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The effect of a continuous low temperature on the operation of waste stabilization lagoons

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THE EFFECT OF A CONTINUOUS LOW TEMPERATURE ON THE OPERATION OF WASTE STABILIZATION LAGOONS

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A

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ABSTRACT

This study was undertaken to determine the effect of a continuous low temperature on the operation of a waste stabilization lagoon and to provide information of value to the sewage treatment field.

The investigation was conducted using two experimental lagoons subjected to a continuous illumination of 550 to 600 foot candles emitted by two fluorescent light fixtures. Of these units, the Cold Room Lagoon was maintained at a controlled temperature of 5° C. and the Warm Room Lagoon was operated at room temperature in the range of 16 to 32° C.

Dissolved oxygen and biochemical oxygen demand determinations were the primary parameters used in this study. In addition pH, suspended solids, and coliform bacteria determinations provided additional information of value.

Several different loadings of raw sewage were applied during the early phases of the investigation to establish the appropriate loadings for this study and to enable the acclimatization of the units. During the main portion of the study 16 fluid ounces of raw sewage were added daily to the Cold Room Lagoon resulting in a BOD loading of 11.3 pounds of BOD per acre per day and 32 ounces were added to the Warm Room Lagoon providing a loading of 22.3 pounds of BOD per acre per day.

It was found that waste stabilization lagoons operated effectively under a continuous low temperature but had a decreased efficiency and required reduced organic loadings.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

With the ever growing population and industrial production there is a rapidly increasing demand for water. In 1962 approximately 300 billion gallons of water were used daily in the United States and it is predicted that by 1980 the demand will be 600 billion gallons per day (1). Although there is a sufficient water supply, it is not always economically available in the areas of rapid development and high demand. The re-use of water becomes therefore apparent and pollution abatement a must.

It is the responsibility of every community to treat its domestic and industrial wastes before discharging them to rivers or other water storage areas. Although many methods can be used to treat effectively waste waters, economics will strongly influence the type of treatment selected.

The conventional sewage treatment plant, because of the expense involved in its construction, operation and maintenance, cannot always be financed by a community with limited funds. Other means of disposal must be utilized. Recently waste stabilization lagoons have received much attention in the treatment of wastes from smaller communities.

Waste stabilization lagoons have been used in this country for many years, but only in the last decade has their use become widespread. A waste stabilization lagoon, lagoon, or oxidation pond as it is also known, is a shallow pond which receives sewage or other wastes and may or may not produce an effluent. Although this method of treatment has been developed by trial and error and had a rather accidental beginning it has been found to be highly successful in the treatment of raw sewage (2). Waste stabilization lagoons are easy to construct and require little operation and maintenance expense. They are often the most economical method of sewage treatment for the smaller communities.

The treatment effected by a waste stabilization lagoon results from a complex symbiosis of bacteria and algae. This symbiotic activity helps reduce the organic matter and produces a relatively stable and inoffensive effluent. Treatment is accomplished by aerobic bacteria, which oxidize the organic matter present in the waste to carbon dioxide and water. Algae, through photosynthesis, convert a major portion of this carbon dioxide to algal cell material and release oxygen which is in turn available for use by the aerobic bacteria (3, p. 240).

It should be noted that in addition to their use for the treatment of domestic sewage, waste stabilization lagoons have been also employed in the treatment of industrial wastes and wastes from motels, lodges and rural schools. Further, lagoons are especially applicable to military installations because their operation is not appreciably affected by the varying waste volumes that result from the periods of high and low water use common to these installations.

Waste stabilization lagoons depend on biological processes for the stabilization of the waste matter and consequently environmental factors have an important effect on their operation. This is illustrated by the loadings permitted by the various State Departments of Health which depend strongly on the climatic conditions prevailing in the area. Thus, while in the Dakotas (4) loadings of 15 to 20 pounds of biochemical oxygen demand (BOD) per acre per day are used, the corresponding recommended loadings in Missouri (5) and California (6) are 34 and 50 pounds of BOD per acre per day respectively.

It has been reported in the literature (4) that in the colder areas the waste stabilization lagoons remain in a "refrigerated" condition during the winter months until the increased temperatures of the spring melt the ice cover and permit biological action. During this winter period lagoons are usually considered to operate as storage areas rather than as stabilization lagoons. However, no information was found in the literature concerning the function of the lagoon microbial population during periods of low temperature, especially in the absence of an ice cover when light can penetrate and be available for photosynthesis.

It was therefore the purpose of this study to investigate the effect of a continuous low temperature on the efficiency and operation of a waste stabilization lagoon under simulated plant conditions. This investigation was undertaken at a temperature of 5^{o} C. using a 15 gallon aquarium and light energy supplied by fluorescent tubes. The study revealed that waste stabilization lagoons can operate under a continuous low temperature but require reduced organic and volume loadings.

II. REVIEW OF LITERATURE

In August, 1960, a symposium on waste stabilization lagoons was held in Kansas City, Missouri. Representatives from many states participated at that meeting and contributed much to a better understanding of this method of waste treatment. The proceedings of this symposium (7) constitute a major portion of the present knowledge of waste stabilization lagoons and they have been used as the basis for this review of literature. However, additional information has been included to supple nt that presented in the proceedings. Although much has been written on waste stabilization lagoons, very little information of value was found in the literature on the effect of continuous low temperatures on their design and operation.

This review of literature has been divided into four parts as follows: (a) Application of Waste Stabilization Lagoons, (b) Design and Operation of Waste Stabilization Lagoons, (c) Previous Research Investigations, and (d) Summary of the Review of Literature.

A. APPLICATION OF WASTE STABILIZATION LAGOONS

1. Historical Development.

According to Svore (2) of the United States Public Health Service, during the mid-twenties lagoons were used in California, Texas, and North Dakota as a means of treating domestic sewage. One of the first cities to use a waste stabilization lagoon was Santa Rosa, California. In 1924, the city discharged raw sewage on an exposed gravel bed in order to obtain a natural filtration of the waste before it was discharged to the highly polluted Santa Rosa Creek. The gravel bed was soon sealed by the sewage solids and an impoundment of sewage to a depth of approximately 3 feet resulted. The effluent from this lagoon had no odor, was easily disinfected and resembled effluents from trickling filters. During the same year Vacaville, California used a dry gulley as an impounding reservoir. It was found that the impounded sewage underwent characteristic changes resulting in a reduction in BOD and an increase in the dissolved oxygen content (2).

One of the best known waste stabilization lagoons is that of Fessenden, North Dakota, which was placed in operation in 1928 to handle the city sewage and consisted of a sealed pothole located about a mile and a half away from the city (2). Svore reported in 1960 that this lagoon was still in operation and had caused neither odors nor any other operational difficulties. The success of the lagoon at Fessenden indicated that these units can function effectively and may be located near a city without causing nuisance.

2. Present Status of Waste Stabilization Lagoons.

At the present time over 1000 waste stabilization lagoons are in operation in the United States and Canada (7). The development and present status of this method of waste treatment is of interest and is summarized in the following pages for several of the states.

a. Missouri (8).

Lagoons have been used in Missouri since 1935 but it was not until 1953 that official interest was expressed in their applications in the treatment of waste waters. An experimental lagoon was developed in 1956 at Fayette, Missouri and has been in continuous use providing experimental data on design and operation. In 1960 over 247 waste stabilization lagoons were serving approximately 300,000 persons and in addition were used to treat industrial wastes from poultry processing plants, dairy plants, slaughter houses, and automatic laundries.

b. North Dakota (2).

Waste stabilization lagoons were first officially accepted in this state in 1948, following the construction of a modern lagoon at Maddock, North Dakota. A rapid adoption of waste stabilization lagoons followed and in 1960 approximately 100 communities, constituting two-thirds of the sewered municipalities, were using waste stabilization lagoons.

c. South Dakota (9).

