Animal Waste Conversion Systems Based on Thermal Discharges

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CONTENTS

ABSTRACT

Society faces many problems related to its growth in numbers and standard of living. Of major concern is environmental degradation resulting from pollution and the consumptive use of non-renewable natural resources. An animal waste management scheme was developed on the premise that one solution to these problems is the development of integrated production systems with recycled sources. The waste product of one industry must become the raw material for another. The feasibility of using waste heat from steam electric plants to sustain a food-producing complex which recycles nutrients is analyzed in this document. Specifically, it is proposed to use microorganisms to convert animal waste into a high protein animal feed and a methane-rich fuel gas. Waste heat from steam electric plants is used as a low cost source of energy for maintaining stable, elevated temperatures in anaerobic digestion and single cell protein production units. Benefits to society include: improved efficiency of energy use and food production, minimization of pollution problems associated with food production, recycling of raw materials, and conservation of non-renewable resources.

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ANIMAL WASTE CONVERSION SYSTEMS BASED ON THERMAL DISCHARGES

STATEMENT OF PROBLEMS AND OPPORTUNITIES

Animal Waste

A major problem confronting animal agriculture is adequate disposal of waste. In the past, livestock were produced by many farmers feeding small numbers of animals. These dispersed operations kept manure concentrations relatively small. The manure was applied to cropland on the farm where it was produced. Changing practices have created situations where the production of animal waste occurs in large quantities on small areas. This concentration is developing in the form of outside feedlots and total confinement rearing units where thousands of animals are contained continuously on a few acres of land. The capacity of the local environment to dilute, stabilize, and dissipate the accumulation of wastes from these systems is exceeded in many locations.

There are about 110 million cattle, 22 million sheep and goats, 54 million swine, 825 million chickens and turkeys, and 7 million horses in the United States. These produce five million tons of waste daily, containing over 800,000 tons of dry matter, 32,000 tons of nitrogen, and 10,000 tons of phosphorus. In comparison, the 210 million humans in the United States produce about 375,000 tons of waste containing 59,000 tons of dry matter, 2,900 tons of nitrogen, and 350 tons of phosphorus daily (Miner, 1968, 1969).

Current manure management is expensive in terms of equipment and labor, and frequently does not provide adequate protection to the environment. Highly mechanized manure management systems which give adequate consideration to environmental quality are essential for the future of livestock production if an abundant supply of high quality meat is to be available at a reasonable cost.

Malodors emanating from animal production units are frequently disagreeable to nearby residents in both rural and urban communities. In several cases such malodors have resulted in legal procedures leading to injunctions to halt the operation of animal units unless some method of waste disposal is followed that controls the malodors.

Public action programs for pollution abatement make it necessary to develop methods for controlling odors and the concentrations of solids, nitrogen, and phosphorus which enter surface and ground water. Animal wastes are also a potential source of pathogenic organisms. These (organisms or wastes) can be scattered into the environment and become a health hazard, particularly under the increasing demand for water-based recreational sites.

Proposed Animal Waste Management Systems

The need for intensified research efforts in animal waste management was recognized about 10 years ago. Since then a series of conferences devoted to this topic have been held, indicating the widespread concern. The urgency of the problem has been discussed, as well as the results of various studies on the characteristics, handling, treatment, utilization, and disposal of animal manures.

Animal manure is a highly concentrated source of organic matter, plant nutrients and microorganisms (Jeffrey et al., 1963; Taiganides and Hazen, 1966). The quantitative character of waste produced by a specific livestock operation is a function of the number and species of animals being raised in addition to the system of manure collection and the ration being fed.

Runoff from unroofed cattle feedlots has been studied to determine quantity and quality as a function of feedlot design, management and climatic conditions (Miner et al., 1966). Similar information for other species of livestock being confined in unroofed pens has not been obtained. Systems for the collection of cattle feedlot runoff have been designed which minimize the quantity of runoff for disposal (Grub et al., 1969).

The storage and treatment of livestock manure are accompanied by odors which are objectionable to both livestock producers and the public (Miner, 1973). Some work has been done in characterizing these odors by identification of the component gases (Taiganides and White, 1968; Merkel, Hazen, and Miner, 1969). Measurement of odors to determine nuisance levels and progress in odor control have been of limited success (Lebeda and Day, 1965; Day, 1966; Hammond, Day, and Hansen, 1968).

Different methods of facilitating manure collection in livestock housing have been evaluated. Sloping floors, flushing gutters, and various designs of slotted floors have been used in commercial installations. Similarly, manure storage tanks of various capacities, configurations, and structural materials have been constructed. Storage remains an expensive aspect of manure management, particularly in northern states where long-term storage is required.

Various devices for the agitation of stored manure and its transfer to cropland have been considered. Centrifugal and positive displacement pumps, augers, and vacuum systems for transferring manure from storage tanks to hauling vehicles were studied (Schacht, 1967). Tank wagons and irrigation pumps for the distribution of manure to cropland are under study (Decker and Reed, 1967). These systems are currently limited by climatic conditions, odor problems, large land area requirements, and cost. The escape of toxic gases during manure tank agitation has been of concern to many operators and has resulted in animal deaths (Miner, 1973).

Various schemes have been proposed for the treatment of animal manure prior to utilization or disposal. Lagoons were found to effectively store manure but did not produce an effluent suitable for discharge into streams. In addition, lagoons have been sources of objectionable odors (Dornbusch and Andersen, 1964; Clark, 1965; Hart and Turner, 1965; McCoy, 1967). More sophisticated anaerobic treatment units have been considered but not adopted by the livestock industry (Taiganides et al., 1963). Aerobic treatment of animal manures has been of considerable interest during the past three to five years. Aerated lagoons and oxidation ditches are effective in minimizing odors from waste treatment. However, they do not produce effluents suitable for discharge to surface watercourses and they have high rates of energy consumption (Dale, 1967; Jones, Converse, and Day, 1968; Hermanson et al., 1969; Pratt et al., 1969). Treated animal waste remains high in organic matter and plant nutrients. Land application is the most suitable disposal method for this liquid.

Research on the utilization of animal manures for purposes other than direct soil enrichment is under way. Two examples are the refeeding to livestock (Bratzler and Long, 1968) and the use as a substrate for the growth of economically useful plants. Alternate methods of manure processing under consideration include dehydration and incineration (Byrley, 1968). These methods are in exploratory stages and must be pursued through the development of usable equipment and the planning of auxiliary equipment and management techniques. Research is continuing on the use of soil as a recipient for animal manures. More sophisticated methods of manure application, more effective use of the nutrients, and use of the soil as a high capacity treatment system are being investigated (Braga, 1967; Novak and Lobl, 1967).

Animal waste management research has been expanding rapidly and an increasing number of papers are published annually. Reviews of these papers are published for easy access (Miner, 1968, 1969). Loehr (1968) published a comprehensive review of animal waste research. Muehling (1969) prepared a review of research on swine wastes.

Photosynthetic reclamation of agricultural solid and liquid wastes was investigated in a pilot scale project at the University of California (Dugan et al., 1970). A partially closed system of animal waste management based on the integration of an anaerobic and aerobic phase, the recycling of water, and the reclamation of algae was studied at the Sanitary Engineering Research Laboratory. The investigators present a detailed materials balance (Dugan et al., 1970) which indicates a favorable economic outlook for the proposed system.

Algae and Food Production

Scope of the Problem.

Efficient production of quality protein is one of the most pressing worldwide problems. Dr. Norman E. Borlaug, winner of the 1970 Nobel Peace Prize for the development and use of high-yielding wheat varieties, indicates that a short-term solution to the problem of large-scale starvation is relatively simple (Leach, 1972). The production potential of several developed countries is large. However, the long-term outlook is not as encouraging. He indicates that the amount of land man has turned into deserts by overgrazing and other pressures is about five times greater than the amount of land brought under irrigation. In India, one-quarter of the cultivated acreage has such heavy erosion that the topsoil will have disappeared before the end of the century. In the Andean regions of Latin America, 50 million people are trying to live on soil that is actually vanishing. Any further development of production potential through use of manufactured fertilizers, irrigation, or large-scale drainage projects requires capital that is not available. Furthermore, the increase in the use of water and fertilizers cannot go on forever. It takes the amount of energy one gets from burning five tons of coal to make one ton of nitrogen fertilizer. The amount of energy that India would have to use to provide enough fertilizer to achieve the production rate attained in Japan makes such a development prohibitive. Thus, alternate methods of food production must be considered.

Advantages of Algae

The importance of single cell protein has been recognized in major reports by the panel on World Food Supply of the President's Science Advisory Committee (The World Food Problem, 1967) and the United Nations Economic and Social Council (1967).

During the period of maximum growth, C_4 photosynthetic plants reach a photosynthetic efficiency that is very close to the theoretical maximum computed on the basis of the amount of incident radiation within the photosynthetic absorption bands. These high efficiencies have been demonstrated for corn and sugar cane. The non-C_4 plants, or C_3 plants, such as wheat and rice, which exhibit photorespiration, do not appear to reach these efficiencies because that a considerable portion of the absorbed energy is lost in photorespiration. Consequently, these plants are not as efficient as the C_4 plants. The theoretical maximum yield has also been obtained with the algae Chlorella and Scenedesmus.

All the common crop species now bred are annuals or biennials and the yield component of these crops is usually the seed portion (except sugar). Furthermore, the crop does not grow throughout the year and only a small portion of the fixed CO_2 is harvested. Therefore, the marketable yield per year of these crops is far short of the theoretical maximum computed on the basis of available radiant energy. In contrast, algae do not suffer under the burden of photoperiodism and unmarketable roots and stubble. The yield components provide some further interesting comparisons. A 10 T/ha crop of corn with 10 percent protein has a protein yield of 1 T/ha. A wheat or rice crop could yield no more than this. By comparison a 32 T/ha Chlorella crop (Ryther, 1959) containing more than 50 percent protein produced 16 T/ha of protein. These observations are further emphasized by data in Table 1.

Table 1. Yield per ha of several crops obtained from the indicated literature reports[1]

Crop	Nitrogen Content	Protein Content	Dry Matter Yield	Protein Yield
	%	%	T/ha/year	T/ha/year
Soybeans[2]	2.60	16.25	14	2.3
Corn[2]	1.20	7.50	30	2.3
Sugarcane[2]	0.29	1.78	125	2.2
Algae[3]	8.19	51.20	112	57.3

1) E. D. Bickford and S. Dunn, 1972.
2) O. W. Wilcox, 1959.
3) R. H. T. Mattoni et al., 1965.

The biological value of algal protein has been shown to be equivalent to milk protein and superior to that of lysine-poor corn and wheat proteins (Soeder and Pabst, 1970). Microorganisms thus have a protein production capacity equal to 10 to 20 times that of cereal crop plants on a unit area basis. Cereal grains may have some advantage over algae in terms of available carbohydrate because, in general, algal cells do not contain large amounts of sugars or starch. Studies have shown algae to be relatively unpalatable to humans, indicating that the protein may have to be extracted for human consumption, or converted to animal protein. Highly efficient protein-extracting machines are now being perfected (Pirie, 1971). The carbonaceous waste from these machines could be utilized by feeding it to ruminant animals.

The potential for genetic improvement of single cell organisms has been little explored. Because of their short generation time these organisms have an inherent advantage for genetic improvement. The potential of these single celled organisms for genetic modification was recently demonstrated when Dixon and Postgate (1972) transferred nitrogen-fixing genes from the bacterium *Klebsiella pneumoniae* to a strain of the common gut bacterium *Escherichia coli*. Thermophilic strains of *Chlorella* and *Scenedesmus* which have already been described can grow in water temperatures of $40^{\circ}C$ and higher. These discoveries would tend to confirm the potential for modification that exists in these organisms.

Conclusions

It may thus be concluded that (i) single cell organisms have a capacity to produce 10 to 20 times as much protein per unit area per year as cereal crops, (ii) single cell organisms are well suited to using recycled nutrient elements, while cereal crops are not well adapted to the use of recycled nutrients because of distribution and transportation costs, (iii) single celled organisms may not be a good source of carbohydrate for people because of their low palatability and digestibility, and (iv) single celled organisms have a little explored potential for genetic improvement.

Feeding Trials with Algae

The attractive aspect of algal production is high protein content (Tables 1, 2, and 3). The relatively high levels of fatty acids (Klenk *et al.*, 1963), carotinoids (Iwata and Sakurai, 1963; Lautner, 1965), and vitamins are also important.

Table 2. Composition of dried *Scenedesmus* 267-3a and *Spirulina maxima* compared with the edible part of soybeans

Component	Scenedesmus[1)]	Spirulina[2)]	Soybean seed[3)]
	%	%	%
Protein	50-56	56-52	34-40
Water	4-8	10	7-10
Lipids	12-14	2-3	16-20
Carbohydrate	10-17	16-18	19-35
Fiber	3-10	?	3-5
Ash	6-10	?	4-5

[1)] C. J. Soeder and W. Pabst, 1970.

[2)] G. Clement *et al.*, 1967.

[3)] S. W. Souci *et al.*, 1962-1969.

The potential value of microalgae for the feeding of animals and people was recently reviewed by Soeder and Pabst (1970). They concluded that the nutritional value of unicellular green algae like *Chlorella* and *Scenedesmus* is greatly influenced by the method used for processing the raw material. Properly processed *Scenedesmus* 276-3a (Dortmundt strain) was found to be a suitable protein source for people and other monogastric organisms. Other reviews of the technical aspects of production of microalgae were prepared by Burlew, 1953; Meffert, 1955; Tamiya, 1957; Muntz, 1967, 1968; Oswald and Golueke, 1968a, 1968b; and Soeder *et al.*, 1970.

Table 3. Spectrum of essential amino acids in Scenedesmus compared with Spirulina maxima, soybeans, and milk in grams/16 gram total nitrogen

Amino acids	Scenedesmus[1)] A	B	C	Spirulina maxima[2)]	Soybean[3)]	Milk[3)]
Valine	7.2	6.2	7.0	6.5	5.2	7.0
Leucine	9.3	8.6	6.6	8.5	8.4	9.9
Isoleucine	4.4	3.2	4.2	6.0	5.3	6.4
Threonine	5.2	4.8	5.8	4.6	4.4	5.4
Methionine	1.4	1.4	1.5	1.4	1.7	2.5
Phenylalanine	4.6	3.9	3.6	5.0	5.8	4.8
Tryptophan	1.4	5.3	5.0	1.4	1.3	1.4
Lysine	5.7	5.3	5.0	4.6	5.6	7.7

[1)] H. D. Bock and J. Wünsche, 1967.

[2)] G. Clement *et al*., 1967.

[3)] S. W. Souci *et al*., 1962-1969.

[4)] C. J. Soeder and W. Pabst, 1970.

