus	1.9	1.1 - 4.8	0.019
Potassium	0.35	0 - 1.0	0.0035
C. <u>Digested</u>			
Total Solids	6.5 ^a	2 - 12	1
Dissolved Solids	7	--	0.07
Volatile Solids	48	30 - 62	0.48
Nitrogen ^b	4.0	1.6 - 6.0	0.04
Phosphorus	1.6	0.8 - 3.9	0.016
Potassium	0.6	0 - 2.5	0.006

^a Solids content of the sludge "as is"

^b The nitrogen is split almost evenly between the liquid and the dissolved solids.

Table C3
Primary and Secondary Sewage Treatment Removal Efficiencies

Item	-----Treatment (%)-----					
	Primary		Secondary		Primary + Secondary ^a	
	<u>Avg.</u>	<u>Range</u>	<u>Avg.</u>	<u>Range</u>	<u>Avg.</u>	<u>Range</u>
B.O.D.	32	22-49	87	81-96	91	88-9
Nitrogen	9	9	--	--	40 ^b	40-60
Phosphorus	11	10-12	--	--	32	32-33
Total Solids	20	20	--	--	--	--
Susp. Solids	66	60-68	79	70-96	93	90-99
Vol. Solids	38	38	--	--	--	--

^aCumulative

^bUncertain

Table C4

Data Regarding Algae Production
(Ranges for Chlorella, Scenedesmus, Spirulina)

Dried Algae

T.S. $\approx$ 90 to 96 percent
Bound Water $\approx$ 4 to 10 percent
Ash $\approx$ 6 to 10 percent

Algal cell is about 80 percent H₂O

Average Composition (dry weight)

N $\approx$ 6 to 8 percent
P $\approx$ 1.2 to 2.6 percent
K $\approx$ 0.4 to 1.6 percent

Yields

45 to 240 kg/ha/day

Concentrations

10⁵ to 10⁷ cells/ml

Pond Depth

Optimum $\approx$ 11 cm
Practical $\approx$ 20 to 35 cm

Evaporation from Pond

0.51 to 5.1 cm/week

BOD Reduction

About 80 to 90 percent

References (17, 33, 84, 85)

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APPENDIX D

This section contains details concerning the mass balance analyses of the integrated complexes studied. Additional detail and calculations are given for the first case to better acquaint the reader with the integration procedure.

Development of the Chicken-Digester-Algae-Tilapia Complex

Relying upon the unit process models developed, the block diagram shown in Figure D1 was drawn. The network analyses used in arriving at transfer functions for the model are as follows:

$$x_1 = u + x_8 + x_9$$

$$x_2 = k_3 x_1$$

$$x_3 = x_5 + x_6 + x_7 + k_7 x_2 = (k_2 + k_4) x_1 + k_{14} x_4 + k_7 k_3 x_1 = (k_2 + k_4 + k_7 k_3) x_1 + k_{14} x_4$$

$$x_4 = k_{10} x_3$$

$$x_5 = k_2 x_1$$

$$x_6 = k_4 x_1$$

$$x_7 = k_{14} x_4$$

$$x_8 = k_9 x_3$$

$$x_9 = k_{11} x_3$$

$$y = k_{13} x_4$$

$$x_3 = (k_2 + k_4 + k_7 k_3)(u + (k_9 + k_{11}) x_3) + k_{14} k_{10} x_3$$

$$x_3 = \frac{k_2 + k_4 + k_7 k_3}{1 - k_{14} k_{10} - (k_2 + k_4 + k_7 k_3)(k_9 + k_{11})} u$$

$$y = k_{13} x_4 = k_{13} k_{10} x_3$$

$$y = \frac{(k_{13} k_{10})(k_2 + k_4 + k_7 k_3)}{1 - k_{14} k_{10} - (k_2 + k_4 + k_7 k_3)(k_9 + k_{11})} u = Ku$$

$$x_2 = k_3 x_1 = k_3(u + x_8 + x_9) = k_3(u + (k_9 + k_{11}) x_3)$$

$$x_2 = k_3(1 + (k_9 + k_{11})) \frac{(k_2 + k_4 + k_7 k_3)}{1 - k_{14} k_{10} - (k_2 + k_4 + k_7 k_3)(k_9 + k_{11})} u = Lu$$

$$x_1 = u + (k_{11} + k_9) \frac{(k_2 + k_4 + k_7 k_3)u}{1 - k_{14} k_{10} - (k_2 + k_4 + k_7 k_3)(k_9 + k_{11})}$$

$$x_1 = (1 + (k_{11} + k_9)) \frac{(k_2 + k_4 + k_7 k_3)}{1 - k_{14} k_{10} - (k_2 + k_4 + k_7 k_3)(k_9 + k_{11})} u = Mu$$