Following the success of lagoons in North Dakota, a waste stabilization lagoon was constructed at Lemmon, South Dakota, in 1951 and attention was centered on this method of waste treatment. According to Carl, et al (9) of the South Dakota Department of Health, the complete acceptance of waste stabilization lagoons in South Dakota was demonstrated by the fact that no conventional treatment plants have been built in any municipality under 5,000 population in the 5 year period preceding 1960 and that at that time a total of 77 waste stabilization lagoons were in operation.

d. Montana (10).

The first waste stabilization lagoon in this state was constructed and placed in operation in 1953 at Plentywood, Montana. Public acceptance of waste stabilization lagoons was rapid and in 1960 approximately 44 lagoons were in operation with plans for additional units.

e. Alaska (11).

The Public Health Service Research Center at Anchorage, Alaska, reported that it has been investigating two experimental lagoons since 1957. One of these was located at Sutton, Alaska and was designed for a population of 50 persons. This lagoon did not hold liquid despite several attempts to seal the bottom. The other experimental lagoon was located at Fort Yukon, Alaska and was designed for an elementary school serving 200 persons. This lagoon was loaded only during the winter months at which time an ice cover prevented spreading of obnoxious odors. It has been found that this unit never froze completely even when the atmospheric temperature dropped to -70° F. Following the disappearance of the ice in the spring stabilization of the sewage was attained within a month without the occurrence of any odors.

The waste stabilization lagoon method of waste treatment is of considerable interest to Alaska because its 160,000 civilian residents are scattered over an area of 586,000 square miles and land is available at low cost.

B. DESIGN AND OPERATION OF WASTE STABILIZATION LAGOONS

The construction of waste stabilization lagoons is simple and relatively inexpensive and they require minimum operation and maintenance. However, lagoons must be properly designed in order to function effectively and prevent the development of nuisance. The BOD loadings, the depth, and the shape of waste stabilization lagoons are of considerable importance and the information found in the literature on these design criteria is summarized in the following pages. In addition the microbial action in a lagoon is outlined to help understand the function of the microbial groups present.

1. Microbial Action.

The stabilization of organic matter in a lagoon strongly depends on the symbiotic activity of two major groups of microorganisms, the algae and the aerobic bacteria (3, p. 140).

According to Babbitt and Baumann (12, p. 359) the microorganisms functioning in a waste stabilization lagoon are the same as those existing in other sewage treatment processes, such as trickling filters, and are predominately bacteria and algae. The reduction of the organic material in a waste stabilization lagoon is accomplished by means of the action of aerobic bacteria. These microorganisms, which multiply very rapidly under favorable conditions, will reduce the organic matter and release carbon dioxide which may be in turn utilized by the algae. Algae by means of photosynthesis release oxygen which is then available to the aerobic bacteria. The reduction of raw sewage in a waste stabilization lagoon is therefore, an excellent example of symbiosis, the situation whereby two organisms, mutually dependent, live together. Light energy is absorbed by the algae in the lagoon and through photosynthesis they release molecular oxygen to the water, thus providing for one of the basic needs of the aerobic bacteria. The aerobic bacteria oxidize the organic material and release carbon dioxide which is vital for the growth of algae (3, p. 140).

2. Recommended BOD Loadings.

The design of waste stabilization lagoons is usually based on area requirements which may be expressed as the permissible loading in pounds of BOD per acre per day or as the recommended number of people served per acre. Of these two, the BOD loading is most commonly used.

The recommended loadings vary in different states and depend considerably on the climatic conditions prevailing in the area. In California (6) waste stabilization lagoons are designed on the basis of 50 pounds of BOD per acre per day, while in the Dakotas (13) only 15 to 20 pounds of BOD per acre per day are used. It should be noted that these two BOD loadings constitute the two extremes found in the literature and the permissible loadings in other states are within this range. Further, higher BOD loadings are generally recommended in warmer climates. Finally, it should be mentioned that in this area, the Missouri Department of Health (14) permits a loading of 34 pounds of BOD per acre per day.

According to Towne and Davis (13) in order to maintain aerobic conditions during all periods of open water the design BOD loadings should be governed by the oxygen production during the critical periods of minimum algal photosynthetic activity occurring with the transition from an ice cover to open water. Towne and Davis also reported that during periods of cloudy weather the dissolved oxygen dropped to zero and remained at that value for several hours during the night. This reduction in dissolved oxygen was necessary to satisfy the respiratory requirements of bacteria, algae, and other biota in the lagoon. They concluded that heavier loadings may be applied during favorable climatic periods without resulting in anaerobic conditions and nuisance.

3. Recommended Depth.

Towne and Davis (13) reported that the optimum depth of a waste stabilization lagoon was 2 feet but varied with the season of the year.

In cold climates with ice thickness ranging from a few inches to over 3 feet, a total depth of 5 feet was not unreasonable. However, experience indicated that spring recovery proceeded more rapidly in waste stabilization lagoons with shallow depths which permitted better mixing and dispersal of settleable matter by wind action.

A minimum depth of 2 1/2 feet appeared to be necessary in order to discourage the growth of rooted aquatic plants. Towne and Davis also reported that during the high temperature months depths of 4 to 5 feet assisted in maintaining more uniform lagoon temperatures. They concluded that it was desirable to provide for depths varying between 2 1/2 and 5 feet.

It should be noted that in order to maintain the lagoon depth at approximately the optimum value seepage plus evaporation should not exceed the sum of precipitation and sewage inflow. Under these conditions an effluent will usually result. If the loss of the lagoon contents by evaporation and seepage through the soil were too great, the depth of the liquid in the lagoon might have been lowered to such an extent that the lagoon could become inoperative. To reduce this loss of liquid the lagoon bottom and dikes are treated to be made relatively impermeable. A layer of compacted clay or asphalt may be placed on the bottom and dikes to reduce the loss from seepage (13).

4. Shape of Waste Stabilization Lagoons.

The shape of the waste stabilization lagoons is in most cases governed by the topography of the available land. It is desirable to provide the greatest possible distance between the inlet and outlet points in order to obtain complete mixing and long detention. In circular lagoons the sewage is introduced at the center and discharged at the circumference. Rectangular lagoons are designed to have a length at least twice as great as the width. To allow for mixing and optimum detention the sewage is introduced at a point located in the center of the width and at a distance equal to two-thirds of the length from the effluent end (15).

5. Operation and Maintenance.

The operation and maintenance of waste stabilization lagoons is of considerable importance although it is comparatively low in cost compared to the operation and maintenance required for a conventional sewage treatment plant.

Towne and Davis (13) reported the following recommendations concerning the operation and maintenance of waste stabilization lagoons: timber should be removed a sufficient distance to prevent shading the lagoon; mowing and maintenace of the dikes should be considered when locating the fence; the lagoon should be posted to identify the facility; the lagoon dikes must be seeded to control erosion; all surface waters must be excluded from the lagoon; vegetation must be kept mowed on the dikes; and the weeds must be kept out of the lagoon since upon decomposition they cause odors. They noted (13) that weed control may be accomplished using a depth of 3 feet although the best operation will be obtained when a 2 feet depth is employed. Also the dikes should be kept in good repair to prevent deterioration of the lagoon structure.

C. PREVIOUS RESEARCH INVESTIGATIONS

Although most of the references found in the literature on waste stabilization lagoons consisted of reports on lagoon operation in different localities under specific loading and climatic conditions, some information was also obtained on the effect of light intensities and temperature.

1. Effect of Light Intensity.

The availability of light is of primary importance to the operation of a waste stabilization lagoon and the permissible organic loading to the lagoon is determined accordingly. Gloyna and Hermann (16) reported that in their investigations they found that a light intensity of 400 foot candles is the upper limit which can be fully utilized by the algae in a waste stabilization lagoon. They noted that the light intensity from the sun is at least 800 foot candles or more on most days in the North Temperate Zone and provides more than the maximum amount of light that is required by the algae.

2. Effect of Environmental Temperature.

Gotaas and Oswald (17, p. 48) have conducted several investigations using pure cultures of algae and reported that temperature more often than light intensity appeared to limit the geographic distribution of algal growth. They also reported that they were able to grow algae at a temperature as low as 4^{o} C.