Feeding Trials with Animals

According to the first trials with Scenedesmus 276-3a by the "Kohlenstof-fBiologischen Forschungsstation," algal protein had a higher biological value for rats than milk or even egg protein measured according to the Protein-Efficiency-Ration (PER) concept (Fink and Herold, 1956, 1957). These researchers further showed that proper processing of algae is necessary. Animals fed wet, live algal material lost weight and showed definite protein deficiency symptoms (Fink and Herold, 1958). Best results were obtained when the algal material was first dried by infrared heat lamps and subsequently pulverized. In later feeding trials (Meffert and Pabst, 1963) the following pretreatments were evaluated: drying on pressure rollers, vacuum drying, freeze drying, raw algae, and short-term boiling. Best growth, digestibility, and protein efficiency were obtained with milk protein, followed closely by the algae dried on steam-heated pressure rollers. The roller drying provides for optimum breakdown of the algae, which apparently cannot be improved by subsequent treatments.

Digestibility of the algal protein can be substantially increased by extraction procedures. After methanol extraction, several membrane fractures of the cells were observed (Strietelmeier and Koch, 1962) and the digestibility of spray-dried algae increased from 57 to 70 percent by treatment with methanol (Nakamura and Yamada, 1960). Digestibility of the cell-free protein concentrate was even higher than that of the roller-dried material (Mitsuda, 1965) and exceeded that of soybean protein (Klyushkina and Fofanov, 1967; Klyushkina et al., 1967). It should be noted that almost 70 percent of the protein as well as several other potentially valuable materials are lost in extraction.

Feeding experiments with pigs at the Max-Planck Institute for Animal Husbandry showed results similar to those obtained with rats (Witt et al., 1962; Witt and Schröder, 1967). Experiments in America (Hintz and Heitmann, 1967) showed that algae supplements were equivalent to fish meal or soybean meal when vitamin B_{12} was added. Algal protein is well suited for feeding to chickens (Schlüter and Querner, 1957) and carp (Soeder et al., 1969).

Feeding Trials with People

Few systematic feeding trials involving humans have been conducted. Soeder and Pabst (1970) reviewed six known experiments and reached the conclusion that up to 100 g of algal material per person per day can be safely taken and toxic side effects have never been observed. They base this conclusion on reviews of experiments by Jorgensen and Convit (1953), Powell et al. (1961), McDowell and Leveille (1963), Dam et al. (1965), Lee et al. (1967), Kondratyev et al. (1966), and Kofrangi and Jekat (1967).

Algae which until recently were only grown in the laboratory for experimental purposes are gradually beginning to be considered of economic value. This change has come about because certain species present high-value protein and vitamin-rich feedstuff. These can, under favorable conditions, be cultivated in an automatic system on a full-year basis. Growth rates with respect to protein and dry matter are considerably higher than those of agronomic crops. Algae in mixed cultures with bacteria can be used for waste water reclamation. In this process, organic matter is broken down while at the same time undesirable mineral materials are removed, and a high-value animal food supplement is obtained.

PROPOSED WASTE MANAGEMENT SYSTEM

Concepts

Design of the proposed waste management system is based on the concept of a livestock confinement building where the manure is quickly removed from the animal quarters. The manure will be hydraulically flushed from the building with a frequency selected to prevent anaerobic decomposition and the associated odors. The flushing water used in the system will be recycled through a treatment scheme as outlined in Figure 1. The animal unit should be designed so that the animals have no access to the manure transport water, eliminating potential disease problems associated with drinking partially treated waste water.

The proposed system (Figure 1) consists of a manure handling unit, nutrient recovery unit, and soil filter unit. Manure is flushed from the animal quarters by the outflow from siphon-activated storage tanks, to a sump. It is then pumped with an air-lift pump to a solid-liquid separator. The solid slurry falls into an anaerobic digester and the liquid flows into algal culture basins after filter treatment to decrease turbidity and remove color caused by dissolved organic matter.

Water from the algal culture basins is passed through a centrifuge for separation from the algal mass, then stored in a reservoir. From there it can be pumped to the flush tanks for reuse in the flushing process. Gases from the anaerobic digester are vented to a storage tank for later use or to a soil filter for the removal of odors. Excess water is applied to a soil filter field.

The proposed system of animal waste management will be analyzed by considering the use of swine manure produced at the Swine Research Center on the Oregon State University campus. The discussion will be based on the management of manure produced by 50 swine. This unit size was selected because it was considered large enough to produce problems similar to those of real-world operations.

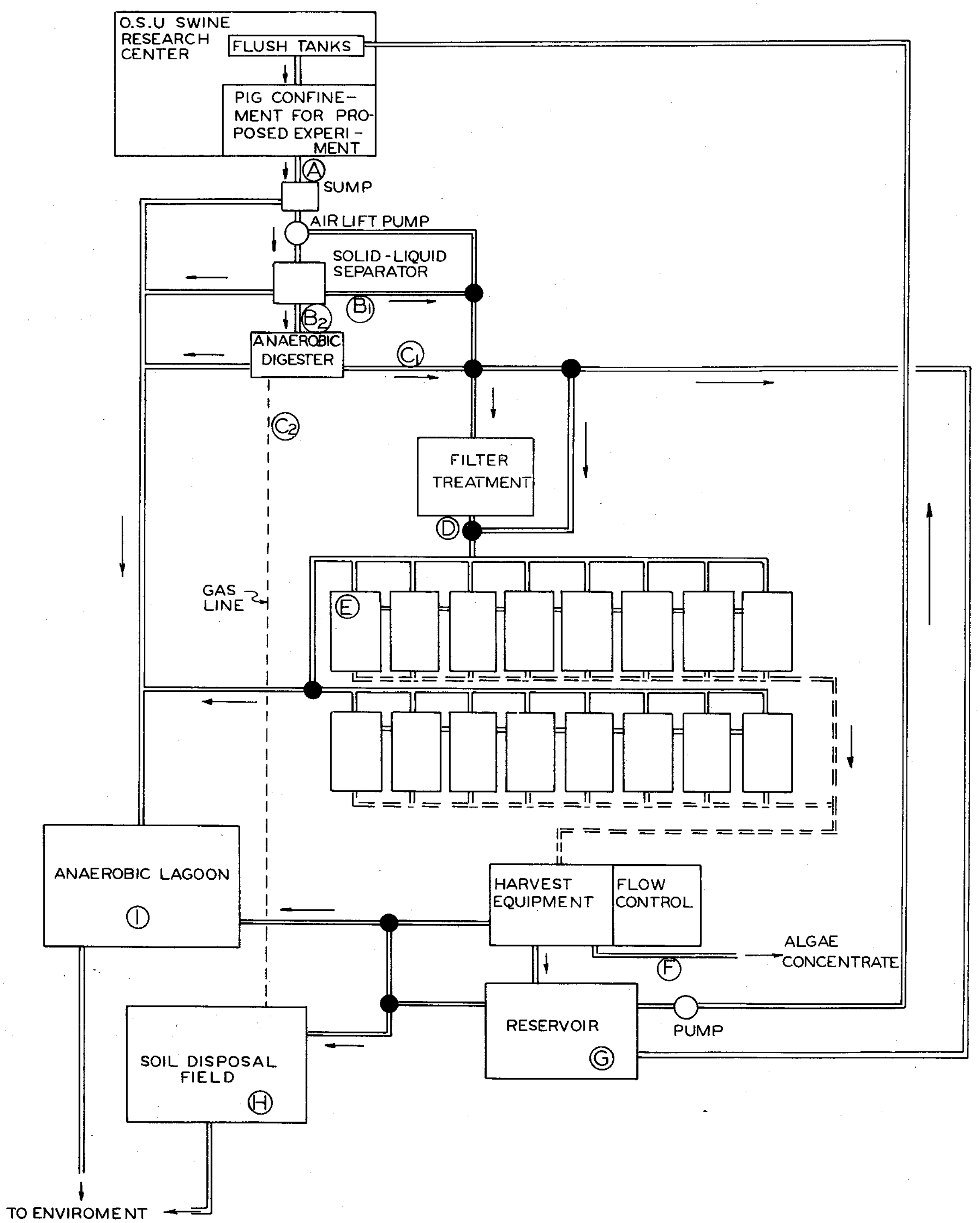

Figure 1. Schematic diagram of the proposed facility. Functions and preliminary designs of components and subsystems are described in the text.

Manure Handling System

Animal Units

The conceptual design of the proposed system of waste management will be developed by considering the management of swine manure from a portion of the confinement finishing building at the Oregon State University Swine Research Center, 2.5 km west of the Corvallis campus. Hogs are kept in this building on partially slotted floors. The manure drops into 1.20-meter-wide pits from which it is periodically drained to a nearby anaerobic lagoon. Pens, 3 meters wide and 2.15 meters deep, are along a central 1.20-meter-wide walkway. Automatic waterers and self-feeders are in each pen. These pens would be modified by replacing the pit floor. The new floor would slope at a rate of 2 percent, allowing the pens to be flushed using flush tanks (Figure 2). Flushing should occur every two to four hours, depending on the odor control achieved within the building. Effluent from the nutrient recovery system is brought into the flush tanks with a timeclock-controlled pump. A siphon is engaged when the flush tanks fill to a prescribed level, and the tank contents are discharged into the gutters with sufficient velocity to carry manure out to a sump (Figure 3). This method of manure removal has been successfully used previously and is adaptable to many buildings.

Manure Input

Six pens of the design described above would have a combined capacity of 50 animals with an average weight of 55 kg each. The anticipated rate of manure production is shown in Table 4. The manure will be flushed from the pens to a sump, then pumped with an air-lift pump to a solid-liquid separator located over an anaerobic digestion tank (Figure 3). The air-lift pump was selected to achieve a high degree of reliability and to lift the slurry at a uniform rate of 100 liters per minute or less, depending upon the flushing frequency desired.

Solid-Liquid Separator

Untreated swine manure contains a large quantity of particulate matter which is resistant to breakdown under aerobic conditions. If not removed prior to introduction into the algal basins, this material would increase turbidity, settle out as a sludge layer, and finally result in a filler of low nutritional value in the harvested algae. The purpose of the solid-liquid separator is to

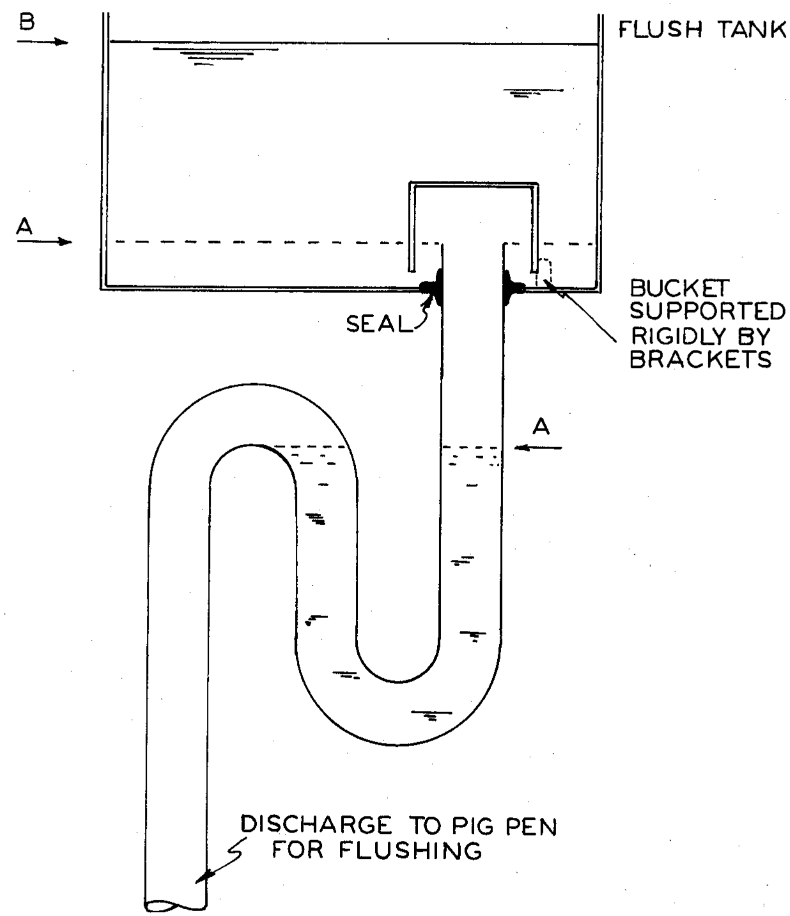

Figure 2. Conceptual design of the siphons used to activate the manure flush tanks.

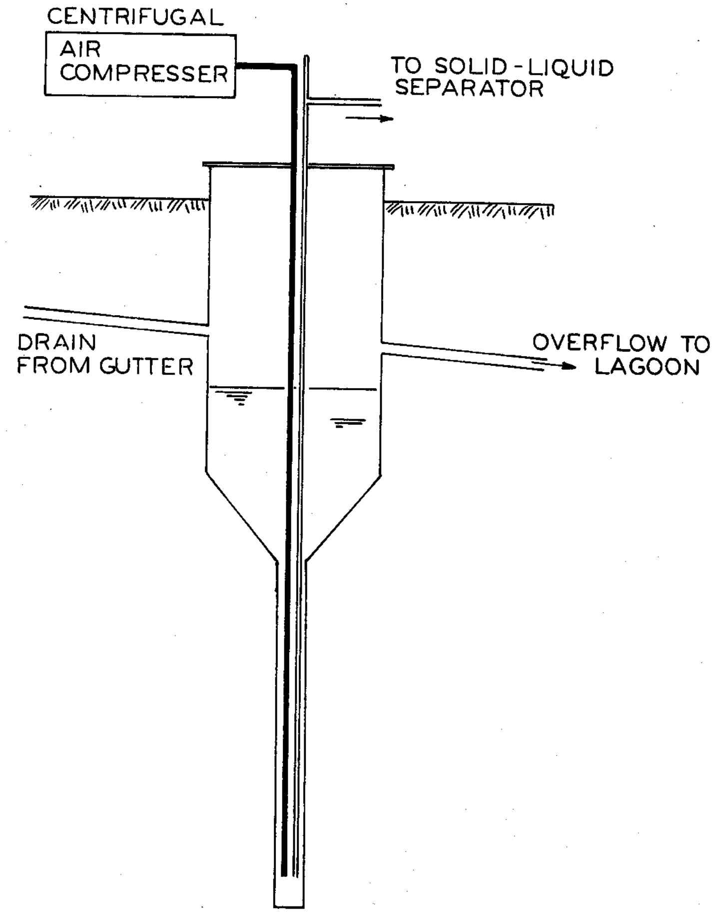

Figure 3. Schematic of the air-lift pump arrangement used to lift the manure to the solid-liquid separator. The sump functions as temporary storage reservoir for the manure after flushing.