The constants assigned to the various elements in the model are numerical values taken either individually from the literature or averaged. They are listed in Table D1. Calculations based on the data and on the analysis are given in Table D2.

Figure D1. Block diagram model of a Chicken-Digester-Algae-Tilapia Complex.

Table D1

Transfer Functions for the Chicken-Digester-Algae-Tilapia Complex

Item	k	Total Solids	Volatile Solids	Nitrogen
Gas	k ₁	0.127	0.172	0.039
Flushwater	k ₂	0.333	0.300	0.536
Settled solids	k ₃	0.181	0.206	0.098
Supernatant	k ₄	0.311	0.323	0.327
Grit	k ₅	0.047	0.0	0.0
Gas	k ₆	0.554	0.680	0.0
Supernatant	k ₇	0.446	0.320	1.0
Gas	k ₈	0.281	0.298	0.167
Sump	k ₉	0.169	0.163	0.243
Algae	k ₁₀	0.100	0.111	0.033
Flushwater	k ₁₁	0.451	0.426	0.557
Gas	k ₁₂	0.595	0.595 ^a	0.600 ^a
Meat solids ^b	k ₁₃	0.155	0.155 ^a	0.212 ^a
Manure	k ₁₄	0.250	0.250 ^a	0.188 ^a

^aEstimated value^bTo arrive at a number for wet fish mass, multiply by 3.23

Table D2
Throughput Constants for the Chicken-Digester-
Algae-Tilapia Complex

Equation Item		Total Solids	Volatile Solids	Nitrogen
$(k_2 + k_4 + k_7k_3)$	=	0.725	0.689	0.961
$(k_{14}k_{10})$	=	0.025	0.0278	0.0062
$(k_9 + k_{11})$	=	0.620	0.589	0.800
x_3	=	1.38 u	1.216 u	4.27 u
x_1	=	1.85 u	1.716 u	4.42 u
$x_2 = k_3x_1$	=	0.335 u	0.354 u	0.433 u
$x_4 = k_{10}x_3$	=	0.138 u	0.135 u	0.141 u
$x_5 = k_2x_1$	=	0.616 u	0.515 u	2.37 u
$x_6 = k_4x_1$	=	0.575 u	0.554 u	1.45 u
$x_7 = k_{14}x_4$	=	0.035 u	0.034 u	0.027 u
$x_8 = k_9x_3$	=	0.233 u	0.198 u	1.04 u
$x_9 = k_{11}x_3$	=	0.622 u	0.518 u	2.38 u

The transfer functions can be used to determine the amounts of nitrogen and phosphate that can be recovered as well as fish and methane production:

1. Yield of fish (wet weight) as a function of input manure: In making this calculation it should be noted that the transfer function is not suited to the determination of fish yield, since the function merely states the fraction of the input total solids that is converted to algal solids. The yield of fish can be ascertained through a determination of x_{4N} which leads to the determination of algal mass, and from the latter to a determination of yield of fish. The calculations are as follows:

$$x_{4N} = Y_N/k_{13N} = \frac{.0298}{.212} = .1406 \frac{\text{g N in algae}}{\text{g N in manure}}$$

$$\frac{.06 \text{ g N in manure}}{\text{g dry manure}} \times \frac{.1406 \text{ g N in algae}}{\text{g N in manure}} \times \frac{\text{g algae}}{.08 \text{ g N in algae}}$$

$$= \frac{.1054 \text{ g algae}}{\text{g dry manure}}$$

$$\frac{.1054 \text{ g algae}}{\text{g manure}} \times \frac{1 \text{ g wet fish}}{2 \text{ g algae}} = .0527 \frac{\text{g wet fish}}{\text{g dry manure}}$$