The effect of temperature was also studied at the experimental lagoons at Fayette, Missouri during 1958 and 1959. It was found (8) that a greater reduction of the BOD through the combined action of algae and aerobic bacteria was possible during the summer months than that obtained in the winter months. Thus, a 92 percent reduction of the BOD was obtained during July when a loading of 20.3 pounds of BOD per acre per day was applied and the average temperature was approximately 74° F. With essentially the same loading the corresponding BOD determined in March was approximately 77 percent when the average temperature was 43° F. During March the temperature fluctuated between 55° F. and 31° F. and while relatively stable conditions were observed at the higher value, when the temperature dropped to 31° F. anaerobic conditions prevailed. It should therefore be pointed out that the average figures for BOD reductions presented did not represent the operational results that might have been obtained if a continuous temperature of 43° F. was maintained.

It may be mentioned that according to Hubbs (18) the waste stabilization lagoons at Anchorage, Alaska, act as storage basins during the winter months until spring when the symbiotic activity of algae and bacteria is reestablished.

D. SUMMARY OF THE REVIEW OF LITERATURE

Waste stabilization lagoons have received rapid acceptance in recent years because they are in many cases an inexpensive method of sewage and industrial waste treatment. It has been estimated that over 1000 units are in operation in the United States and Canada.

The recommended BOD loadings depend on the climatic conditions prevailing and range between 15 and 50 pounds of BOD per acre per day, the loadings for North Dakota and California, respectively.

Very little information was found on the effect of continuous low temperatures on the design and operation of waste stabilization lagoons. However the available data indicated that the microorganisms in waste stabilization lagoons may function under low temperatures but they may operate at a reduced efficiency.

III. DISCUSSION

A. EXPERIMENTAL LAGOONS

Two experimental lagoons were used in this study which was undertaken to determine the effect of a continuous low temperature on the treatment of raw sewage by waste stabilization lagoons. Of these two, one was designated as the Cold Room Lagoon and the other as the Warm Room Lagoon.

The Cold Room Lagoon was maintained constantly at 5° C. and was used to simulate the operation of waste stabilization lagoons under conditions of low temperatures. The Warm Room Lagoon was operated in parallel at room temperatures and was used to provide a basis for comparison of the results obtained.

1. Description.

The lagoons were rectangular 15 gallon aquariums having glass sides and a slate bottom. The inside dimensions of each unit were as follows: depth 11 3/4 inches, width 12 inches and length 23 1/2 inches. Each aquarium had a surface area of 1.96 square feet and a volume of 1.84 cubic feet at the depth of 11 1/4 inches which was used in the studies. One of the experimental lagoons is shown in Figure 1.

2. Location and Temperature.

The two experimental lagoons were located in two separate rooms in the Materials Testing Laboratories of the Civil Engineering Department. The Cold Room Lagoon was located in one of the rooms which was equipped with heating and refrigeration units and was maintained at 5° C. ± 1° C.

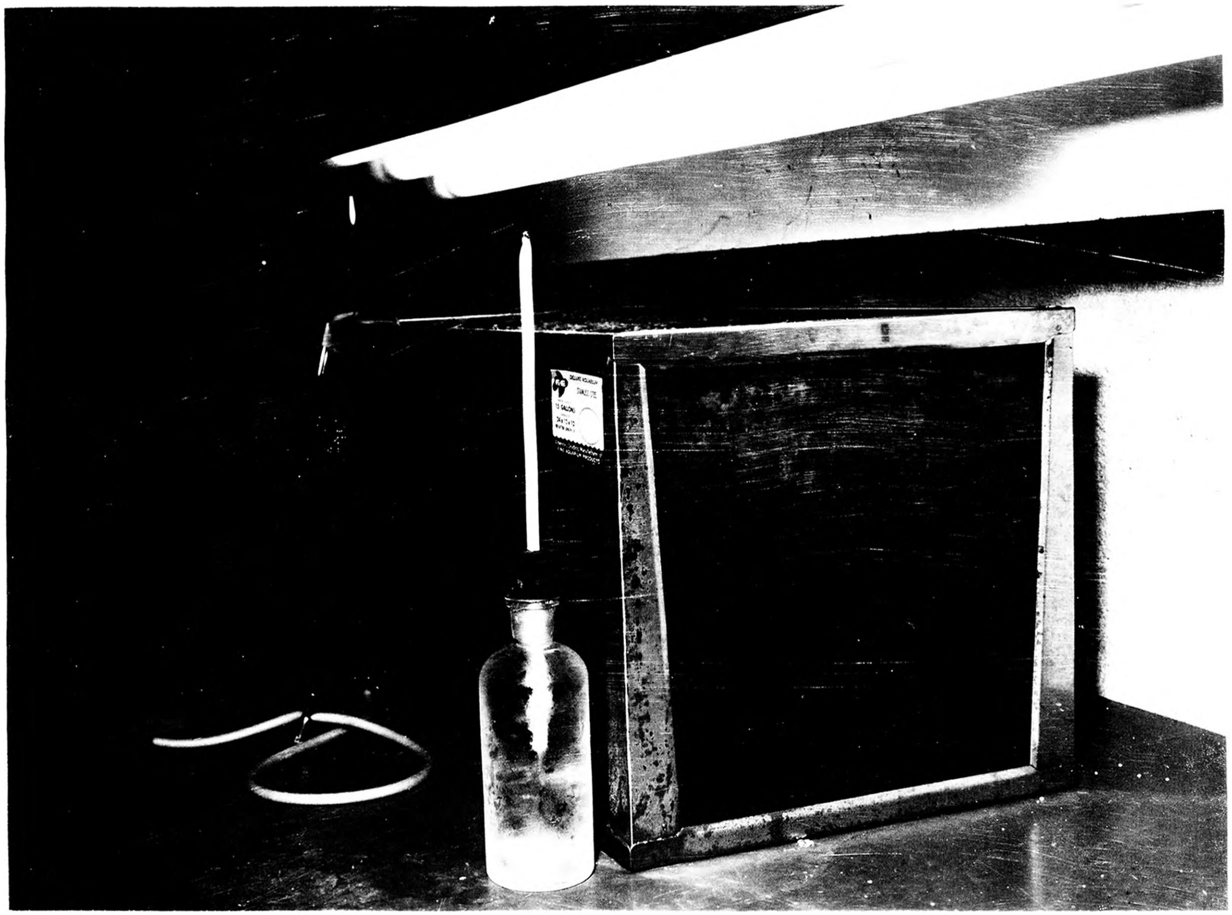

FIGURE 1

THE COLD ROOM EXPERIMENTAL LAGOON

The Warm Room Lagoon was placed in the other room where the temperature was not controlled but fluctuated during the studies with the atmospheric changes and ranged between 16° and 32° C. The cold room experimental arrangement is presented in Figure 2.

3. Light.

Each experimental lagoon was illuminated by means of a fluorescent light fixture which was approximately 40 inches long and was placed 6 inches above the liquid surface. Each light fixture was equipped with a reflector and had three 40 watt fluorescent tubes. The light intensities at the surface of the lagoons were measured by means of a Photronic Foot-Candle Meter, Model 614 manufactured by the Weston Electrical Instrument Corporation, Newark, New Jersey. These intensities ranged from 600 foot candles at the center of the lagoon to 550 foot candles at the ends of the lagoon and were maintained constant throughout the investigation. It should be noted that the light intensities provided were above 400 foot candles, the reported (16) maximum requirements for algal photosynthetic activity. The arrangement of the light fixtures may be seen in Figures 1 and 2.

B. EXPERIMENTAL PROCEDURES

1. Experimental Parameters.

A number of experimental parameters were employed in order to evaluate the effect of a continuous low temperature on the operation of waste stabilization lagoons. The primary parameters used in this study were the dissolved oxygen and biochemical oxygen demand determinations, and were supplemented with the pH, solids, and coliform group determinations.