Table 4. Daily rate of manure production in the test facility

Parameter	Value
No. of swine	50
Average live weight	55 kg
Total live weight	2750 kg
Manure	136 kg dry weight
Solids content	15 percent
Total solids	20.4 kg dry weight
Volatile solids	17.0 kg dry weight
BOD	5.7 kg
Nitrogen (as N)	1134 grams
Phosphorus (as P)	227 grams
Potassium (as K)	136 grams

remove these particles and direct them to the anaerobic digester where they can be liquefied more efficiently. The separator concentrates the solids to a 5 percent slurry which is suitable for feeding the digester.

The solid-liquid separator selected for use in the proposed management system was recently developed at Oregon State University for the removal of coarse solids from animal manures (Verley and Miner, 1973). It is intended for use in water recycling systems where large particulate matter that could interfere with the functioning of conventional water handling equipment is troublesome.

The device consists of a 70-centimeter-diameter cylinder with flighting 15 centimeters deep attached perpendicularly to the inside surface of the cylinder (Figure 4). In operating position, the cylinder is supported at an incline of approximately 17 degrees and rotated at the rate of 0.2 to 0.5 rpm. The design of the flighting and the rate of rotation are chosen to allow solids to settle into the spaces between the vanes while the liquid passes over the upper edges and flows out at the lower end of the device. The settled solids are worked upwards by the rotation of the cylinder and dropped from the upper end in the form of a slurry into the inlet box of the anaerobic digester.

Anaerobic Digestion Tank

The slurry containing the solid particles drops into the inlet box of an anaerobic digester (Figure 5) whose purpose is to convert the solids to a liquid from which nutrient recovery is possible. A water seal will be provided to prevent the escape of gases through this port. The contents of the digestion tank need to be continuously mixed and maintained at a temperature of 35 to 37 C.

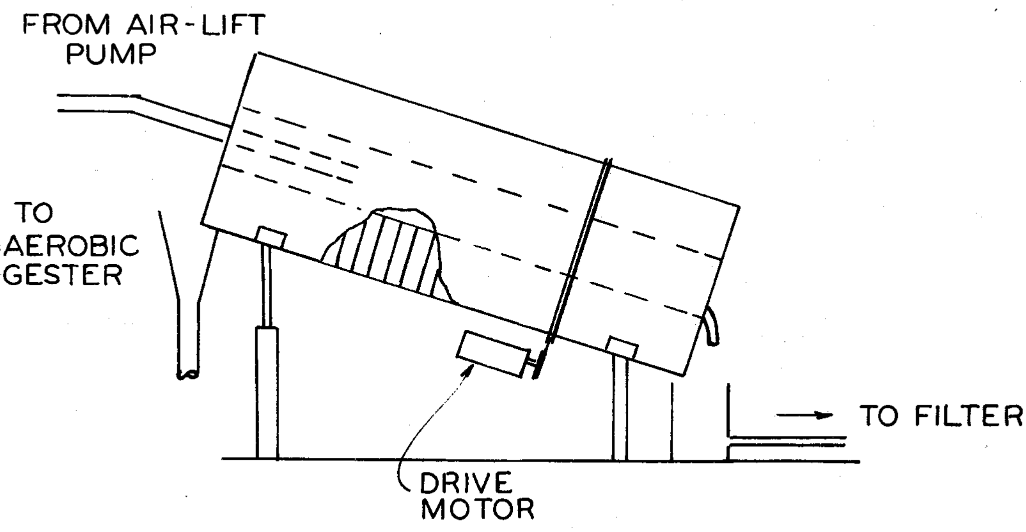

Figure 4. Schematic diagram of the rotating flighted solid-liquid separator. The cut-out portion of the cylinder shows the flighting, which has a continuous winding from the lower end to the upper end of the cylinder.

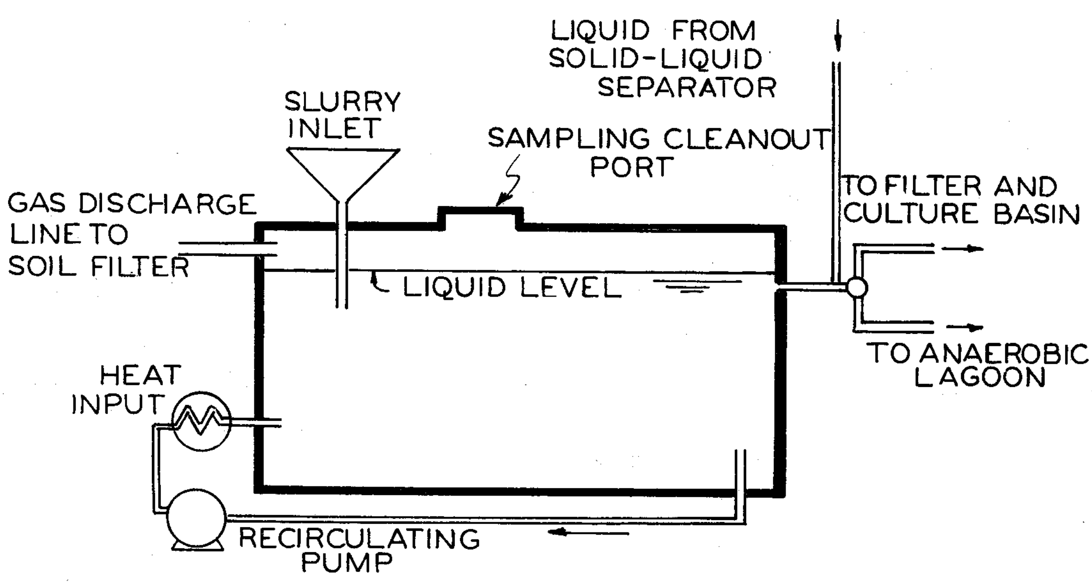

Figure 5. Schematic diagram of the anaerobic digester. The digester contents will be well stirred and recirculated through an exterior heat exchanger for temperature control.

Both heating and mixing can be accomplished by passing a recirculating pump discharge through an exterior heat exchanger, using power plant waste heat or other energy sources. The effluent from the anaerobic digester will be subsequently added to the effluent from the solid-liquid separator.

The anaerobic digester in this report was designed on the basis of a daily loading rate of 1.00 kg of volatile solids per cubic meter. The conservative rate minimizes the potential for digestive upset. The volume required to accept the 17.0 kg of volatile solids produced daily is 17 m^3. Thus, a tank 3.0 x 4.0 meters in plan, 2.0 meters deep is specified. The water depth will be about 1.5 meters. The tank will be covered. Gases produced can be stored for later use or vented to a soil absorption field for odor control.

Gas Storage

The design discussed here is based on the rate of manure production of 50 pigs. The rate of gas production from the anaerobic digester would be small and provisions for storing the gas for later use were not made. An energy balance of the proposed system should include an analysis of the use which can be made of the digester gases as an energy source in the system. The gases would probably best be used as an energy source for the algal harvesting device.

System Safeguards

Precautions must be taken to insure manure removal when breakdown occurs in one of the various units of the system. System safeguards in the form of an anaerobic lagoon seem appropriate. Such a lagoon exists at the site selected for the demonstration of this concept (Figure 6). Overflow lines receiving raw waste, will be constructed at the sump at the control box ahead of the algal culture basins, and at the water storage tank. These lines will be designed to discharge directly into the anaerobic lagoon when diversion is necessary.

Nutrient Recovery System

General Design Consideration

The objective of the nutrient recovery system is to use waste heat and the excreta from 50 swine to sustain a high yield of single cell protein. The goal of the proposed procedure is to recover nutrient elements, not to decrease the concentration of any specific ion below a predetermined level on a given pass

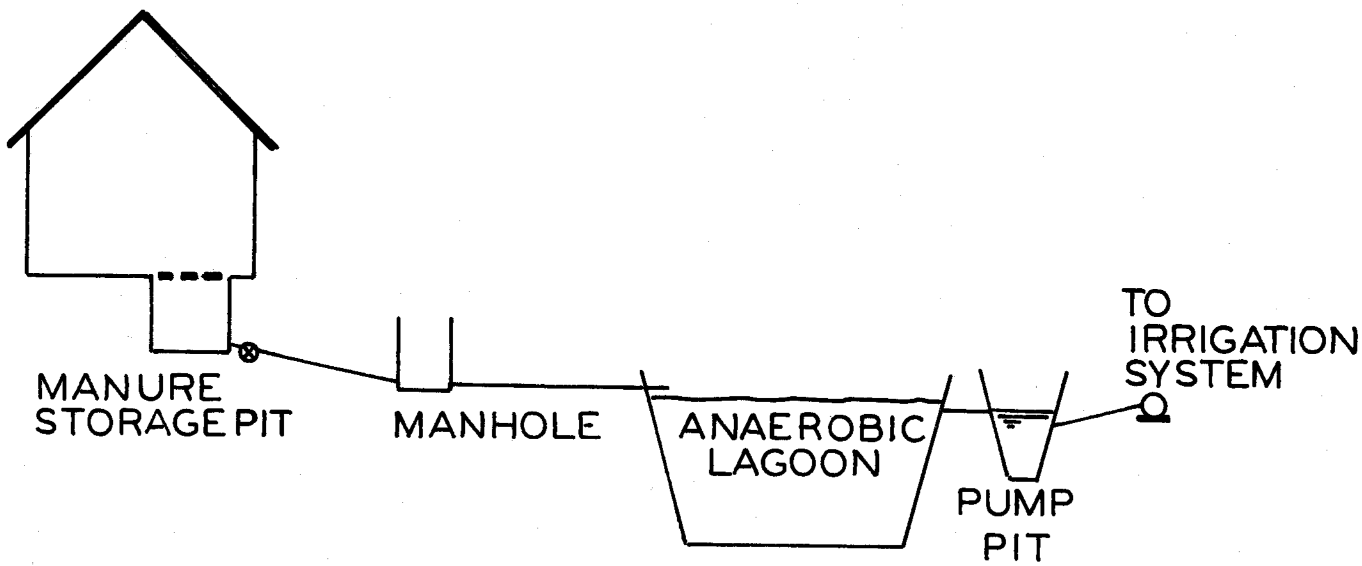

Figure 6. Schematic diagram of the existing manure handling facility at the site of the field experiments.

through the basins. Management objectives differ in this respect from many earlier systems where attempts were made to reduce the nutrient concentrations, particularly nitrogen, so that prescribed water quality standards would be met. Most standards specify a nitrogen concentration of less than 10 mg/l as safe for drinking water. This nitrogen concentration is suboptimal for protein production by many organisms otherwise suitable for mass culture. For instance, Spoehr and Milner (1949) have shown that nitrogen concentrations below 30-40 mg/liter limit the growth and protein production of Chlorella. It is clear that the reduction of the nitrogen concentration below 10 mg/l is not compatible with most efficient use of waste heat to sustain high yields of single cell protein using swine waste as substrate. Obtaining maximum rates of protein production suggests the use of a continuous flow system in which nitrogen concentrations remain high.

Selection of Organism (Photoautotrophs vs. Heterotrophs)

It was decided to culture an algal photoautotroph as the source of single cell protein. Consideration was given to several advantages and disadvantages of using a heterotrophic system as the alternative (Table 5). The presence of relatively large amounts of organic substrates in animal wastes would appear to favor use of a heterotroph as the source of the single cell protein.

Five considerations dictated the decision not to use a heterotroph, namely: 1) the necessity of sterilizing the culture medium prior to its being introduced into the culture basins, to prevent competitive exclusion by undesirable species of heterotrophs, 2) the probable need for additional energy in the form of sugar to facilitate the efficient assimilation of nitrogen from low energy substrates contained in animal wastes, 3) the potential accumulation of populations of animal disease organisms in a recirculating system, 4) the impossibility of real time monitoring of the culture community by direct microscopic examination, and 5) the possibility of the accumulation of extracellular metabolic products possessing antibiotic (staling) activity which would exist in a recirculating system.

Five considerations favor the use of a photoautotroph, namely: 1) ability to use nitrogen from low energy substrate (ammonia) using light energy, 2) the alternation of anaerobic digestion and aerobic culture conditions will inhibit the accumulation of either populations of animal pathogens or antibiotic extracellular metabolic products, 3) direct determination of the composition of the cultured flora is possible by microscopic examination, 4) the feasibility of

Table 5. Advantages and disadvantages of the use of photoautotrophic and heterotrophic organisms in the proposed waste management scheme

Advantage	Disadvantage
Autotroph	
1. Utilization of low energy substrates with energy input from sunlight	1. Need for mineralization of nutrients to support growth of algae
2. Alternation of anaerobic and aerobic decomposition will inhibit the build-up of populations of animal parasitic (disease) species	2. Must be an open (non-sterile) system which is liable to contamination with competitors from air
3. Accumulation of antibiotic or otherwise undesirable metabolic end products unlikely	3. Most species have relatively large amounts of crude fiber
4. Mechanical harvesting procedures relatively simple	4. Generation times of many otherwise suitable forms relatively long
5. Open culture tanks can be operated with low probability of local nuisance (odor)	5. Relatively fewer thermophilic forms available
6. Direct monitoring of the culture community possible with a microscope	
Heterotroph	
1. Direct conversion of organic substrates in wastes to single cell protein	1. Probable need for addition of energy (sugar) to convert low energy substrates (urea, ammonia)
2. Operation in either open (non-sterile) or closed basins	2. Open tanks make local nuisance (odors) probable
3. Large number of thermophilic forms available	3. Great adaptability of heterotrophs makes contamination highly probable
4. Most species have relatively short generation times	4. Build-up of populations of disease organisms from swine herd possible
5. Crude fiber content relatively low	5. With recirculation there is the possibility of the accumulation of antibiotic or otherwise undesirable metabolic products
	6. Mechanical harvesting procedures difficult
	7. Monitoring of the culture community only by culture techniques

non-sterile cultures in open basins is greater than when culturing heterotrophs, and 5) mechanical procedures in harvesting are more easily achieved.

Selection of Photoautotroph Species

The primary objective of the operation of the proposed system is the production of single cell protein, thus the choice of the organism to be grown must conform to a number of criteria. The chosen organism must: (i) be non-toxic, ii) possess a biochemical composition suitable for use as a feed supplement, (iii) be capable of being harvested with minimal difficulty and expense, (iv) be physiologically adapted for growth in the dilution of the culture medium imposed by the system, (v) have a rate of growth (generation time) that is adequate to support an economically feasible system, and (vi) be strongly competitive under the imposed culture conditions, thus making possible the operation of an "open" (i.e., non-sterile) system. In addition, a form with a minimal fiber (indigestible polysaccharide) content would be desirable. However, naked and thin-walled species tend to be more susceptible to predation by rotifers and other microfaunal predators.