2. Nitrogen recovery: The extent of nitrogen recovery is calculated as follows:

$$Y_N = \frac{(.212)(.033)(.536 + .327 + .098)}{1 - (.0188)(.033) - (.536 + .327 + .098)(.243 + .557)}$$

$$Y_N = .0298 \frac{\text{g N in fish}}{\text{g N in manure}}$$

$$\frac{\text{g dry fish solids}}{.109 \text{ g N in fish}} \times \frac{.0298 \text{ g N in fish}}{\text{g N in manure}} \times \frac{.06 \text{ g N in manure}}{\text{g manure}}$$

$$= .0164 \frac{\text{g dry fish solids}}{\text{g manure solids}}$$

3. Methane Production: The calculation for arriving at methane production on the basis of total solids is as follows:

$$x_2 = k_3 \left(1 + \frac{(k_9 + k_{11})(k_2 + k_4 + k_7 k_3)}{1 - k_{14} k_{10} - (k_2 + k_4 + k_7 k_3)(k_9 + k_{11})} \right)$$

$$= (.181) \left(1 + \frac{(.62)(.725)}{1 - (.025) - (.62)(.725)} \right) = .336 \frac{\text{g biogas}}{\text{g manure solids}}$$

Sixty percent of CH_4 (by volume) gives

$$\frac{.60 \times 16}{.6 \times 16 + .4 \times 44} = .353 \text{ or } 35.3\% \text{ of } \text{CH}_4 \text{ by weight}$$

$$\text{the yield is } (.353)(.336) = .119 \frac{\text{g } \text{CH}_4}{\text{g dry manure solids}}$$

4. Phosphate Recovery: In calculating the ratio of phosphate recovery to manure input, it is assumed that one percent of the wet weight of fish is phosphorus. Then, allowing for algal uptake, 98.3 percent of the phosphate in the manure would be precipitated in the algae pond during times of high pH levels. The potential precipitation of phosphorus would then be:

$$\frac{0.03 \text{ g P}}{\text{g dry manure}} \times \frac{0.98 \text{ g P precip.}}{\text{g P input}} \times \frac{310 \text{ g } \text{Ca}_3(\text{PO}_4)_2}{62 \text{ g P}}$$

$$= 0.148 \frac{\text{g } \text{Ca}_3(\text{PO}_4)_2}{\text{g dry manure}}$$

The transfer functions are applicable throughout for nitrogen. However, with respect to total mass, the coefficients for total solids can not be used to determine algal mass (x_4) and fish mass (y). The reason is that CO_2 exchange at the pond surface is not taken into account. Total solids cannot be taken as a feedback, because no data are given for gas exchange (O_2 and CO_2) between the atmosphere and the pond surface. Yet, this exchange could strongly affect the amount of algae produced. The effects on the transfer function values of various hypothetical feedback loops are more easily expressed by way of the nitrogen balances. Thus, algal mass production can be estimated through the use of

nitrogen x_{4N} , the usual nitrogen content of algae (0.08), and a fish mass based on a 2:1 feed conversion.

Development of the Greenhouse-Cattle-Digester-Open Field Complex

A proposed block diagram model for a complex in which tomatoes would constitute the greenhouse crop; and corn, the open field crop is shown in Figure D2. The network analysis used in arriving at transfer functions for the model is as follows:

$$x_1 = k_2 u$$

$$x_2 = x_1 + x_6$$

$$x_3 = k_4 x_2$$

$$x_4 = x_3 + x_7 + x_8$$

$$x_5 = k_6 x_4 = k_6 (x_3 + x_7 + x_8) = k_6 (k_4 x_2 + k_{10} x_5 + k_1 u)$$

$$x_5 = \frac{k_6 (k_4 k_2 + k_1)}{1 - (k_6 k_4 k_8 + k_6 k_{10})} u$$

$$x_6 = k_8 x_5$$

$$x_7 = k_{10} x_5$$

$$x_8 = k_1 u$$

$$y = k_9 x_5$$

The equations given above can be solved by multiplying the inputs to the unit processes by the corresponding transfer functions given in Table D3.

Figure D2.. Block diagram model of a Greenhouse-Cattle-Digester-Open Field Complex.