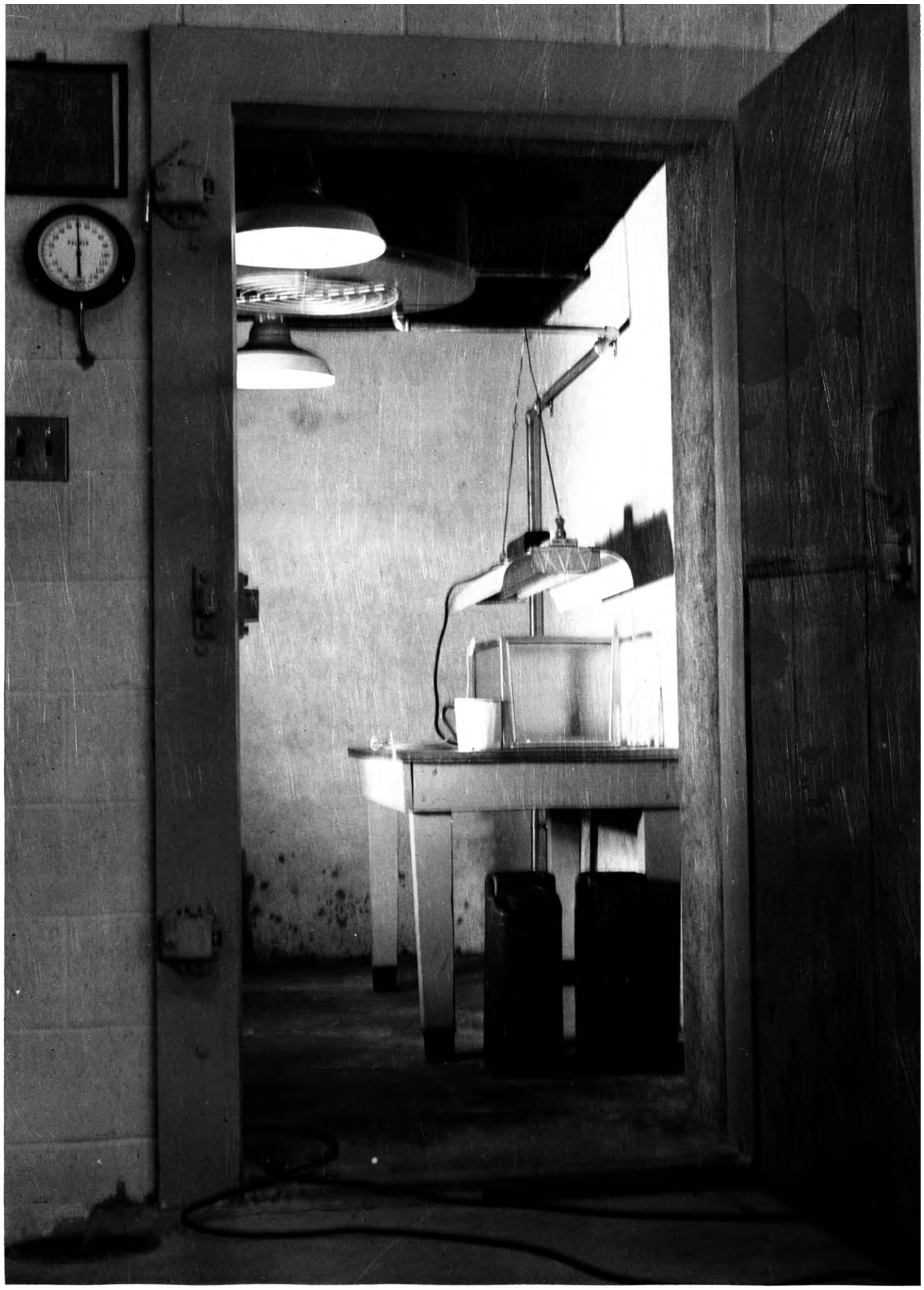

FIGURE 2

THE COLD ROOM ARRANGEMENT

a. The Dissolved Oxygen Determination.

The dissolved oxygen determination, one of the most important tests in the Sanitary Engineering Field (19, p. 263), was performed to ascertain the amount of free oxygen available in the lagoon water. Dissolved oxygen in polluted waters is needed to permit decomposition of the organic matter by aerobic bacteria. In the absence of free oxygen, waters heavily laden with organic load will give off highly offensive odors as anaerobic decomposition takes place. The presence of dissolved oxygen was therefore essential for the proper operation of the experimental lagoons. The dissolved oxygen determination was also used as the basis of the biochemical oxygen demand test.

The Alsterberg (Azide) modification of the Winkler Method, as outlined in the Standard Methods for the Examination of Water and Wastewater (20) was used for the determination of dissolved oxygen. This modification was necessary in order to eliminate the possibility of interference caused by the presence of nitrites in the samples. It should be noted that nitrites may be expected to be present in sewage.

The ability of water to hold oxygen in solution is limited, and is reduced with higher water temperatures. Table I indicates the saturation values of oxygen in fresh water at various temperatures (21, p. 216). The dissolved oxygen content of a water is expressed either in mg/1 or in per cent of the saturation value at a specific temperature. It may be noted that dissolved oxygen values in excess of 100 per cent of saturation are possible and result from the action of algae and other aquatic plants (13) (22).

TABLE I

SOLUBILITY OF OXYGEN IN FRESH WATER (21)

Temperature		Dissolved Oxygen mg/l
°C.	°F.	
0	32.0	14.62
1	33.8	14.23
2	35.6	13.84
3	37.4	13.48
4	39.2	13.13
5	41.0	12.80
6	42.8	12.48
7	44.6	12.17
8	46.4	11.87
9	48.2	11.59
10	50.0	11.33
11	51.8	11.08
12	53.6	10.83
13	55.4	10.60
14	57.2	10.37
15	59.0	10.15
16	60.8	9.95
17	62.6	9.74
18	64.4	9.54
19	66.2	9.35
20	68.0	9.17
21	69.8	8.99
22	71.6	8.83
23	73.4	8.68
24	75.2	8.53
25	77.0	8.38
26	78.8	8.22
27	80.6	8.07
28	82.4	7.92
29	84.2	7.77
30	86.0	7.63

b. The Biochemical Oxygen Demand Determination.

The biochemical oxygen demand (BOD) test is the principal parameter used to determine the strength of a sewage or other organic wastes and has wide application in sanitary engineering practice.

Essentially the BOD determination consists of measuring the amount of dissolved oxygen utilized by the aerobic microorganisms in a 5 day period at 20° C. when stabilizing the organic matter present in sewage or other wastes.

According to Sawyer (19, p. 27) the temperature of 20° C. is a median value as far as natural bodies of water are concerned. Although, for all practical purposes, 20 days of incubation are required for the complete biological oxidation of the organic matter, a significant percentage of the BOD is exerted in 5 days. The 5 day incubation period is therefore employed to permit the completion of the test in a reasonable length of time and to eliminate problems caused by nitrification.

Nitrification is the oxidation of nitrogen in the form of ammonia (NH_3) to nitrites (NO_2^-) and nitrates (NO_3^-) by means of autotrophic nitrifying bacteria. These autotrophic microorganisms utilize noncarbonaceous matter and are present in domestic sewage together with the saprophytic bacteria that utilize the carbonaceous matter. Both bacterial types require oxygen when acting on the carbonaceous and noncarbonaceous matter but the autotrophic bacteria do not exert any appreciable demand on the dissolved oxygen supply until approximately 8 to 10 days have elapsed. Therefore, the 5 day BOD test is a measure of the amount of dissolved oxygen required for the reduction of the organic material present and is not subject to interference by the nitrifying bacteria (19, p. 274).

The procedure used for the determination of the biochemical oxygen demand is outlined in Standard Methods (20). It was found necessary to use dilutions of the samples tested. A dilution of 0.67 per cent was required for the sewage which was obtained from Fort Leonard Wood, Missouri and dilutions of 3.33 and 5.0 per cent were needed for the effluents from the Cold Room and Warm Room Lagoons, respectively.