The absence of known toxic species in the Chlorophycophyta (green algae) makes this group of definite interest. Although the majority have fibrous walls, this may prove to be an advantage in retarding predation. Most unicellular algae do not have an appreciable amount of cellulose in their walls (Siegel and Siegel, 1973). However, in the species Chlorophycophyta, cellulose is frequently replaced by similar polysaccharide polymers of mannose, galactose, or xylose, which form walls of the same basic structure as cellulose, namely, polysaccharide gels of varying fibrous character on a protein matrix. Such a fibrous polysaccharide gel cell wall may be considered to be an advantage in retarding predation.

A large number of species of chlorophytes are maintained in cultures at various institutions. The approximate biochemical composition and culture requirements of some of these are well established. A number of species are being evaluated in preliminary studies with particular emphasis on thermophilic varieties or strains. Species in the genera Chlorella, Scenedesmus, and Ankistrodesmus are being considered initially.

Species of algae show decreasing generation times at elevated temperatures. Light-saturated, well-mixed cultures of both green and blue-green algae in optimal culture media at temperatures of 30 to 40 C have been reported to have generation times as short as 2 to 3 hrs. Thermophilic strains of Chlorella pyrenoidosa, C. vulgaris, and Scenedesmus quadricauda are available and should be tested for suitability, as should thermophilic strains of Anacystis nidulans and Synechococcus lividus (Cyanophycophyta, Chroococcales). It is understood that the imposed culture medium may not support the growth of some or all of these forms at the optimal temperature for their maximum division rate.

Manure Pretreatment Requirements

To determine the optical transmittance and nutrient composition of swine waste, samples were collected from the manure treatment facility consisting of collection pits below partially slotted pens (Figure 6) which are periodically drained to an anaerobic lagoon. The supernatant from the anaerobic lagoon flows into a small earthen pit from which it is pumped onto agricultural land using standard irrigation equipment. Samples were collected from the collection pits filled with waste suspensions and from the surface of the anaerobic lagoon.

All samples were highly turbid, indicating a high content of suspended solids and colloidal material. This turbidity was removed by filtering the samples through Whatman's #1 filter paper. However, the filtered samples were still colored enough to impede the transmittance of visible light. The lagoon samples were dark, greenish brown, indicating the presence of a large amount of organic material and reduced sulfur compounds. The filtered samples from the collection pit were pale brown and transmitted some light. The color was removed from all filtered samples by an activated carbon filter.

As light penetration was limited to a few centimeters in the unfiltered and filtered lagoon samples and the unfiltered collection pit sample, a treatment to clarify the waste is indicated if waste is to be used as a substrate for growth of photoautotrophic organisms. The solid-liquid separator described earlier does not provide the necessary clarifying treatment. Filtering treatments are therefore suggested. The filtering treatment may consist of a mechanical filtering (sand, diatomaceous earth, or porous cleaner) or a mechanical filtering followed by a charcoal filter to remove the color. The degree of color removal required is not completely defined at this time and would depend on the pretreatment of the manure.

The need for filtering would be potentially one of the biggest bottlenecks in the proposed system. The disadvantages are: (i) the added complexity of operation and need for close control, (ii) the added cost to the final product, and (iii) the removal of some organic material that otherwise could be recovered.

A series of experiments were initiated to screen several algae with respect to growth rate at a range of temperatures in different dilutions of untreated and clarified manure. The organisms being tested are:

Chlorella pyrenoidosa 211-8K
Chlorella pyrenoidosa 1230 IV
Chlorella vulgaris
Scenedesmus quadricauda
Scenedesmus obliquus ScD3WT
Spirulina major
Botyrococcus

Chlorella pyrenoidosa 211-8K, which has a temperature optimum at 35 to 37 C, appears to be the most promising species. It grows well on untreated, liquid swine manure directly from the underfloor storage pit. A culture density of 1 g/liter dry weight was reached in 2.5 days at 28 C. In these experiments where light penetration problems have been avoided by growing the algae in shallow culture flasks, untreated swine waste has produced better yields than treated swine waste or prepared inorganic nutrient media.

The Chlorella pyrenoidosa 211-8K has also been grown in 18-liter carboys and in small open basins with a surface area of 0.1 m^2 under continuous flow conditions. In the continuous flow system, algal concentrations of 1.5 to 2.5 g/1 were maintained using fresh, untreated swine waste at 35 to 37 C. The growth rates corresponded to photosynthetic efficiencies of 4 to 5 percent. Additional experiments seek to determine optimal flow rates at a range of temperatures and irradiance levels, as well as the effects of pH control and CO_2 enrichment on the production and biological stability of the cultures.

Temperature and Light Requirements

The objective of the proposed system is maximum use of available radiant energy in outdoor mass cultures of algae by optimizing culture temperature and nutrient level using waste heat and swine manure.

Estimates of production rates achieved in outdoor mass cultures vary widely. Stengel (1970) reports production rates for Scenedesmus of 28 g/m^2/day in Rupite, Bulgaria. He indicates that these rates were obtained at high levels of radiation during the summer and estimates an average yearly production rate of 10-12 g/m^2/day. Wesselius (1973), growing Scenedesmus in small outdoor basins, obtained growth rates of about 20 g/m^2/day at a radiation level of 1800 $Kcal/m^2$

day. Kok and Van Oorschot (1954) reported yields as high as 33 $g/m^2/day$ for Scenedesmus grown in outdoor cultures at a radiation level of 4300 $Kcal/m^2/day$. Tamiya (1957) obtained a growth rate of 20 $g/m^2/day$ for a thermophilic strain of Chlorella (TX 71105) grown in outdoor culture without temperature control.

The spectral quality of light utilized by algae for photosynthesis is limited to the visible region (4,000 to 7,000 Å) which comprises about 40 percent of the solar radiation. The maximum efficiency of light utilization by Chlorella has been determined to be approximately 20 percent (Meyers, 1971) when all available energy can be used for the photosynthetic process. Most algal species are expected to have similar photosynthetic efficiencies. A maximum efficiency of about 8 percent, therefore, may be expected in outdoor basins since 40 percent of the sun's energy is in the proper range. The energy content of algal material is about 5.5 Kcal/g. Figure 7 shows daily radiation levels measured during a one-year period at Corvallis, Oregon (Boersma and Simonson, 1970). The solid curve describing the level of radiation was drawn without the benefit of a statistical procedure, but may be considered a good estimate of normal radiation levels at the site of the proposed experiments. Algal production rates were calculated using the indicated efficiency of 8 percent and an energy content of 5.5 Kcal/g (Figure 8).

The high production rates suggested by this calculation have not been achieved in mass cultures. Measured energy conversion efficiencies have ranged from less than 1 percent to about 5 percent. The production corresponding to a 5 percent efficiency is also indicated in Figure 8.

The low energy conversion efficiencies of algal cultures are due to the fact that most algae are light saturated at very low light intensities (500 ft. c.). Attempts to increase the growth rate of algae must be directed toward better utilization of available light energy. This may be achieved by finding algae with high levels of light saturation. These are often thermophilic forms which require high culture temperatures. Recently mutants of certain algal species with very high saturation levels of light have become available. It is also known that the saturating light intensity of thermophilic strains of Chlorella can be increased by increasing the temperature of the culture media (Table 6).

The increase in the saturating light intensity at temperatures close to 40 C is due to the increased photosynthetic rate of the organism (Sorokin, 1971), and in particular the increased rate of enzymatic fixation of CO_2. These enzymes then require an increased supply of chemical energy from the light-absorbing

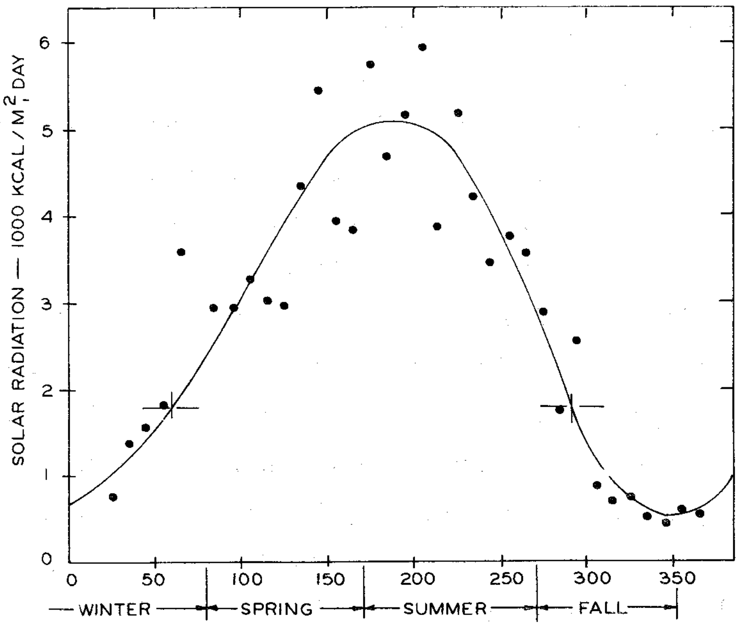

Figure 7. Solar radiation measured at Corvallis, Oregon, during 1964-1965 (Boersma and Simonson, 1970).

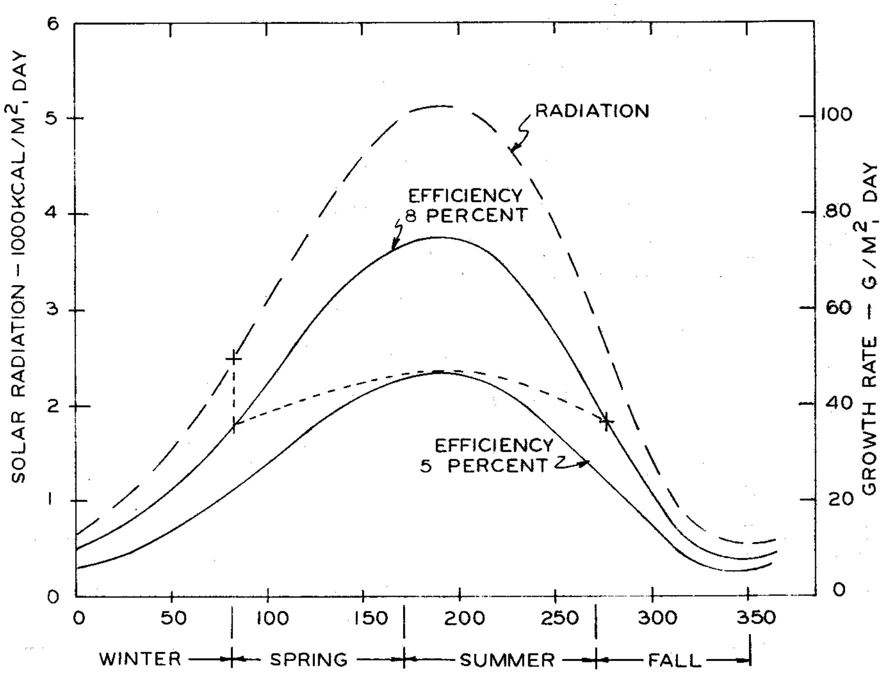

Figure 8. Rates of algal growth calculated by assuming the indicated light utilization efficiencies and an algal energy content of 5.5 Kcal/g. The procedure for obtaining the growth rates indicated by the broken line is described in the text.

pigment systems and the light requirement is correspondingly increased. These observations are consistent with Tamiya's (1957) conclusion that light energy conversion efficiency increases with increasing culture temperature. The growth rate of thermophilic algae also increases linearly with temperature until it reaches a maximum at approximately 39 C (Figure 9).

Table 6. Effect of light intensity and temperature on the growth of Chlorella pyrenoidosa 7-11-05[1)]

	Growth Rate		Critical Light Intensities	
Temperature	Half Saturation	Saturation	Saturation	Inhibition
C	----Cell Doublings Per Day--		---------Ft.c.---------	
25	2.3	3.0	500	3500
39	7.0	9.2	1400	8500

1) C. Sorokin and R. W. Kraus, 1958.

The broken line between the two growth rate curves in Figure 8 represents a possible projection of achievable growth rates in heated basins near Corvallis, Oregon. The assumptions made were: (i) photosynthetic efficiency is 8 percent at light intensities less than light saturation, (ii) algae with light saturation intensities up to 2500 Kcal/m^2/day can be developed, (iii) the photosynthetic efficiency gradually decreases at light intensities above 2500 Kcal/m^2/day to reach 5 percent at the highest light intensity indicated. The resulting rate corresponds to an annual growth rate of 32 g/m^2/day. The average annual growth rates indicated by the 5 percent and 8 percent efficiency lines are 26 and 42 g/m^2/day respectively. It should be recognized that with a full-scale outdoor pond, light penetration, rather than light saturation, becomes the limiting factor. Light saturation is a problem only with very shallow ponds.

The growth curves shown in Figure 8 are not well-documented speculations. Studies to investigate the technical and economic feasibility of increasing the energy conversion efficiency and production of thermophilic algae by culturing selected organisms at elevated temperatures using waste heat are in progress.