Table D3
Transfer Functions for the Greenhouse-
Cattle-Digester-Open Field Complex

		<u>N</u>	<u>P</u>	<u>K</u>
Greenhouse vine wastes	k ₁	0.31	0.30	0.25
Cannery wastes	k ₂	0.01	0.01	0.01
Tomatoes	k ₃	0.67	0.70	0.74
Manure	k ₄	0.80	0.73	0.67
Beef	k ₅	0.20	0.27	0.33
Digester effluent	k ₆	1.00	1.00	1.00
Digester gas	k ₇	0.00	0.00	0.00
Open field crops (corn)	k ₈	0.49	0.42	0.14
Output (corn)	k ₉	0.00	0.00	0.00
Crop wastes (corn)	k ₁₀	0.31	0.26	0.58
Open field losses (corn)	k ₁₁	0.20	0.32	0.28

Development of the Chicken-Cattle-Digester-Open Field Complex

A block diagram model of this system is presented in Figure D3. The network analysis used in arriving at transfer functions for the model is as follows.

$$\begin{aligned}
 x_1 &= x_{17} + x_{26} + x_{31} \\
 x_2 &= k_1 x_1 \\
 x_3 &= k_3 x_3 \\
 x_4 &= k_2 x_1 \\
 x_5 &= x_4 + x_{16} + x_{22} + x_{27} \\
 x_6 &= k_6 x_5 \\
 x_7 &= k_4 x_5 \\
 x_8 &= k_5 x_5 \\
 x_9 &= x_8 + x_{19} + x_{29} \\
 x_{10} &= k_7 x_9 \\
 x_{11} &= k_8 x_9 \\
 x_{12} &= k_9 x_9 \\
 x_{13} &= k_{10} x_9 \\
 x_{14} &= u_2 + x_{12} \\
 x_{15} &= k_{13} x_{14} \\
 x_{16} &= k_{14} x_{14} \\
 x_{17} &= k_{12} x_{14} \\
 x_{18} &= k_{11} x_{14} \\
 x_{19} &= k_{11} x_{14} \\
 x_{20} &= u_3 + x_{11} \\
 x_{21} &= k_{16} x_{20} \\
 x_{22} &= k_{15} x_{20} \\
 x_{23} &= x_2 + x_7 \\
 x_{24} &= k_{23} x_{23} \\
 x_{25} &= k_{22} x_{23} \\
 x_{26} &= k_{20} x_{23} \\
 x_{27} &= k_{21} x_{23} \\
 x_{28} &= u_1 + x_{13} \\
 x_{29} &= k_{17} x_{28} \\
 x_{30} &= k_{19} x_{30} \\
 x_{31} &= k_{18} x_{30}
 \end{aligned}$$

Figure D3. Block diagram model of a Chicken-Cattle-Digester-Open Field Complex.

The equations given above can be solved by multiplying the inputs to the unit processes by the corresponding transfer functions given in Table D4.

Table D4

Transfer Functions for the Chicken-
Cattle-Digester-Open Field Complex

		<u>N</u>	<u>P</u>	<u>K</u>
Chicken body	k_1	0.60	0.38	--
Chicken manure	k_2	0.40	0.62	--
Chicken respiration	k_3	0.00	0.00	0.00
Cattle body	k_4	0.18	0.27	--
Cattle manure	k_5	0.82	0.73	--
Cattle respiration	k_6	0.00	0.00	0.00
Digester gas	k_7	0.00	0.00	0.00
Digester effluent	k_8	0.29	0.29	0.29
Digester effluent	k_9	0.66	0.66	0.66
Digester effluent	k_{10}	0.053	0.053	0.053
Corn waste	k_{11}	0.27	0.28	0.72
Corn grain	k_{12}	0.12	0.13	0.05
Corn field loss	k_{13}	0.30	0.24	0.10
Corn grain	k_{14}	0.32	0.35	0.14
Hay	k_{15}	0.80	0.76	--
Hay field loss	k_{16}	0.20	0.24	--
Sorghum waste	k_{17}	0.30	0.19	0.61
Sorghum grain	k_{18}	0.30	0.27	0.11
Sorghum field loss	k_{19}	0.40	0.54	0.28
Slaughter wastes	k_{20}	0.15	0.15	--
Slaughter wastes	k_{21}	0.21	0.21	--
Chicken	k_{22}	0.29	0.24	--
Beef	k_{23}	0.34	0.40	--