Deionized distilled water was used to prepare the dilution water which in addition contained appropriate concentrations of ferric chloride, magnesium sulfate, ammonium chloride, and a phosphate buffer solution. The chemicals were added to provide the microorganisms with the necessary elements for growth and metabolism and buffering was needed to help maintain the pH at about 7. Sewage seed was not added and the dilution water was aerated prior to use to insure a concentration of dissolved oxygen of approximately 8 mg/l or near the saturation value (19, p. 276).

The biochemical oxygen demand was calculated as follows:

$$\text{mg/l BOD} = \frac{DO_1 - DO_2}{P}$$

Where:

DO_1 = The amount of dissolved oxygen in mg/l present in the initial sample.

DO_2 = The amount of dissolved oxygen in mg/l remaining in the final sample after 5 days incubation at 20° C.

P = The amount of the specific organic waste being tested, expressed as a decimal fraction.

c. The pH Determination.

The pH is defined as the logarithm of the reciprocal of the hydrogen ion concentration in a solution and is a measure of its acidity or alkalinity (19, p. 205). Although bacterial life can survive at pH values as low as 4.0 and as high as 11.0 (3, p. 135), the optimum pH for the growth of most bacteria is between 6.5 and 7.5 (23, p. 60).

The pH of the liquid in a waste stabilization lagoon may be used as an indication of the algal activity. Sawyer (19, p. 226) reported that pH values as high as 10 had been observed in areas where algae were growing rapidly and particularly in shallow waters. He explained that since algae use carbon dioxide in their photosynthetic activity, the removal of carbon dioxide must be responsible for the development of high pH conditions. The removal of free carbon dioxide will result in a pH approximately 8.3. Higher pH values will develop when additional carbon dioxide is extracted from the bicarbonates present in the water.

The pH values were determined using a Beckman Zeromatic pH meter, manufactured by the Beckman Instrument Company, Inc., Fullerton, California.

d. The Suspended Solids Determination.

The suspended solids determination is one of the major parameters used to evaluate the strength of raw sewage and to determine the efficiency of a treatment plant (19, p. 306). The suspended solids that are present in the effluent of a waste treatment plant will settle in the receiving stream and will decompose causing offensive odors. Therefore, the measurement of the suspended solids is as significant as BOD determinations. This is true not only for the mechanical treatment processes but also for waste stabilization lagoons (12, p. 342).

It has been reported (24) that the effluent of a properly functioning waste stabilization lagoon will contain suspended organic matter in the form of algal cells. These algae however are not detrimental and will assist in the reduction of organic matter by means of their symbiotic activity with aerobic bacteria (24) (25, p. 464).

Total and volatile suspended solids were determined in this study using the procedures outlined in Standard Methods (20) which were briefly as follows: A portion of the sample was filtered through the asbestos mat of a preweighed Gooch crucible and the Gooch crucible was dried at 103° C. for at least one hour. It was then cooled in a dessicator and weighed. The gain in weight was used to compute the total suspended solids which were expressed in mg/l. To determine the volatile suspended solids the Gooch crucible previously used was ignited in the muffle furnace at 600° C. for 15 minutes. The loss following ignition constituted the volatile suspended solids which were again expressed in mg/l.

e. The Coliform Bacteria Determination.

The coliform bacteria are found in the intestinal tract of humans and warm blooded animals and are used to detect fecal contamination of waters and indicate possible presence of pathogenic organisms (26, p. 287). The coliform population is expressed as the number of coliform organisms per 100 ml of water sample (20, p. 513).

The Membrane Filter (MF) procedure (20, p. 508) was employed in the determination of coliform bacteria. It is a relatively new technique and was developed during World War II (27). Briefly, the procedure consisted of passing a certain volume of sample through a membrane filter which removed and retained all bacteria present. The filter was then placed in a petri dish on a pad saturated with a differential media and was incubated for a period of 20 hours at 35° C. The distinctive coliform colonies that resulted were counted and the results obtained were expressed as the number of coliform bacteria per 100 milliliters using the following formula:

$$\text{coliform organisms/100 ml} = \frac{\text{coliform colonies counted x 100}}{\text{ml sample filtered}}$$

2. Daily Experimental Procedure.

The two experimental lagoons were operated in a fill and draw manner throughout the study and were exposed to constant illumination. The same intensity of light was applied to both the Cold Room and Warm Room Lagoons.

The daily experimental procedure that was employed in this study was as follows:

a. An appropriate volume of effluent was siphoned from each experimental lagoon and depended on the loading to be applied and the evaporation that had occurred in the previous 24 hours. It should be noted that the siphon was located at one of the corners of the aquariums and had its inlet 2 inches below the liquid surface.

b. The quantity of sewage necessary to give the desired loading was added to each experimental lagoon. This addition resulted in a certain amount of mixing and helped improve the operation by preventing stratification and development of localized anaerobic conditions (15). The sewage was taken from the 5 gallon storage cans after they were shaken to provide mixing.

c. A portion of the effluent from the experimental lagoons was used for the various determinations performed and the remaining effluent was wasted. Dissolved oxygen determinations were made on a regular basis throughout the investigation. In addition during the latter part of the study BOD, pH, suspended solids, and coliform bacteria determinations were undertaken.

d. Occasionally a heavy concentration of algae was observed in the Warm Room Lagoon and they were removed by skimming. Algae mats did not occur in the Cold Room Lagoon. The effluent from the Warm Room Lagoon was relatively clear but the Cold Room Lagoon effluent had an intense green color.

3. Acclimatization of Experimental Lagoons.

This study was initiated on May 31, 1961, when an experimental lagoon was seeded with 12 gallons of effluent from a waste stabilization lagoon located at Sullivan, Missouri. The experimental lagoon was placed on the roof of the Civil Engineering building to facilitate additional seeding with algae floating in the atmosphere. The lagoon was fed daily with one gallon of raw sewage collected at the treatment plant in Saint James, Missouri, until the capacity of the container was reached. At that time the contents were divided equally in three 15 gallon aquariums. One of these aquariums was placed in the cold room and became the Cold Room Lagoon, while the other was installed in the warm room and was designated as the Warm Room Lagoon. The third lagoon was retained on the roof of the building and served as a reservoir for algae. The operation of this lagoon was discontinued in November, 1961, because of freezing temperatures and since it had served its purpose.

During the early period of the study, sewage continued to be collected at Saint James. In addition, a source of sewage closer to the laboratory was investigated but it was quickly abandoned after it was found that the samples were highly diluted with an effluent from a commercial laundry and contained high concentrations of soaps and synthetic detergents.

Upon further investigation, it was decided to use sewage from the Fort Leonard Wood treatment plant. A 24 hour composite sample was obtained weekly in 5 gallon Army water cans and was stored in the cold room. This sewage was used to feed the experimental lagoons throughout the week.

C. EXPERIMENTAL LOADINGS

In the early phase of the investigation it was necessary to establish the appropriate volume loadings for the Cold Room and Warm Room Lagoons. It was therefore desired to determine the maximum quantity of sewage that could be added to the lagoons without causing a complete depletion of the dissolved oxygen and the development of anaerobic conditions.

A volume loading of 0.46 gallons of sewage per square foot of lagoon surface area was computed using values specified by the Missouri Water Pollution Control Board (14). This Board recommends that the design of waste stabilization lagoons be based on 200 persons per acre and 100 gallons of sewage per day per person. On this basis the volume loading may be calculated as follows:

$$\frac{200 \text{ persons/acre} \times 100 \text{ gallons/person}}{43560 \text{ sq ft/acre}} = 0.46 \text{ gallon/sq ft}$$

It should be noted that for the major part of the study the sewage was obtained at Fort Leonard Wood. However, during the early phase of the investigation sewage was obtained from either Rolla or Saint James.

1. Cold Room Lagoon.

The initial volume loading applied to the Cold Room Lagoon was approximately one gallon and was determined on the basis of the 1.96 square foot surface area of the unit and a loading of 0.46 gallons per square foot. However, as the study progressed other quantities of sewage were added to the lagoon in an effort to establish an appropriate loading. The entire length of the investigation has been divided into 9 periods as follows:

a. June 3 to July 19, 1961.