Mixing Requirements

Mixing of algal suspensions in the culture basins is required to keep the algal cells exposed equally to the light available at the pond surface through random motion. It also eliminates or reduces the thickness of the boundary layer around individual algal cells so that concentration gradients of nutrients

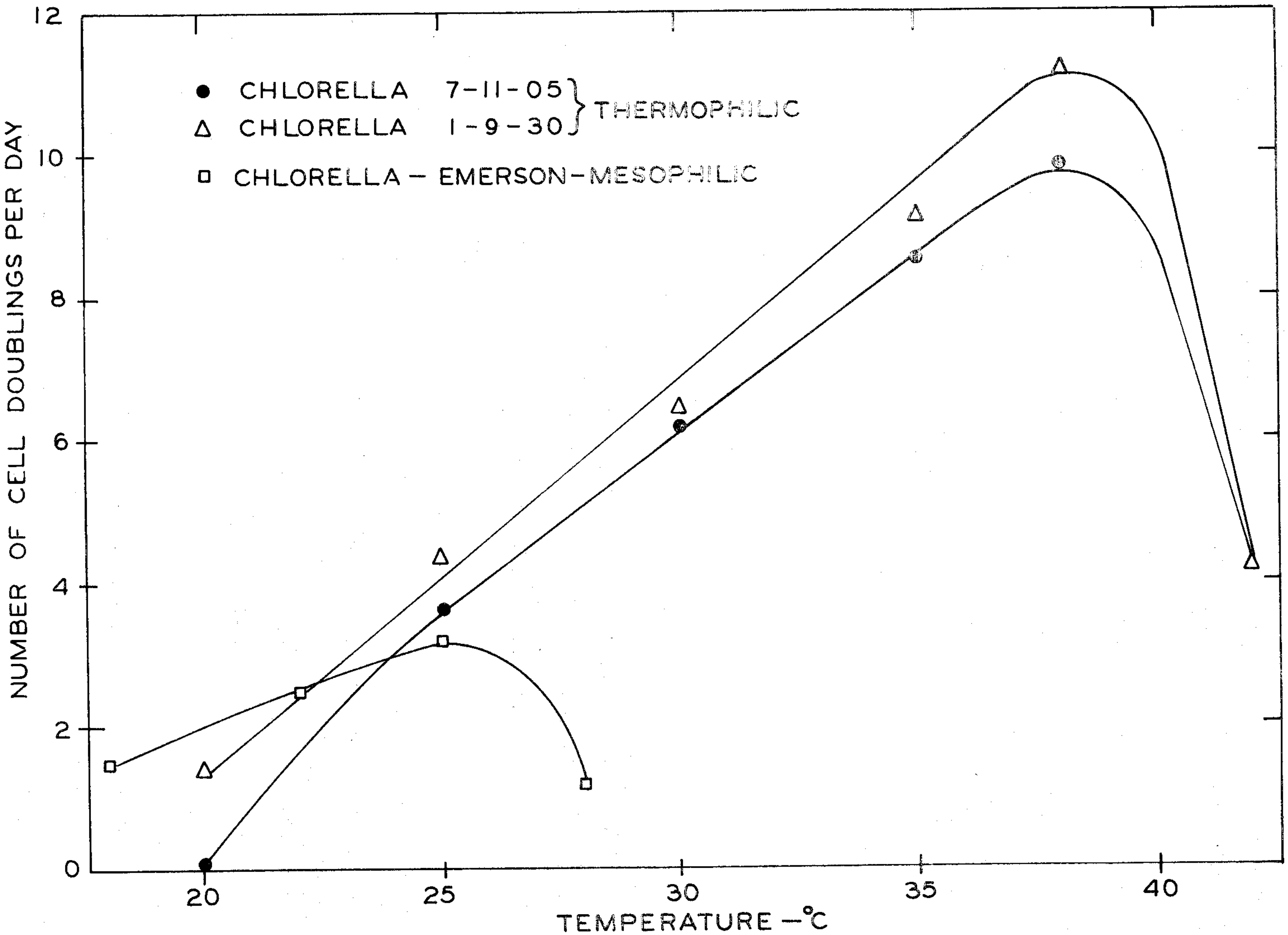

Figure 9. Growth rate of mesophilic and thermophilic algae in number of cell doublings per day as a function of culture temperature (Sorokin, 1971).

or carbon dioxide in the aqueous medium are reduced. Mixing is further needed to promote efficient heat transfer and to obtain uniform temperatures throughout the basins.

Satisfactory mixing can be obtained by recirculating the culture solution in circular or oval basins at a rate which moves the entire body of liquid at a velocity of 30 to 60 cm/sec for a period of several hours during each day, while slow continuous motion is required during the rest of the time (Oswald and Golueke, 1968a, 1968b).

CO_2 Enrichment

Rapidly growing algal cultures consume large quantities of carbon dioxide. This can be supplied by diffusion from the air, by aeration, and by injection from a gas supply. The culture basins have large surface areas because only shallow water depths can be used. However, even this large surface area is not sufficient to absorb enough CO_2 from the atmosphere to meet the requirements of rapidly growing cells. Thus, a continuous supply of CO_2 gas is needed in rapidly growing cultures. A CO_2-injection system coupled with the mixing mechanism can be used. It is expected that adequate buffer capacity will be present in the digester supernatant to prevent excessive lowering of the pH as a result of CO_2 addition.

Composition of the Manure and Expected Nutrient Balance

The mineral composition of several swine waste samples was determined and compared with that of nutrient media used for the mass culture of microalgae (Table 7). Swine waste samples were taken from the collection pit and anaerobic lagoon of the manure handling facility illustrated in Figure 6. The samples were passed through a charcoal filter to remove turbidity and soluble organic matter before analysis. The mineral composition of the collection pit sample is representative of that which can be expected in the filtered effluent from the solid-liquid separator because waste in the collection pit had no time to decompose. Similarly, the mineral composition of the anaerobic lagoon sample is representative of the final nutrient composition that may be obtained in the algal basins, after the filtered flows from the solid-liquid separator and anaerobic digester have been combined. A literature report of the mineral composition of swine waste with iron and sulfur analyses was also included in Table 7.

Table 7. The mineral composition of swine waste compared to that of several nutrient media used in the mass culture of algae

Element	Swine Waste			Mass Culture Media[2)]		
	Pit	Lagoon	Literature[1)]	A	B	C
	--------------------	--------------------	mg/liter	--------------------	--------------------	--------------------
Nitrogen (NO_3 + NH_4)	282	443	330	173	139	139
Phosphorus (PO_4)	90	100	84	285	62	171
Potassium	189	276	228	842	543	600
Magnesium	45	37	48	346	25	70
Sulfur (SO_4)	-	-	81	325	33	64
Calcium	96	109	342	30	9	1
Sodium	88	101	-	-	67	-
Chloride	-	-	-	60	119	-
Iron	-	-	168	10	-	1
Zinc	0.11	0.11	-	20	0.05	0.005
Manganese	0.28	0.10	-	4	0.50	0.05
Copper	0.01	0.01	-	4	0.02	0.002
Boron	0.14	0.20	-	20	0.35	0.05
Cobalt	--	--	-	1	0.02	0.001
Molybdenum	--	--	-	4	0.06	0.001

1) Calculated from E. J. Benne et al., 1961.

2) A J. Meyers, 1971 (Chlorella media).
B G. Hemerick, 1973.
C R. W. Krauss and W. H. Thomas, 1954 (Scenedesmus obliquus media).

The concentrated Chlorella culture media used by Meyers (1971), which can support cell concentrations of 30 g/liter or greater, illustrates the adaptability of Chlorella to high salt concentrations. Scenedesmus also has a wide salt tolerance (Tamiya, 1957). Therefore, the salt concentration of the swine waste is unlikely to affect the growth of Chlorella or Scenedesmus. In most outdoor algal cultures the cell density is much lower, ranging from 0 to 3 g/liter (Tamiya, 1957), and more dilute nutrient media such as those of Hemerick (1973) or Krauss and Thomas (1954) may be used. The concentration of nitrogen in the liquiefied swine manure can be maintained at the levels required for algal concentrations of 0.5 to 3 g/liter by adjusting the flow rate in the proposed recycling system.

The other macronutrients, --phosphorus, sulfur, magnesium, and potassium-- are unlikely to become limiting in the proposed design, since only part of the nitrogen is removed on each pass through the algal basins. Although the potassium concentration of the swine waste is much lower than in the nutrient media, it is sufficient because the potassium concentrations of the nutrient media are far in excess of algal requirements (Table 8). The concentration of the micronutrients, --zinc, manganese, copper, and boron-- in the swine waste also appears adequate to support algal culture. Nutrients could be added if needed.

A more rational method of determining the nutrient requirements of mass cultures is the replenishment method of Krauss and Thomas (1954). In this method, nutrients are added to the media at the same rate in which they are removed in the harvested algae. This approach has been used to compare the relative mineral composition of the swine waste to that of *Scenedesmus* and *Chlorella* in Table 8. It is apparent that potassium, calcium, and, to a lesser extent, sulfur will not be fully utilized and therefore will eventually accumulate. The moderate accumulation of these elements in the recycled water is unlikely to affect the growth of *Scenedesmus* and *Chlorella*, because of their tolerance to high salt concentrations (Table 7).

Table 8. The mineral composition of swine waste compared with literature values of the mineral composition of *Scenedesmus* and *Chlorella*[1)]

	Content Based on Dry Weight					Relative Composition	
Element	A	B	C	D	E	Algae[2)]	Waste[3)]
	--------------	------	%	------	--------------	-----% of	N-----
Nitrogen	8.14	7.90	6.10	8.00	6.80	100	100
Phosphorus	2.22	1.72	1.23	1.10	1.42	21	26
Potassium	0.92	1.60	0.74	1.50	1.41	16	67
Magnesium	1.60	0.57	0.89	0.50	0.54	11	12
Sulfur	--	1.12	0.91	1.10	0.34	9	23
Calcium	1.93	--	0.76	--	0.06	12	53

1) A mixture of *Scenedesmus* and *Chorella* (H. G. Hintz *et al*., 1966).
B *Chlorella* (B. V. Gromov, 1968).
C *Chlorella* (R. W. Krauss, 1953).
D *Chlorella vulgaris* (M. J. Groghegan, 1953).
E *Scenedesmus obliquus* (R. W. Krauss and W. H. Thomas, 1954).

2) Mean of A-E.

3) Mean of values presented in Table 7.

It appears that swine waste is a good substrate for algal protein production and is probably capable of supporting algal cell concentrations in the order of 0.5 to 3 g/liter.

Temperature Control of the Culture Basins

The use of waste heat to maintain a productive temperature within the algal basins throughout the year is integral to the proposed nutrient recovery system. The most productive temperature may be within the thermophilic range. Temperatures in this range will help control invasion of the basins by nonproductive species and result in higher growth rates. Preliminary investigations supported by the Office of Water Resources Research and in progress at Oregon State University aim to clarify this question. Waste heat will be used in the manner described below.

Methods of Heating

Energy can be supplied to the basin water with a system of pipe heat exchangers. The rate of heating depends on the temperature difference between the water in the pipes (condenser cooling water) and the basin water, the rate of mixing near the pipes, the contact surface area (number of pipes), thermal conductivity of the pipe material (metal versus plastic), and the flow rate in the pipes. The surface area of pipe required for different values of these parameters was considered in a study at the University of Minnesota (Stefan *et al.*, 1970) and is under study at Oregon State University.

The temperature of the condenser cooling water must be higher than the desired basin temperature. The availability of condenser cooling water at the needed temperature depends on the power plant design and type of cooling system used. The two annual profiles of condenser discharge temperatures shown in Figure 10 indicate that the temperatures would be sufficiently high throughout the year when a cooling tower is used, but only during part of the year when a cooling pond is used.

A heat pump system or steam extraction procedure could be used to provide water of the desired temperature when the condenser cooling water is too cold, as would be the case at the Pendleton location during part of the year. This mechanism would add to the total cost of providing the needed energy, the additional cost possibly exceeding the benefits of increased growth. It might be more advantageous to let basin temperatures vary throughout the year as dictated by the condenser cooling water temperatures.

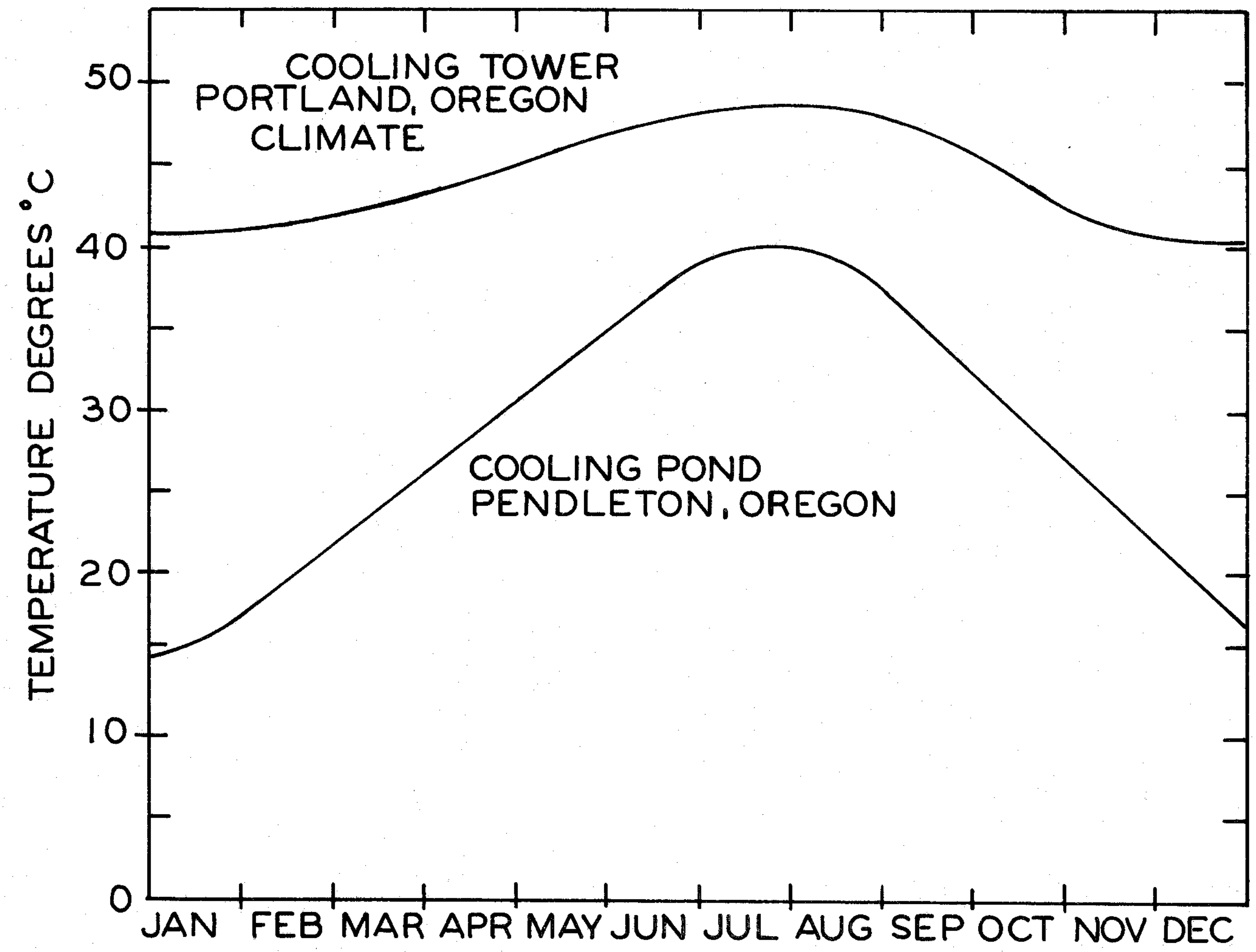

Figure 10. Temperature profiles of condenser cooling water at the point of discharge for a location near Portland, Oregon, using a cooling tower and a location near Pendleton, Oregon, using a cooling pond.