Development of the Sewage-Digester-Hyacinth-Swine Complex

A block diagram model of this system is presented in Figure D4. The network analysis used in arriving at transfer functions for the model is as follows.

$$x_1 = k_1 u$$

$$x_2 = k_2 u$$

$$x_3 = k_3 u$$

$$x_4 = x_2 + x_{12} + x_{16} = k_2 u + k_{10} x_8 + k_{13} x_{15}$$

Substituting and solving:

$$x_4 = \frac{k_2 + k_{10}(k_1 + k_{11}k_3) + \frac{k_{13}}{1 - k_{16}k_{14}} (k_9(k_1 + k_{11}k_3) + k_{12}k_3)}{1 - (k_{10}k_5 + \frac{k_{13}(k_6 + k_9k_5)}{1 - k_{16}k_{14}})} u$$

$$x_5 = k_4 x_4$$

$$x_6 = k_5 x_4$$

$$x_7 = k_6 x_4$$

$$x_8 = x_1 + x_6 + x_{13}$$

$$x_9 = k_7 x_8$$

$$x_{10} = k_8 x_8$$

$$x_{11} = k_9 x_8$$

$$x_{12} = k_{10} x_8$$

$$x_{13} = k_{11} x_3$$

$$x_{14} = k_{12} x_3$$

$$x_{15} = x_7 + x_{11} + x_{14} + x_{18} = k_6 x_4 + k_9 x_8 + k_{12} k_3 u + k_{16} k_{14} x_{15}$$

$$x_{15} = \frac{(k_6 + k_9 k_5) x_4 + (k_9 k_1 + k_9 k_{11} k_3 + k_{12} k_3) u}{1 - k_{16} k_{14}}$$

$$x_{16} = k_{13} x_{15}$$

$$x_{17} = k_{14} x_{15}$$

$$x_{18} = k_{16} x_{17}$$

$$y = k_{15} x_{17}$$

$$y = k_{14} k_{15} x_{15} = (k_{14} k_{15}) \frac{(k_6 + k_9 k_5) x_4 + (k_9 k_1 + k_9 k_{11} k_3 + k_{12} k_3) u}{1 - k_{16} k_{14}}$$

Figure D4. Block diagram model of a Sewage-Digester-Hyacinth-Swine-Open Field Complex.

The equations given above can be solved by multiplying the inputs to the unit processes by the corresponding transfer functions given in Table D5.

Table D5
Transfer Functions for the Sewage-
Digester-Hyacinth-Swine Complex

		<u>N</u>	<u>P</u>	<u>K</u>
Sewage effluent	k_1	0.45	0.49	0.63
Sewage sludge	k_2	0.37	0.32	0.12
Sewage effluent	k_3	0.18	0.19	0.25
Digester gas	k_4	0.00	0.00	0.00
Digester effluent	k_5	0.88	0.77	0.97
Digester sludge	k_6	0.12	0.23	0.03
Field losses (gas)	k_7	0.20	0.00	0.00
Field losses (solids)	k_8	0.20	0.56	0.49
Grain	k_9	0.34	0.26	0.09
Crop wastes	k_{10}	0.26	0.18	0.42
Pond effluent	k_{11}	0.12	0.22	0.30
Hyacinths	k_{12}	0.88	0.78	0.70
Swine manure	k_{13}	0.54	0.72	0.80
Swine body	k_{14}	0.46	0.28	0.20
Pork	k_{15}	0.69	0.69	0.69
Slaughter wastes	k_{16}	0.31	0.31	0.31

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APPENDIX E

Figure E1. Integration of mass balances in the Chicken Manure-Digester-Algae-Tilapia Complex.

Figure E2. Integration of mass balances in the Greenhouse-Cattle-Digester-Open Field Complex.

Figure E3. Integration of mass balances in the Chicken-Cattle-Digester-Open Field Complex.

Figure E4. Integration of mass balances in the Sewage-Digester-Hyacinth-Swine-Open Field Complex.

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