During this period one gallon of raw sewage was generally added to the Cold Room Lagoon. The sewage was initially collected from Rolla or Saint James. However, the use of Fort Leonard Wood sewage was initiated on June 21 and continued for the remainder of the study. A wide fluctuation in the dissolved oxygen content was observed and extended from 14.4 mg/1 to zero.

b. July 20 July 25, 1961.

A reduced loading of 13 fluid ounces was applied during this period in an effort to improve the lagoon operation and the dissolved oxygen content remained above 1 mg/1.

c. July 26 to July 30, 1961.

The loading was increased to 26 ounces in order to determine whether the algal activity and the corresponding release of dissolved oxygen were limited because of a lack of carbon dioxide. It was expected that the higher quantities of sewage added would stimulate increased bacterial activity and result in higher carbon dioxide production. The dissolved oxygen content determined during this period was low, ranging from 0.5 0.1 mg/1. Nevertheless, the lagoon remained aerobic.

d. July 31 to August 4, 1961.

The loading was further increased to 30 ounces during this 5 day period and resulted in a complete depletion of the dissolved oxygen. The lagoon became anaerobic and remained in this condition for the duration of this period of the study.

e. August 5 to August 11, 1961.

In an effort to overcome the anaerobic conditions the loading was reduced to 1/2 gallon of raw sewage. However, the situation did not improve, the dissolved oxygen remained at zero and the lagoon had an offensive odor which was attributed to anaerobic action.

f. August 12 to August 25, 1961.

The addition of sewage to the Cold Room Lagoon during this 13 day period was discontinued with the exception that on August 16, 32 ounces of seed from the lagoon on the roof of the Civil Engineering building were added. Aerobic conditions were reestablished and the dissolved oxygen was increased to about 5 mg/1.

g. August 26 to September 6, 1961.

The loading of the lagoon was resumed and 32 ounces of sewage were added daily. It should be noted that the dissolved oxygen content showed an upward trend until a maximum of 8.9 mg/1 was measured on September 3, and then decreased rapidly to 1.8 mg/1 on September 7, 1961.

h. September 7, 1961 to February 2, 1962.

It was decided that for the remainder of the studies a loading of 16 fluid ounces be applied. During this period the lagoon remained aerobic but the dissolved oxygen content fluctuated widely and increased from 1.8 mg/l on September 7 to 12.8 mg/l on November 12. It may be noted that the 12.8 mg/l value is the saturation point for distilled water at 5° C. Although prior to that date dissolved oxygen determinations were made daily, starting with November 12, only periodic determinations were found necessary.

i. February 3 to March 4, 1962.

Beginning with February 3, 1962 daily BOD testing was undertaken. The sewage used during this phase of the investigation had an average BOD value of 490 mg/l and the 16 fluid ounces that were added daily applied a loading of 11.3 pounds of BOD per acre per day. This loading was approximately 1/3 of that recommended by the Missouri Water Pollution Control Board (14).

2. Warm Room Lagoon.

Various quantities of sewage were added to this experimental lagoon in order to determine the optimum loading. The lagoon was operated to provide a basis of comparison for the Cold Room Lagoon studies.

It should be pointed out that although the temperature in the Warm Room Lagoon was not controlled it remained in the range of 16 to 32° C. throughout the investigation.

This phase of the study has been divided into 7 periods as follows:

a. June 3 to July 2, 1961.

The loading applied during this period was usually one gallon of sewage and corresponded to the 0.46 gallons per square foot that is recommended by the Missouri Water Pollution Control Board. The dissolved oxygen varied considerably during this period and a maximum of 19.1 mg/l was observed on June 10. However, on June 27 the lagoon became anaerobic and remained so for the remainder of this period. It should be noted that on June 21 the use of Fort Leonard Wood sewage began and that this sewage was considerably stronger than the Saint James sewage that was previously used.

b. July 3 to July 10, 1961.

In spite of the anaerobic conditions present in the lagoons the volume loading was increased to 1 1/2 gallons during this period in an effort to stimulate carbon dioxide production and algal activity. This loading, however, did not improve the situation and the lagoon remained anaerobic.

c. July 11 to July 24, 1961.

The loading was reduced to one gallon of sewage daily during this period but the Warm Room Lagoon continued to remain anaerobic.

d. July 25 to August 11, 1961.

Sewage was not added to the lagoon during this period in an effort to restore proper aerobic operations. However, since the oxygen content remained at zero it was concluded that seeding was necessary.

e. August 12 to August 27, 1961.

During this period the Warm Room Lagoon was generally seeded with 1/2 gallon of effluent from the lagoon that was located on the roof of the Civil Engineering building and in addition it was loaded with 32 ounces of raw sewage daily. Aerobic conditions were reestablished and the dissolved oxygen content fluctuated from a low of 0.5 mg/l to a high of 10 mg/l.

f. August 28, 1961 to February 2, 1962.

On August 28 seeding was discontinued but the loading was maintained at 32 ounces daily. It should be noted that the dissolved oxygen determination was performed on a regular basis until September 7. From that date the dissolved oxygen content was only periodically checked. The Warm Room Lagoon functioned properly during this period and the minimum dissolved oxygen that was measured was 4.6 mg/l.

g. February 3 to March 4, 1962.

Biochemical oxygen demand determinations were made daily during this final period of study to facilitate the comparison of the operational data obtained from the two experimental lagoons. The volume loading continued at 32 ounces of sewage per day and the Fort Leonard Wood composite sewage samples that were used had an average BOD of 490 mg/l. The corresponding organic loading to the Warm Room Lagoon was 22.6 pounds of BOD per acre per day or twice the loading applied to the Cold Room Lagoon.

D. EXPERIMENTAL RESULTS

Two experimental waste stabilization lagoons were used in the study and were operated in a fill and draw manner. The Cold Room Lagoon was maintained at a temperature of 5^{o} C. throughout the investigation, but the temperature of the Warm Room Lagoon ranged between 16 and 32^{o} C. Both lagoons were subjected to continuous illumination in the range of 550 to 600 foot candles which was provided by fluorescent lamps placed 6 inches above the liquid surface.

Dissolved oxygen and BOD determinations were the major parameters employed. In addition suspended solids, pH and coliform bacteria determinations were used.

The results obtained are presented in three groups as follows: (a) The Preliminary Study, (b) The Cold Room Lagoon Study, and (c) The Warm Room Lagoon Study.

1. The Preliminary Study.

Various loadings were applied to the two experimental lagoons in the early phases of the investigation in an attempt to select the loadings giving optimum operational characteristics. These loadings were previously discussed in detail under "Experimental Loadings". This phase of the study extended for a period of 100 days from May 31 to September 6, 1961. The dissolved oxygen determination was the only experimental parameter used during this period and was employed to provide an indication of the operational condition of the units.

Seven different loadings were applied to the Cold Room Lagoon ranging from 13 ounces to one gallon of sewage. At the same time the Warm Room Lagoon received three different loadings ranging from 16 ounces to 2 gallons. The dissolved oxygen content of both lagoons varied widely and it was often at or very near zero. It should be noted that in one case feeding of the lagoons was discontinued in order to reestablish aerobic conditions and also that seeding with effluent from a well operating lagoon was required.

2. The Cold Room Lagoon Study.

The experimental lagoon located in the cold room was loaded daily with 16 ounces of Fort Leonard Wood sewage from September 7, 1961 until the study was terminated on March 4, 1962. Since the operating volume of the lagoon was 13.7 gallons the detention time under this loading was 110 days.

The liquid level of the lagoon was, for all practical purposes, constant during the entire study. The evaporation which took place in the Cold Room Lagoon was negligible and it was considered in the removal of effluent before the addition of sewage.

During the first 2 months of this study the dissolved oxygen content fluctuated and then leveled off at or near the saturation value of 12.8 mg/1. It should be noted that the dissolved oxygen determination was used as the major parameter in determining the proper functioning of the lagoon.