Energy Requirements

The use of heat is integral to the proposed scheme. The restrictive environment of thermophilic conditions should partially provide the needed control of the microorganism population in the system. The energy required to maintain open-air water basins at a constant temperature is determined by the sum of the terms which make up the energy balance. These include: incoming shortwave solar radiation, atmospheric longwave radiation, back radiation from the pond surface, convective heat loss, latent heat of vaporization lost as a result of the evaporation process, and gains and losses in energy resulting from precipitation (Davis, Shew, and Boersma, 1973). Stefan et al., (1970) showed conduction to the surrounding soil to be negligible. These factors combine to produce the heating requirements (shown in Figure 11) for a summer day and a winter day at Corvallis, Oregon. A short period when no heating was required to maintain a 20.6 C water temperature occurred during the warm day. The temperature rise of a 20-cm-deep basin during this period would be less than 0.5 C.

Temperature Fluctuations

Daily temperature fluctuations of basins heated at a constant rate were calculated in an earlier study (Lindstrom and Boersma, 1971). Basin temperatures were obtained using a constant rate of heat input and values of climatic conditions measured at hourly intervals. Figure 12 shows that the basin temperature varied only about 5 C even though the air temperature varied from 0 to 40 C and the rate of heat loss by evaporation varied from 2 $mcal/cm^2 sec$ to 20 $mcal/cm^2 sec$. Expected changes in climatic conditions would be much smaller under normal operating conditions. The thermal inertia of the large mass of water in the basins is sufficient to maintain nearly constant temperatures.

Energy Consumption

The energy requirements of a complex of algal-growing basins depend on the rate of heat loss at the water surface. This rate varies during a day and year as a function of climatic conditions (Figures 11 and 12). Two questions which frequently arise are "What fraction of waste heat produced by a power plant can be dissipated in a system of algal culture basins?" and its corollary "How large an open basin algal culture system can be sustained by the waste heat produced by a power plant?" The answers to these questions can be derived in part from Table 9. The calculations shown were based on a 1,000 MWe power plant operating

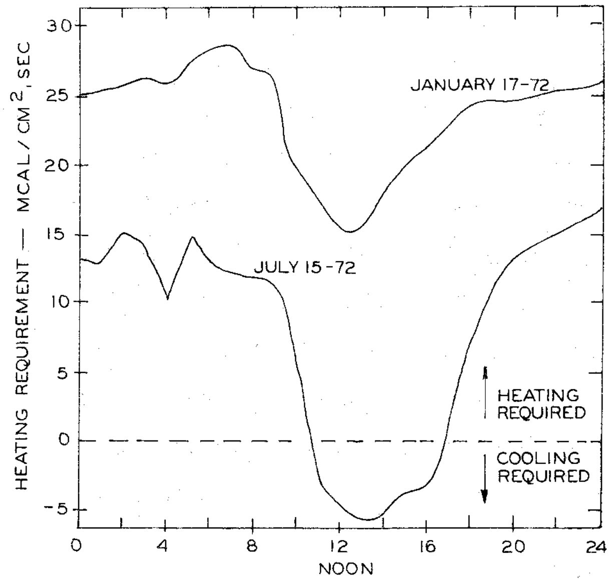

Figure 11. Heating requirements of open-air, free water surfaces on a summer day and a sinter day at Corvallis, Oregon (Davis, Shew, and Boersma, 1973).

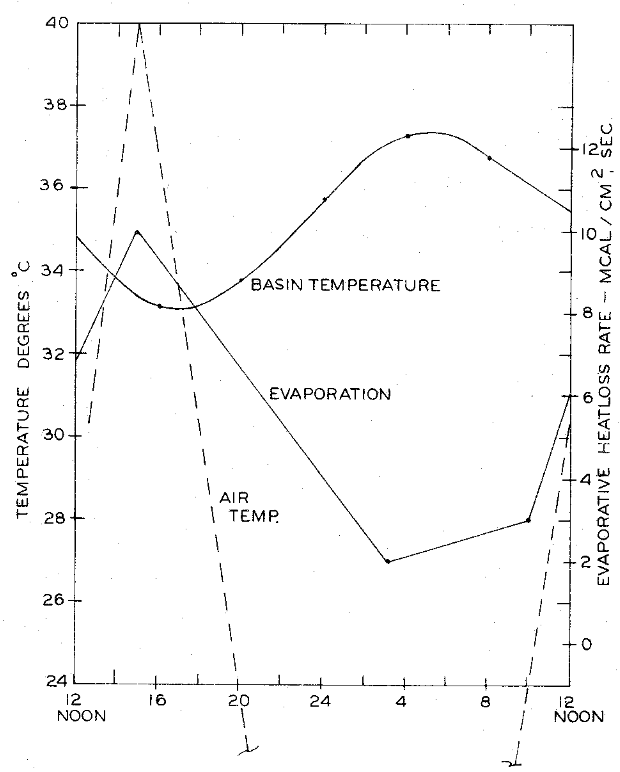

Figure 12. Daily temperature fluctuations of an open-air free water surface near Corvallis, Oregon, heated at a constant rate (Lindstrom and Boersma, 1973).

with a thermal efficiency of 34 percent. The rate of heat rejection is then 1,941 MW or 462 x 10^6 cal/sec. Table 9 shows the surface area required to dissipate the waste energy for several rates of heat loss. Figure 11 indicates that the design rate of heat loss in the Willamette Valley should be about 30 mcal/cm^2/sec for a 24.2 C basin temperature. This means that the basin area should not exceed 150 ha (Table 9). The design rate of heat loss for higher basin temperatures would be substantially higher and the area would be correspondingly smaller. Allowance must be made for inefficiency of the heating process. Not all available reject energy can be imparted to the basins. Surface areas for 100 percent and 75 percent use of the available reject energy are shown.

The energy requirements of the basins vary on a daily and on a seasonal cycle. The fraction of available reject energy being used will also vary, being highest during the winter and lowest during the summer. Figure 11 indicates that the demand for energy remains substantial even during the summer.

Value of the Waste Heat

An economic evaluation of the proposed system should include the cost of providing the waste heat, the market price of the product produced, and the possible production rates at various temperatures. Reliable information about algal production rates at various temperatures in open-air basins is not now available.

The value of the protein produced per hectare per year was calculated for several possible, but not experimentally verified, production rates for a range of protein values (Table 10). Analysis of the production cost of the proposed system including the cost of operating and owning the heating system has not been completed. The dotted line shown in Table 10 outlines the growth rate and protein value combinations which would be profitable at a gross production cost of $15,000 per hectare per year.

Table 9. The surface area required to dissipate 100 percent and 75 percent of the reject energy produced by a 1,000 MWe power plant with a 34 percent thermal efficiency at several rates of heat loss

Rate of Heat Loss	Surface Area	
	100%	75%
$mcal/cm^2 sec$	ha	ha
46.2	100	75
37.0	125	94
30.8	150	113
26.4	175	131
23.1	200	150
18.5	250	188
15.4	300	225
13.2	350	263
11.6	400	300
10.3	450	338
9.2	500	375

Table 10. Value of the protein produced per hectare per year assuming a 50 percent protein content at several indicated values of the protein

Protein[1)] Value	Growth Rate - $g/m^2/day$				
	10	20	30	40	50
$/kg	$/ha/year				
0.10	1,825	3,650	5,475	7,300	9,125
0.25	4,563	9,125	13,688	18,250	22,813
0.50	9,125	18,250	27,375	36,500	45,625
1.00	18,250	36,500	54,750	73,000	91,250

[1)] Current prices of soybean meal (44% protein) F.O.B. Portland, Ore. October 1973, $0.60 per kg protein; high for 1973 was $1.19 per kg protein; expected minimum 1973-74 $0.50 per kg protein.

Design and Operation

Design Criteria

The possible flow diagram for the proposed system is shown in Figure 13. A preliminary design of the nutrient recovery facility was based on the rate of manure effluent produced by 50 swine. The basin surface area required for complete assimilation by the algae of all nitrogen produced was estimated by assuming a growth rate of 20 g/m^2/day (Table 11). The daily nitrogen consumption rate, assuming a 7 percent nitrogen content of the algal material, will be 1.4 g/m^2, so that 800 m^2 of surface area will be required to assimilate the 1,135 g produced daily. This surface area of algal ponds would correspond to 8 ha for 5,000 swine, certainly not a very large land area requirement. A much larger surface area would be required for land disposal of the same waste.

A total daily flow rate of 10,000 liters was obtained by specifying 12 daily flushings requiring 833 liters each. Effluent concentrations of several variables were obtained from this rate. The nitrogen concentration in the water would be 114 mg/liter per day at the indicated flow rate. The assumption of complete assimilation of the daily rate of nitrogen production does not imply that the concentration will be reduced to zero. The system might, for example, reduce the nitrogen concentration to 50 mg/liter so that the concentration would range from 164 to 40 mg/liter. The expected changes in the concentration of other elements were discussed.

Two modes of operation are possible. In the continuous flow, parallel mode, a selected percentage of each basin volume is being replaced each day with fresh inflow from the animal quarters. The equivalent outflow from each basin is then passed through the harvesting device. This mode of operation is best suited to the objective of high rates of protein production. In the batch flow, series mode, several basins are used in sequence with only the outflow from the last one in the series being harvested. A selected percentage of the volume of the first basin in the series is passed to the second one and replaced with fresh effluent from the animal quarters. This mode of operation is best suited for a system in which the principal objective is complete nitrogen removal.

Manure Pretreatment

Treatment of the swine waste for removal of suspended solids seems to be

Table 11. Values of design parameters for the proposed waste management research facility[1)]

Parameter	Value
No. of animals (swine)	50
Total live weight	2,750 kg
Pen dimension (6 pens; 3.0 x 2.15 meter)	3.0 x 12.8 m
Pen area	38.4 m^2
Waste production	
total solids	20.4 kg/day
BOD	5.7 kg/day
N	1.135 kg/day
manure	136 kg/day
volatile solids	17 kg/day
Growth rate of algae	
summer	40 $g/m^2/day$
winter	20 $g/m^2/day$
Nitrogen content of algae	7% of dry weight
Surface area required to assimilate all available nitrogen at growth rates of:	
40 $g/m^2/day$	400 m^2/50 swine
20 $g/m^2/day$	800 m^2/50 swine
Flushing frequency	12 times/day
Flushing flow rate	833 liters/flushing
Flushing flow rate per pen	140 liters/flushing
Daily flow rate through system	10,000 liters/day
Concentrations in effluent based on flow rate of 10,000 liters/day	
total solids	2,041 mg/liter
volatile solids	1,701 mg/liter
BOD	570 mg/liter
nitrogen	114 mg/liter
phosphorus	23 mg/liter
potassium	14 mg/liter
Basin dimensions	
length	40 m
width	20 m
surface area	800 m^2
depth of water	30 cm
Basin temperature	30 to 40 C

[1)] These values represent current estimates. Some of these may be changed in the final design.

indicated. Light penetration is limited to only a few centimeters even in the fresh manure effluent. Several filtering techniques were evaluated. It was found that mechanical filtering does not remove the turbidity from the fresh manure runoff. Preliminary tests indicated that the most effective clarifying treatment is the precipitation obtained by adding ferric chloride. This produces a clear liquid which supported algal growth well in laboratory studies.

Recent experiments with the fresh, unfiltered effluent, however, have shown that it supports high growth rates of Chlorella when mixed with an air bubbling device. Cell densities of 1.0 to 1.50 g/liter are easily maintained. If these efforts develop satisfactorily, the filtering treatment can be eliminated. The possibility to do so would greatly enchance the potential for economic success of the system.

Mixing the Culture

Several procedures are available for mixing. The most commonly used one is to maintain the body of water in continuous motion with a minimum velocity during most of the day and with rapid mixing at higher velocities during short periods. This mixing method requires a substantial amount of energy. A less energy-demanding method would be the use of air curtains. This method is based on the release of air bubbles at the bottom of the basin. The rising bubbles move the water due to viscous drag, creating slowly moving cells. The mixing regime has not been defined. It has been suggested that outdoor ponds should not be mixed continuously. These should have a bottom layer of sludge 2 to 4 cm thick, which would produce excessive turbidity with continuous mixing.

CO_2 Enrichment

It is essential that sufficiently high CO_2 concentrations be maintained in the basins. The carbon dioxide could be injected with the air stream through the mixing device. The rate of addition can be controlled by a timing device. Engineering problems which may exist with respect to securing a uniform distribution of the CO_2 in large basins have not been analyzed in detail.

Heating the Basin Water

Several methods for heating the basin water using power plant waste heat as the energy source have been described (Stefan et al., 1970; Lindstrom and

Boersma, 1973; Davis, Shew, and Boersma, 1973). Assuming that only systems in which the basin water and the condenser cooling water remain separated can be considered, three methods are recognized, namely: (i) a single conduit below the basin and separated from it by a septum with a high thermal conductivity, (ii) a series of parallel pipes through the basins, and (iii) a heat pump used in combination with (i) and (ii) to increase the condenser cooling water temperature. The first two applications were described in detail by Stefan et al., (1970) and Lindstrom and Boersma, (1973). The size of the heat exchange device needed to impart the necessary energy to the basin water is determined by the difference between the desired basin water temperature and cooling water temperature. This difference will generally be low because of low cooling water temperatures and the need to maintain high basin temperatures. Thus, a large, which means very costly, heat exchange surface is required. The needed surface area may be decreased by increasing the condenser cooling water temperature through the use of a heat pump (Reistad et al. 1974).

Several engineering designs for the heat exchange device are being analyzed. The costs of owning and operating each system will be determined. Results are needed for the economic analysis of the total system.

Preparation of the Inoculum and Inoculation Procedures

Inoculum can be produced from stock, axenic, or unialgal cultures obtainable from several sources. In each case the recipe for a suitable culture medium is provided. Using sterile techniques, the stock culture is inoculated into the appropriate medium contained in 250-ml Erlenmeyer or Fernbach flasks. The flasks are placed on shakers in growth chambers at appropriate light intensities (50 to 2,000 ft. c.) and temperatures (20 to 45 C). When cell population densities on the order of 2 to 5 x 10^6 cells/ml are attained, the total volume of one culture is added to a 500-ml flask containing the filtered, pasteurized culture medium (animal waste) as it is supplied in the algal culture basins. These cultures are maintained on shakers in the culture chambers.

When a population of cells in the logarithmic phase of growth of 2 to 10 x 10^6 cells/ml is reached (10 to 15 days), these second generation cultures are used to inoculate 2-liter flasks of the animal waste medium. When suitable cell densities have developed, each 2-liter culture is used as the inoculum for a 20 liter carboy culture. The carboy cultures are agitated by a stream of

20-liter carboy culture. The carboy cultures are agitated by a stream of compressed air containing 2 to 5 percent CO_2 since they cannot be accommodated on shakers.