On February 3, 1962, daily BOD determinations were taken to determine the effectiveness of the lagoon in stabilizing the organic load applied to it. The BOD data is presented in Table II. It may be seen from this table that the raw sewage had an average BOD of 490 mg/1 and that the BOD ranged between 265 and 790 mg/1. The effluent from the Cold Room Lagoon varied between 34 and 143 mg/1 and had an average value of 98 mg/1. Therefore, the average BOD reduction obtained was 80.0 per cent.

The organic loading applied during this period was 11.3 pounds of BOD per acre per day and was calculated as follows:

$$0.000490 \frac{\text{lb}}{\text{lb}} \text{BOD} \times 16 \frac{\text{fl oz}}{\text{day}} \times \frac{1}{128} \frac{\text{gal}}{\text{fl oz}} \times 8.33 \frac{\text{lb}}{\text{gal}} \times \frac{1}{1.96 \text{ sq ft}} \times 43560 \frac{\text{sq ft}}{\text{acre}}$$

$$= 11.3 \text{ pounds BOD per acre per day}$$

Where: Average BOD of sewage: 490 mg/1 or 0.000490 lb/lb

Volume loading: 16 fl oz/day

Lagoon surface area: 1.96 sq ft

This loading was approximately one third of the 34 pounds of BOD per acre per day value which is recommended by the Missouri Water Pollution Control Board (14).

The pH was determined during this period to assure that optimum conditions for microbial growth were maintained. The data obtained is given in Table II. The pH of the lagoon effluent ranged from 8.1 to 9.2 and that of the raw sewage from 6.6 to 7.6.

The suspended solids data is presented in Table III. It may be seen from the results obtained that the effluent suspended solids ranged from 29 to 63 mg/1 and had an average value of 42 mg/1. The reduction in the suspended solids content which was effected by the Cold Room Lagoon at a detention period of 110 days was equal to 88.8 per cent. It should be noted that some information was also obtained on the volatile solids. From the limited data available it was indicated that the volatile suspended solids in both the raw sewage and the Cold Room Lagoon effluent were approximately 90 per cent of the total.

The coliform bacteria were measured using the Membrane Filter technique. The results obtained indicated a concentration of 20,000,000 coliform bacteria per 100 ml in the raw sewage and a corresponding number of 15,000 coliforms per 100 ml in the Cold Room Lagoon effluent. The reduction effected was approximately 99.9 per cent.

3. The Warm Room Lagoon Study.

Thirty two ounces of raw sewage were added daily to the Warm Room Lagoon during the main portion of the studies which extended for a period of 6 months from September 7, 1961, to March 4, 1962. This loading was twice as much as that applied to the Cold Room Lagoon and resulted in a detention time of 55 days.

The liquid level in this unit varied considerably because of the evaporation which took place. However, this volume reduction was taken into consideration and the amount of effluent removed daily was adjusted accordingly.

During the early portion of this study the dissolved oxygen determination was used as a control parameter to assure proper aerobic operation of the lagoon. The dissolved oxygen content ranged from a minimum of 4.6 mg/1 to a maximum of 8.6 mg/1 or the saturation value at the temperature in the lagoon.

BOD determinations were made daily during the 28 day period from February 3 to March 4, 1962, in order to determine the reduction in organic matter. The results obtained are presented in Table II. While the BOD of the raw sewage used averaged 490 mg/1 and ranged from 265 to 790 mg/1 the Warm Room Lagoon effluent BOD varied between 12 and 100 mg/1 and had an average value of 31 mg/1. The average reduction obtained under these conditions was 94.0 per cent and the BOD loading applied was 22.6 pounds BOD per acre per day.

The pH fluctuated from 7.9 to 9.5 throughout this period and compared closely with the pH values determined in the Cold Room Lagoon. The pH data is shown in Table II.

Additional tests were undertaken to determine the efficiency of the Warm Room Lagoon in removing suspended solids. The results obtained are presented in Table III. It may be seen from this table that an average removal of 92.3 per cent was observed and was approximately 5 per cent higher than that obtained in the Cold Room Lagoon. The Warm Room Lagoon

TABLE II

BIOCHEMICAL OXYGEN DEMAND AND pH DATA

Date	Raw Sewage		Cold Room Lagoon			Warm Room Lagoon		
	BOD mg/1	pH	Effluent BOD mg/1	Per cent BOD Reduction	pH	Effluent BOD mg/1	Per cent BOD Reduction	pH
Feb 3, 62	---	---	100	80.0*	9.1	40	92.0*	9.2
Feb 4, 62	---	---	100	80.0*	9.0	---	---	9.1
Feb 7, 62	---	---	115	76.5*	8.8	100	80.0*	9.5
Feb 8, 62	---	---	92	81.0*	---	---	---	9.1
Feb 9, 62	660	7.5	101	85.0	8.7	24	96.0	8.8
Feb 10, 62	645	7.5	98	85.0	8.7	27	96.0	8.6
Feb 11, 62	760	7.3	122	84.0	9.1	78	90.0	8.9
Feb 12, 62	720	7.1	131	84.0	9.1	38	96.0	9.2
Feb 13, 62	763	6.8	143	84.0	8.7	27	98.0	9.0
Feb 14, 62	---	6.6	---	---	8.7	---	---	8.7
Feb 15, 62	790	6.8	109	86.0	8.7	15	98.0	8.7
Feb 16, 62	390	7.5	88	77.5	9.2	12	---	9.2
Feb 17, 62	306	6.7	82	70.0	8.5	13	96.0	8.3
Feb 18, 62	440	7.0	34	88.0	8.7	54	84.0	8.4
Feb 19, 62	375	6.8	107	72.0	8.4	19	95.0	8.4

*This per cent value computed on the basis of the average raw sewage BOD of 490 mg/1.

TABLE II (Continued)

BIOCHEMICAL OXYGEN DEMAND AND pH DATA

Date	Raw Sewage		Cold Room Lagoon			Warm Room Lagoon		
	BOD mg/l	pH	Effluent BOD mg/l	Per cent BOD Reduction	pH	Effluent BOD mg/l	Per cent BOD Reduction	pH
Feb 20, 62	306	6.7	108	65.0	8.1	16	95.0	8.3
Feb 21, 62	300	7.0	71	76.0	8.5	30	90.0	8.2
Feb 22, 62	382	7.0	80	79.0	9.1	10	97.0	8.5
Feb 23, 62	640	7.0	100	85.0	8.8	33	95.0	8.1
Feb 24, 62	375	7.5	102	73.0	8.4	39	90.0	7.9
Feb 25, 62	386	7.6	102	74.0	8.7	26	93.0	8.3
Feb 26, 62	265	7.3	100	63.0	8.9	16	94.0	8.3
Feb 27, 62	360	7.4	96	74.0	8.7	19	92.0	8.5
Feb 28, 62	315	7.1	70	78.0	8.6	31	91.0	8.4
Mar 1, 62	450	7.1	88	81.0	8.5	50	89.0	8.7
Mar 2, 62	300	7.6	107	65.0	8.5	18	94.0	9.0
Mar 3, 62	700	7.6	112	84.0	8.5	25	97.0	9.0
Mar 4, 62	620	7.4	88	86.0	8.7	14	99.0	9.4
Average	490	---	98	80.0	---	31	94.0	---

TABLE III

SUSPENDED SOLIDS DATA

a. Total Suspended Solids

Date	Raw Sewage	Cold Room Lagoon Effluent		Warm Room Lagoon Effluent	
	mg/1	mg/1	% Removed	mg/1	% Removed
Feb 24, 62	394	43	89.0	22	94.5
Feb 25, 62	430	40	91.0	68	84.5
Feb 26, 62	310	33	89.5	5	98.5
Feb 27, 62	370	52	86.0	49	87.0
Feb 28, 62	320	50	84.5	19	94.0
Mar 1, 62	378	63	83.5	11	97.0
Mar 2, 62	400	29	92.7	52	87.0
Mar 3, 62	360	32	91.0	22	94.0
Mar 4, 62	406	33	92.0	12	97.0
Average	373	42	88.8	29	92.3

b. Volatile Suspended Solids

Date	Raw Sewage			Cold Room Lagoon Effluent			Warm Room Lagoon Effluent		
	Total	Volatile		Total	Volatile		Total	Volatile	
	mg/1	mg/1	% of total	mg/1	mg/1	% of total	mg/1	mg/1	% of total
Mar 3, 62	360	320	89.0	32	29	90.7	22	19	86.5
Mar 4, 62	406	366	90.0	33	30	91.0	12	10	83.5
Average	---	---	89.5	--	--	90.8	--	--	85.0

effluent had a suspended solids concentration ranging between 5 and 68 mg/l with an average of 29 mg/l. The volatile matter in these suspended solids was less than that found in both the raw sewage and Cold Room Lagoon effluent and averaged 85.0 per cent.