All culture media and containers up to the stage of the 20-liter carboys are autoclaved,and sterile techniques must be used throughout. The carboys are sterilized by standing 24 hours while filled with a 2 percent solution of sodium hypochlorite, then scalded with hot 2 percent sodium thiosulfate and rinsed repeatedly with boiling water. The pasteurized animal waste medium is placed in the hot carboys. After cooling, the carboys are inoculated by adding the 2-liter cultures.

The inoculation of the algal basin cultures from the carboys should provide enough cells to provide an initial concentration of more than 10^3 cells/ml. On this basis a 20-liter carboy containing 10^{10} cells (5×10^6 cells/ml) should be adequate to inoculate an algal basin containing 10,000 liters. For a larger volume, more than one 20-liter carboy culture must be used.

At the appropriate cell concentration, the contents of one algal basin culture can be divided to provide inoculum for other basins.

Harvesting Equipment

Harvesting microalgae is difficult because of the small size of the organisms. The process usually involves three major steps: (i) initial concentration, (ii) dewatering of the resulting slurry, and (iii) drying of the dewatered slurry for storage and handling.

Oswald and Golueke (1968b) state that centrifugation and coagulation are the most promising methods. Coagulation is less expensive but has the disadvantage that it might add possible contaminants to the recycling water and to the algal mass. Centrifugation has several advantages, namely: (i) the straightforward method can be used by inexperienced personnel, (ii) the method is well suited for continuity of operation required in a recycling system, (iii) the method produces a material without additives, (iv) the expense of the power requirements may be partially overcome by using energy produced within the system (gases from the anaerobic digester), (v) improved design may reduce power requirements, and (vi) the method will yield a product which may be usable for refeeding without further dewatering and drying.

Air flotation is a promising method which should be considered. The ultimate application of this system would not include drying of the algae. A liquid or slurried feed would be offered to the animals. Thus the energy required for concentrating the algae into a form suitable for pumping to feeding stations might be minimized.

Soil Filter System

Water Disposal

Although the hydraulic transport system is basically of recycling design, water will accumulate. This water will result from the manure and urine contributed by the animals, spillage from the waterers, rainfall striking the algal basins, water used in cleaning the animal pens, and water added to avoid high concentrations of certain elements. This input of water controls the salt accumulation in the system but does require disposal. A soil filter bed should be available to accept this water. It is anticipated that this water volume will be approximately 20 percent of the flow rate or 2,000 liter per day. The water can be stored in a reservoir following the harvesting equipment and applied with a float-activated pump to a soil absorption field to be located near the treatment facility. Perforated plastic pipe in this field provides drainage to control the water table in the area. Effluent can be applied to the drainage field with small sprinklers. This method for disposal of excess partially treated swine effluent has proven to be an effective and acceptable pollution-control approach.

POTENTIAL PROBLEMS

The proposed system has not been experimentally evaluated. Several difficulties are envisioned and anticipated, but the authors believe that these problems can be overcome. Anticipated difficulties are described below.

Flushing Gutter Malfunction

The manure handling system to be used was selected for its simplicity and freedom from normal operating difficulties. In spite of this, difficulties may be anticipated. Among the most likely are plugging of the sewer line or flush tank malfunction. The drain line should be designed and constructed for easy cleaning and repair. The dosing siphon historically has been a trouble-free device once properly installed and adjusted. Regular cleaning and biological growth removal with normal cleaning solutions will help assure its continued function.

Failure of the Air-Lift Pump

Any pump designed to lift manure slurry may be expected to malfunction. The air-lift pump was selected because it is reliable and easy to repair when malfunction does occur. No moving parts are in contact with the manure slurry, thus minimizing accelerated corrosion and clogging. Hog hair, straw, sticks, and other foreign material may collect across the inlet to the pump. When this occurs, it will be possible to lift the entire pump assembly from the pit for cleaning. In the pump chamber is an overflow line directing excess water to the anaerobic lagoon if failure occurs during the night.

Anaerobic Digester Failure

Among the most common failures of waste handling systems has been anaerobic digester upset. The digester design presented above is conservative to reduce the likelihood of digester upset. The temperature of the anaerobic digester should be maintained at the optimum 35 to 37 C level. Minimal sludge accumulation within the anaerobic digester is anticipated. When this does occur the tank will be accessible to pumping with a diaphragm pump. When necessary the sludge can be transferred into the anaerobic lagoon and prevent excess accumulation.

Algae Harvesting Equipment

A centrifuge was selected for the harvesting of algae in the proposed design. A high harvesting efficiency is not required because of the recycling nature of the system. A relatively conservative harvesting efficiency will not adversely affect the performance of this system. The centrifuge was also selected for its simplicity and demonstrated low incidence of malfunction. Provisions are included in the planning to bypass the centrifuge and maintain the flushing action of the water when malfunction occurs. Air flotation techniques will be evaluated. These techniques are less energy demanding and high harvesting efficiencies can be obtained.

Growth of Algae in Other Component Parts

The waste water management scheme consists of water with a high nutrient level and rich in seed cultures of various organisms. Growth of organisms considered a nuisance in other parts of the system is promoted in the culture basins. They could become a problem by clogging pumps or pipes. All water transporting facilities, therefore, must be constructed to avoid clogging and simplify cleaning.

Soil Absorption System

The soil absorption system is used to dispose of the excess water from the system. This function is not critical to the overall performance of the system. However, this function is necessary and requires demonstration if the total system concept is to be judged effective.

Mechanical Malfunctions of the Algal Basins

No major problems with mechanical malfunctions of the culture basins are expected. The mechanical parts involve the heating system, mixing devices, CO_2 supply systems, and hydraulic systems. All components are standard, field-tested items, available commercially. Stand-by basins should be available to receive the flow if one of these components malfunctions. This will allow continuity of operations and allow time for making needed repairs.

Biological Malfunctions of the Algal Basins

Fundamental biological malfunction of the production in the algal culture basins can be caused by (i) one or more species of photoautotrophs eliminating the species of interest, (ii) heterotrophic species (bacteria or fungi) utilizing any extracellular organic materials in the medium, (iii) heterotrophic forms (bacteria, viruses, and fungi) parasitizing the desired species of autotroph, or (iv) adventive microfaunal species (animals) that are predators on the species of interest. Invasion by these agents is usually evidenced by a gradual reduction in the standing crop and/or a decline in the growth rate.

Direct daily microscopic examination of the flora in the culture basins will reveal the presence of invading species and provide advanced warning of the decline in population to come. If cultures are not monitored carefully and routinely, the first indication of a problem may be the unexpected crash of the population of the species of interest. Little can be done to prevent or alleviate such problems in a non-sterile system. It has been proposed that maintaining a uni-specific culture under non-sterile conditions is impossible, and that the only successful procedure is to initiate deliberately a mixed culture with the objective of maintaining domination (in bulk of organic material) by the species of interest. This is the basis of agricultural practice. Thus, it appears defensible that careful organism selection and management of cultural conditions can prevail in aquiculture as well. It should be pointed out that there is a great need for a program to screen large numbers of available organisms to identify those adapted for growth under the imposed cultural conditions.

Invasion of the culture by "foreign" photoautotrophs is an exercise in competitive exclusion. The invaders give evidence of ability to use scarce resources (nutrients, light, space) more efficiently than the species of interest. Presumably the invaders possess inherent qualities that make them better adapted to the cultural conditions than the species of interest. Managing the culture regime to provide cultural conditions more favorable to the species of interest would seem to be the only defense.

Invasion by heterotrophic species (bacteria and fungi) indicates that excessive organic material is present in the culture medium introduced into the culture basin, or it may consist of extracellular metabolic products of the algae growth. In the first case, prolonging anaerobic digestion or simply greater dilution may improve the ability of the culture solutions to support the species of interest. In the second case, more rapid harvest of the algae to prevent the accumulation of extracellular products is a probable solution.

Massive invasion of parasitic heterotrophs (bacteria and fungi) may be an indication that the prevailing cultural conditions (nutrient supply contained in the medium, temperature, pH, or other factors) are subjecting the species of interest to stresses that make it subject to attack by parasites. Manipulating the cultural conditions by modifying the nutrient concentrations, temperature, or pH may provide defense against the parasites.

Defense against the incursion of predators is most difficult. Rotifers and other microfaunal forms are notorious for destroying non-sterile, open cultures. At present there is no practical defense. It has been suggested that predators can be readily removed by a microstrainer placed in the recirculation line. However, the use of microfilters ($<100\mu m$) would greatly increase engineering problems, maintenance problems, and power needs. Furthermore, a predator smaller than $50\mu m$ was encountered in preliminary experiments, thus the mechanical control of predators does not appear feasible. The possibility of using chemicals interfering with nerve functions might be explored. This material would be separated from the algal organic material during the dewatering process but final disposal may be a problem. The solution may be the use of mixed cultures of algae that others have found to possess the necessary vigor to resist competition, parasitism, and predation.

Apparent biological malfunction may indicate mismanagement of the culture system. As previously mentioned, a population developing under physical or chemical stress may evidence a reduced growth rate, low standing crop, and susceptibility to competition, parasitism, or predation. When operating in the continuous flow mode, two types of malfunction may result from management. These are: depletion of the standing crop in the culture basin resulting from harvesting cells faster than they are replaced at the prevailing rate of growth, and staling or the accumulation of scenescent cells in the population resulting from a rate of cell harvest significantly lower than optimal. When harvesting occurs at too high a rate, the depletion of the standing crop will be relatively rapid and unless closely monitored the concentration of cells may approach zero in 48 to 72 hours. The decline of the population in the case of staling will usually be more gradual and is often accompanied by a change in color or the physical appearance of the suspension of cells.

A type of malfunction that results from the presence of undesirable, competitive species is sufficiently distinctive to warrant discussion separately. Termed "wall growth," this malfunction usually results from invasion by heterotrophic or autotrophic forms that develop gelatinous or slimy growth on the walls of the culture container. Cells from the cultured cell suspension become trapped in this slimy layer, increasing its thickness until sloughing occurs. Sheets of this slimy biological material are then suspended in the culture basin. As an increasing proportion of the cells of the species of interest are trapped in the slime and become scenescent, a crash of the cultured cell population may result. The development of this slime can be monitored in the open basins by suspending microscope slides in the water that are examined every two days to detect early stages in the development of the wall growth.

In general, there is little that can be done to prevent the development of competing populations in an open culture basin. The most effective preventive steps are: (i) the selection of a species that is well adapted to the culture conditions, (ii) maximum modification of the cultural conditions (nutrients, temperature, pH, gas supply, etc.) to produce the shortest possible generation time, (iii) harvest the culture at the optimal rate to prevent the accumulation of scenescent cells.

When a biological malfunction is detected by the monitoring program, the cause should be established. Corrective measures, when available, should be instituted immediately. In any case, fresh two liter log phase inoculation cultures should be on hand at all times. If a threat to basin cultures is apparent, 20- liter carboy cultures are to be inoculated, reducing the "down time" of the algal culture system to the minimum.

Failure of Economics

The proposed system can be considered of value only if the proposed use of animal waste and power plant waste heat produces a product at a competitive price. The possible "failure of economics" is raised in the discussion of potential failures because biological reliability is an important aspect of economic considerations. It will not be sufficient to demonstrate successful operation for short periods of time. It must be demonstrated that the system can reliably operate for a year under all possible conditions which may occur during that time. Biological upset is a major hurdle to overcome and its potential occurrence must be part of the economic evaluations.

Failure of Energy Conservation

Several sources of energy will be required; i.e., harvesting of the algae by centrifugation or some other method, drying of algae, mixing of the culture basins, aeration or CO_2 injection, heating and pumping. It will have to be determined if the expenditure of this energy can be warranted by the amount of product obtained and recycled. The question should be resolved by producing a complete energy balance of the proposed system once energy sources and sinks are more clearly quantified by an experimental system.

LITERATURE CITED

Benne, E. J., C. R. Hogland, E. D. Longnecker, and R. L. Cook. 1961. Animal manures - what are they worth today? Agric. Expt. Sta. Bull. No. 231, Michigan State University, East Lansing.

Bickford, E. D., and S. Dunn. 1972. Lighting for Plant Growth. The Kent State University Press, Kent, Ohio.

Bock, H. D., and J. Wünsche. 1967. Möglichkeiten zur Verbesserung der Proteinqualität von Grünalgenmehl. Sitzungsber. Dtsch. Akad. Landw. Wiss., 16:113-119.

Boersma, L.,and G. S. Simonson. 1970. Characterization of water tables in Oregon soils with reference to trafficability. Contract report M-70-1, U. S. Army Engineer Waterways' Experiment Station, Vicksburg, Mississippi.

Braga, A. 1967. Research of the survival of Salmonellae in farmyard effluent used in a fertilizing irrigation plant. Water Poll. Abs. (Brit.), 40: No. 845.

Bratzler, M. W., and T. A. Long. 1968. Digestion of hydrolyzed and cooled poultry waste by ruminants. Jour. of Animal Sci., 27:1509-1516.

Burlew, J. S. (ed.). 1953. Algal Culture: From Laboratory to Pilot Plant. Publ. No. 600. Carnegie Inst., Washington, D. C.

Byrley, T. 1968. Manure dryers opening promising new market. Heating and Air Conditioning Contractor, 59:56-58.

Clark, C. E. 1965. Hog waste disposal by lagooning. Jour. San. Eng. Div., Proc. Amer. Soc. Civil Engr., 91 (SA6):27-42.

Clement, G., C. Giddey, and R. Menzi. 1967. Amino acid composition and nutritive value of the alga Spirulina maxima. Jour. Sci. Food Agric. 18:497-501.

Dale, A. C. 1967. Tentative criteria for design, construction, and operation of the batch type Pasveer oxidation ditch system for the treatment of animal wastes. Dept. of Agr. Engr., Purdue University, Lafayette.

Dam, R., L. Lees, P. C. Fry, and H. Fox. 1965. Utilization of algae as a protein source for humans. Jour. Nutrition, 86:376-382.

Davis, L. R., J. A. Shew, and L. Boersma. 1973. Energy requirements of outdoor basins for aquaculture using power plant waste heat. Paper presented at ASME meeting. Stillwater, Oklahoma (Proceedings in press).

Day, D. L. 1966. Liquid hog manure can be deodorized by treatment with chlorine or lime. Agric. Expt. Sta., Univ. of Ill., Urbana. Illinois Res., 16:10-12.

Decker, M. A., and C. H. Reed. 1967. The plow-furrow cover method of waste disposal. Proc. 10th Nat'l. Pork Ind. Conf., Univ. of Nebraska.

Dixon, R. A., and J. R. Postgate. 1972. Genetic transfer of nitrogen fixation from Klebsiella pneumoniae to Escherichia coli. Nature, 237:102-103.

Dornbusch, J. M., and J. R. Andersen. 1964. Lagooning of livestock wastes in South Dakota. Proc. 19th Ind. Waste Conf., Purdue Univ. Ext. Ser., 177:317-325.

Dugan, G. L., A. G. Golueke, W. J. Oswald, and C. E. Rixford. 1970. Photosynthetic Reclamation of Agricultural Solid and Liquid Wastes. San. Eng. Res. Lab. SERL Report No. 70-1, Univ. of California, Berkeley.

Fink, H., and E. Herold. 1956. Uber die Eiweiszqualität einzelliger Grünalgen and ihre Lebernekrose verhütende Wirkung. I. Hoppe-Seyler's Z. Physiol. Chem., 307:182-191.

Fink, H., and E. Herold. 1957. Uber die Eiweiszqualität einzelliger Grünalgen und ihre Lebernekrose verhütende Wirkung. II. Hoppe-Seyler's Z. Physiol. Chem., 307:202-216.

Fink, H., and E. Herold. 1958. Uber den Einflusz des Trocknens auf das diätetische Verhalten der einzelligen Zuchtalge Scenedesmus obliquus. III. Hoppe-Seyler's Z. Physiol. Chem., 311:13-18.

Groghegan, M. J. 1953. Experiments with Chlorella, pp. 182-189. In: J. S. Burlew (ed.), Algal Culture: From Laboratory to Pilot Plant. Publ. No. 600, Carnegie Inst., Washington, D. C.

Gromov, B. V. 1968. Main trends in experimental work with algae cultures in the U.S.S.R. pp. 249-278. In: D. F. Jackson (ed.), Algae, Men and the Environment. Syracuse University Press, Syracuse, N. Y.

Grub, W., R. C. Albin, D. M. Wells, and R. Z. Wheaton. 1969. Engineering analyses of cattle feedlots to reduce water pollution. Trans. Amer. Soc. Agr. Engr., 12:490-492.

Hammond, C. W., D. L. Day, and E. L. Hansen. 1968. Can lime and chlorine suppress odors in liquid hog manure? Agr. Engr., 49:340-343.

Hart, S. A., and M. E. Turner. 1965. Lagoons for livestock manure. Jour. Water Poll. Control Fed., 37:1578-1586.

Hemerick, G. 1973. Mass culture. In: Handbook of Phycological Methods. In press.

Hermanson, R. E., T. E. Hazen, and H. P. Johnson. 1969. Biooxidation of swine waste by the activated sludge process. Trans. Amer. Soc. Agr. Eng., 12:342-353.

Hintz, H. F., and H. Heitmann. 1967. Sewage-grown algae as a protein supplement for swine. Animal Prod., 9:135-140.

Hintz, H. F., H. Heitmann, W. C. Wier, D. T. Torell, and J. H. Meyer. 1966. Nutritive value of algae grown on sewage. Jour. Animal Sci., 25:675-681.

Iwata, I., and Y. Sakurai. 1963. Lipids of algae. IV. Carotenoid pigments of Scenedesmus. Agric. Biol. Chem. (Tokyo), 27:259-264.

Jeffrey, E. A., W. C. Blackman, Jr., and R. L. Ricketts. 1963. Aerobic and anaerobic digestion characteristics of livestock wastes. Eng. Ser. Bull. No. 57, Univ. of Missouri, Columbia.

Jones, D. D., J. C. Converse, and D. L. Day. 1968. Aerobic digestion of cattle waste. Trans. Amer. Soc. Agr. Eng., 11:757-762.

Jorgensen, J., and J. Convit. 1953. Cultivation of complexes of algae with other freshwater microorganisms in the tropics. In: J. S. Burlew (ed.), Algal Culture: From Laboratory to Pilot Plant. Publ. No. 600, Carnegie Inst., Washington, D. C.

Klenk, E., W. Knipprath, D. Eberhagen, and H. P. Koof. 1963. Uber die ungesättigten Fettsäuren der Fettstoffe von Süszwasser und Meeresalgen. Hoppe-Seyler's Z. Physiol. Chem., 334:44-59.

Klyushkina, N. S., and V. I. Fofanov. 1967. Biological value of proteins of unicellular algae. Kosm. Biol. Med., 1:52-56.

Klyushkina, N. S., V. I. Fofanov, and I. T. Troitskaya. 1967. A study of the biological value of plant proteins in relation to their possible utilization in a life-support system. Kosm. Biol. Med., 1:38-43.

Kofranyi, E., and F. Jekat. 1967. Zur Bestimmung der Biologischen Wertigkeit von Nahrungsproteinen. XII Die Mischung von Ei mit Reis, Mais, Soja, Algen. Hoppe-Seyler's Z. Physiol. Chem., 348:84-88.

Kok, B., and J. L. P. Van Oorschot. 1954. Improved yields in algal mass cultures. Acta Bot. Neerlandica, 3:534-546.

Kondratyev, Y. I., V. P. Bychkov, A. S. Ushakov, N. N. Boiko, and N. S. Klyushikina. 1966. Use of 50 and 100 g dry material from unicellular algae in human diets. Vop. Pitan, 25:9-14.

Krauss, R. W. 1953. Inorganic nutrition of algae, pp. 85-102. In: J. S. Burlew (ed.), Algal Culture: From Laboratory to Pilot Plant. Publ. No. 600, Carnegie Inst. Washington, D. C.

Krauss, R. W., and W. H. Thomas. 1954. The growth and inorganic nutrition of Scenedesmus obliquus in mass culture. Plant Physiol., 29:205-214.

Lautner, V. 1965. Carotenoid pigments of the alga Scenedesmus quadricauda. Biol. Chem. Vyz. Zvirat, 1:265-274.

Leach, G. 1972. Mankind faces starvation. Interview with G. Borgstrom and N. Borlaug reported in the Gazette-Times, Corvallis, Oregon, April 26.

Lebeda, D. L., and D. L. Day. 1965. Waste caused air pollutants are measured in swine buildings. Agric. Expt. Sta., Univ. of Illinois, Urbana, Illinois Res. Bull. No. 15.

Lee, S. K., H. M. Fox, C. Kies, and R. Dam. 1967. The supplementary value of algae in human diets. Jour. Nutrition, 92:281-285.

Lindstrom, F. T., and L. Boersma. 1973. Heat budget of cooling basins. Jour. Env. Qual., 2:197-203.

Loehr, R. C. 1968. Pollution Implications of Animal Wastes--a Forward Oriented Review. Dept. of the Interior, FWPCA, Robert S. Kerr Water Res. Center.

Mattoni, R. H. J., E. C. Keller, Jr., and H. N. Myrick. 1965. Industrial photosynthesis, a means to a beginning. Bio. Science, 15:403-407.

McCoy, E. 1967. Lagooning of liquid manure (bovine): bacteriological aspects. Trans. Amer. Soc. Agr. Eng., 10:784-790.

McDowell, M. E., and G. A. Leveille. 1963. Feeding experiments with algae. Fed. Proc., 22:1431-1438.

Meffert, M. E. 1955. Groszkultur von Grünalgen. Eine neue Nahrungsquelle? Umschau Wiss. Tech., 13:388-390.

Meffert, M. E., and W. Pabst. 1963. Über die Verwertbarkeit der Substanz von Scenedesmus obliquus als Eiweiszquelle in Ratten-Bilanz-Versuchen. Nutr. Dieta, 5:235-254.

Merkel, J. A., T. E. Hazen, and J. R. Miner. 1969. Identification of gases in a confinement swine building atmosphere. Trans. Amer. Soc. Agr. Eng., 12:310-314.

Meyers, J. 1971. Algal culture, pp. 649-668. In: R. E. Kirk and D. F. Othmer (eds.) Encyclopedia of Chemical Technology, First Supp. Interscience Publ. New York.

Miner, J. R. 1968. Annual review of literature: agricultural (livestock) wastes. Jour. Water Poll. Control Fed., 40:1150-1158.

Miner, J. R. 1969. Annual review of literature: agricultural (livestock) wastes. Jour. Water Poll. Control Fed., 41:1169-1178.

Miner, J. R., R. I. Lipper, L. R. Rina, and J. W. Funk. 1966. Cattle feedlot runoff: nature and behavior. Proc. 21st Ind. Waste Conf., Purdue Univ. Ext. Serv., 121:834-847.

Miner, J. R. 1973. Odor from livestock production. Dept. of Agr. Engr., Oregon State Univ., Corvallis.

Mitsuda, H. 1965. Utilization of Chlorella as food. Food Sci. Technol., Proc. 1st Intern. Congr. Food Sci. and Technol. II, 529-539.

Muehling, A. J. 1969. Swine housing and waste management. Agr. Eng. Publ. No. 873, Dept. Agric Eng., Univ. of Illinois.

Müntz, K. 1967. Die Massenkultur von Kleinalgen (bisherige Ergebnisse). Kulturpflanze, 15:311-350.

Müntz, K. 1968. Uber die bei Algenmassenkulturen bisher erzielten Produktionsergebnisse. Kulturpflanze,16:277-281.

Nakamura, N., and K. Yamada. 1960. Evaluation of nutritive value of unicellular green algae. Jap. Microalgae Res. Inst. Rep. I/2.

Novak, B., and F. Lobl. 1967. The complex effect of manures and fertilizers on the yield of crops. Biol. Abs., 48, 82605.

Oswald, W. J. and C. G. Golueke. 1968a. Large-scale production of algae, pp. 271-301. In: R. I. Mateles and S. R. Tannenbaum (eds.), Single Cell Protein. Mass. Inst. Techn. Press, Cambridge, Mass.

Oswald, W. J., and C. G. Golueke. 1968b. Harvesting and processing of waste-grown microalgae, pp. 371-389. In: D. F. Jackson (ed.), Algae, Man, and Environment. Syracuse University Press, Syracuse, N. Y.

Pirie, N. W. 1971. Equipment and methods for extracting and separating protein. pp. 53-63. In: N. W. Pirie (ed.), Leaf Protein: Its Agronomy Preparation, Quality, and Use. IPB Handbook No. 20, International Biological Programm. Blackwell Scientific Publications, Oxford.

Pratt, G. L., R. E. Harkness, R. J. Butler, J. L. Parsons, and M. L. Buchanan. 1969. Treatment of beef cattle waste water for possible reuse. Trans. Amer. Soc. Agr. Eng., 12:471-474.

Powell, R. C., E. M. Nevels, and M. E. McDowell. 1961. Algae feeding in humans. Jour. Nutrition, 75:7-12.

Reistad, R. M., Arif Ileri, and W. E. Schmisseurr. 1974. Waste Heat for Urban Use. Project Report. Dept. of Mechanical Engineering, Oregon State Univ.

Ryther, J. H. 1959. Potential productivity of the sea. Science, 130:602-608.

Schacht, C. J. 1967. Development of liquid-manure-handling equipment. Trans. Amer. Soc. Agr. Eng., 10:161-163.

Schlüter, H., and H. Querner. 1957. Untersuchungen über die Verwendung von einzelligen Grünalgen in der Fütterung von waschsendem Junggeflügel. pp. 18-24. (Tätigkeitsber. 1956 Lehr- und Versuchsanst. Geflügel und Kleintierzucht), Krefeld-Groszhüttenhof.

Siegel, B. Z., and S. M. Siegel. 1973. The chemical composition of algal cell walls. CRC Critical Reviews in Bacteriology, pp. 1-26.

Soeder, C. J., E. Hegewald, W. Pabst, H. D. Payer, I. Rolle, and E. Stengel. 1970. Zwanzig Jahre angewandte Mikroalgenforschung in Nordrhein-Westfalen. Jb. Landesamt Forschg. Nordrhein-Westfalen, pp. 1-34.

Soeder, C. J., and W. Pabst. 1970. Gesichtspunkte für die Verwendung von Mikroalgen in der Ernährung von Mensch und Tier. Ber. Dtsch. Bot. Ges. 83:607-625.

Soeder, C. J., A. Strotmann, and E. Stengel. 1969. Aufzucht von Karpfen mit Grünalgenfutter. Umschau, 69:342.

Sorokin, C. 1971. Calefaction and phytoplankton. Bioscience, 28:1153-1159.

Sorokin, C., and R. W. Krauss. 1958. The effects of light intensity on the growth rates of green algae. Plant Physiol., 33:109-113.

Souci, S. W., W. Fachmann, and H. Kraut. 1962-1969. Die Zusammensetzung der Lebensmittel. I-III. Wiss. Verlags-Ges. mbH., Stuttgart.

Spoehr, H. A., and H. W. Milner. 1949. The chemical composition of Chlorella: effect of environmental conditions. Plant Physiol., 24:120-149.

Stefan, H., E. Silberman, P. Vaidyaraman, and W. Geiger. 1970. Temperature control in outdoor experimental ponds. University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis.

Stengel, E. 1970. Anlagen und Verfahren der Technischen Algenmassen Produktion. Ber. Dtsch. Bot. Ges., 83:589-606.

Strietelmeier, D., and R. B. Koch. 1962. Modifications of green algae to be used as food. Nature, 195:474-476.

Taiganides, E. P., E. R. Baumann, E. P. Johnson, and T. E. Hazen. 1963. Anaerobic digestion of swine wastes. Jour. of Agr. Engr. Res. (Brit.), 8:327-331.

Taiganides, E. P., and T. E. Hazen. 1966. Properties of farm animal excreta. Trans. Amer. Soc. Agr. Eng., 9:374-379.

Taiganides, E. P., and R. K. White. 1968. Mission impossible: control odors in poultry production units. Proc. 2nd. Nat'l Poultry Litter and Waste Management Seminar, Texas A & M Univ., p. 10.

Tamiya, H. 1957. Mass culture of algae. Ann. Rev. Plant Physiol., 8:309-334.

The World Food Problem; report of the President's Science Advisory Committee. 1967. Vols. I, II, and III. The White House. U.S. Government Printing Office.

United Nations Economic and Social Council. 1967. Increasing the production and use of edible protein. Document E 4343, 25 May, New York.

Verley, W. E., and J. R. Miner. 1973. A rotating flighted cylinder to separate manure solids. ASAE Paper No. 73-470. Trans. Am. Soc. Agr. Eng. (in press).

Wesselius, J. C. 1973. Influence of light intensity on growth and energy conversion in mass cultures of Scenedesmus sp. In: R. O. Slatyer (ed.), Plant Response to Climatic Factors. UNESCO, Paris.

Wilcox, O. W. 1959. Footnote to freedom from want. Jour. Agr. Food. Chem., 7:813-822.

Witt, M. J., and J. Schröder. 1967. Die einzellige Süszwasser Grünalge Scenedesmus obliquus, ein vollwertiges Eiweiszfutter in der Schweinemast. Landw. Forschg., 20:148-156.

Witt, M., J. Schröder, and H. von der Mehden. 1962. Zur Frage der Verwendung von Algeneiweisz in der Schweinemast. Züchtungskde., 34:272-281.