The coliform bacteria determination indicated that the coliforms were reduced nearly 100 per cent in the Warm Room Lagoon. Thus, while the raw sewage contained approximately 20,000,000 coliform organisms per 100 ml the effluent had a coliform bacteria concentration of 4,000 per 100 ml.

E. DISCUSSION OF EXPERIMENTAL RESULTS

It may be seen from the results obtained that the Cold Room Lagoon was effective in reducing the organic matter in the sewage but not as effective as the Warm Room Lagoon.

The two experimental lagoons that were used in this study successfully simulated the operation of waste stabilization lagoons under different environmental conditions. The units were operated in a fill and draw manner, but this did not cause any noticeable operational difficulty. Svore (2) has also found that "slugging" of a lagoon at different intervals during the day did not hinder its operation.

The experimental units had an operating depth of 11 1/4 inches which was considerably smaller than the recommended range of 2 1/2 to 5 feet. This lesser depth permitted better light penetration and assured the availability of light at all depths. It should be noted that light penetration depends on light intensity and it has been reported that during the winter months the light intensity is sufficient to penetrate to a depth of only 4 inches (28). Also (16) the light intensity of 400 foot candles is the upper limit which can be effectively utilized by the algae, although on most days approximately 800 foot candles may be available. The two units were illuminated by means of three 40 watt fluorescent tubes which provided an intensity of 550 to 600 foot candles at the surface of each experimental lagoon. Therefore, the artificial illumination was more than enough. It must be pointed out that the experimental lagoons were subjected to a continuous illumination which is contrary to actual lagoon practice.

These experimental factors were selected to provide optimum conditions for the operation of the lagoons and enable the determination of the upper limit of effectiveness.

The loadings that were applied to the Cold Room and Warm Room Lagoons were 11.3 and 22.6 pounds of BOD per acre per day, respectively. Lagoons in the Dakotas and Alaska are loaded on a basis of 15 to 20 pounds of BOD per acre per day (4) (18) and those in Missouri on the basis of 34 pounds (14). Temperature has a decisive effect on the permissible loadings, and when the prevailing temperature in an area is low, moderate loadings are recommended. Although both the experimental lagoons could have been loaded heavier, these loadings were selected to enable a near optimum operation.

The detention periods that were provided in the units were 110 and 55 days for the Cold Room and Warm Room Lagoons, respectively. No information was found in the literature on recommended detention periods. However, on the basis of the operational data reported (14) (18) for waste stabilization lagoon in the Dakotas and Alaska it was estimated that sewage detention in those units varied between 49 and 81 days and depended on the season of the year. It may be seen that the detention time available in the Warm Room Lagoon compared favorably with those recommended, but that the Cold Room Lagoon operated at a considerably longer detention.

The daily addition of sewage to the lagoons caused mixing of the liquid in the lagoon and simulated the mixing that may be expected in a waste stabilization lagoon because of wind action and other factors.

Fort Leonard Wood sewage was used in the major portion of this study. This sewage had an average BOD and suspended solids concentration of 490 and 373 mg/1, respectively, and a pH in the range of 6.6 to 7.6. On the basis of these characteristics the sewage may be classified as strong (12, p. 341). It should be noted that the relatively high BOD of this sewage can be attributed to the nature of the area from which it was collected and to a limited infiltration of ground water.

The main experimental parameters used in this study were the dissolved oxygen and BOD determinations and provided valuable information on the operation and efficiency of the units. The dissolved oxygen determination was used to ascertain whether aerobic or anaerobic action was taking place, and the BOD determination was employed as a means for the investigation of the reduction of the organic matter in the daily sewage feed. In addition the pH, suspended solids, and coliform bacteria determinations were used to help further evaluate the operation of the units.

Dissolved oxygen determinations in both experimental lagoons during the study indicated that there was sufficient dissolved oxygen in each unit. In fact the dissolved oxygen content of both experimental lagoons was very near the saturation values at the respective temperatures at which the units operated. It should be mentioned that during the preliminary studies it was established that the presence of as little as 0.1 mg/1 of dissolved oxygen was sufficient to prevent the development of odors.

The operational characteristics of both experimental lagoons are summarized in Table IV. It may be seen from this table that a reduction of 80.0 per cent resulted in the Cold Room Lagoon when the loading of 11.3 pounds of BOD per acre per day was applied. Although this reduction was a little below the reported usual efficiencies of well designed waste stabilization lagoons and other secondary treatment plants, it nonetheless indicated that even at the low temperature of 5^{o} C. the waste stabilization lagoon can be an effective method of sewage treatment. This was further substantiated by the suspended solids data which showed that a removal of 88.8 per cent was obtained. It should be noted that the fill and draw method of operation which allowed a 24 hour quiescent settling helped realize this per cent solids removal.

As it was expected, the Warm Room Lagoon was more effective even though it was loaded with twice the BOD loading. This lagoon had a reduction of 94.0 per cent in BOD which compared very favorably with other biological methods of waste treatment. In addition the suspended solids removal was over 92.0 per cent and very close to the efficiencies expected of mechanical treatment plants.

TABLE IV

A COMPARISON OF THE COLD ROOM AND WARM ROOM LAGOONS*

Characteristic	Cold Room Lagoon	Warm Room Lagoon
Temperature, °C.	5	16-32
Light Intensity, foot candles	550-600	550-600
Raw Sewage Volume Loading, ounces per day	16	32
BOD Loading, pounds BOD per acre per day	11.3	22.6
Loading, persons per acre	67	134
Detention Period, days	110	55
Raw Sewage 5-day BOD, mg/1	490	490
Effluent 5-day BOD, mg/1	98	31
BOD Removal, per cent	80.0	94.0
Raw Sewage Suspended Solids, mg/1	373	373
Effluent Suspended Solids, mg/1	42	29
Suspended Solids Removal, per cent	88.8	92.3
pH range	8.1-9.2	7.9-9.5
Coliform Bacteria in Raw Sewage, coliforms per 100 ml	20,000,000	20,000,000
Coliform Bacteria in Effluent, coliforms per 100 ml	15,000	4,000
Coliform Bacteria Removal, per cent	99.9+	100

*Period: February 3 to March 4, 1962

pH determinations were made to assure that the experimental lagoons operated under conditions conducive to algal and bacteria growth. The ranges of pH in both the Cold Room and Warm Room Lagoons were approximately the same and were higher than that of the raw sewage. Thus the pH ranges of 8.1 to 9.2 and 7.9 to 9.5 were observed in the Cold Room and Warm Room Lagoon, respectively, and the pH of the raw sewage varied between 6.6 and 7.6. The pH values in the experimental lagoons indicated that the algae effectively utilized the carbon dioxide released from bacterial action and in addition used part of the bicarbonate alkalinity present (19, p. 226). This was further proof that in both experimental lagoons aerobic conditions were maintained and substantiated the report found in the literature (28) that pH determinations may be used instead of dissolved oxygen determinations for routine analysis.

The coliform bacteria test was useful in establishing the fate of the pathogenic organisms in the experimental units. While a concentration of 20,000,000 coliforms per 100 ml was determined in the raw sewage the Cold Room and Warm Room Lagoon effluents had only an average concentration of 15,000 and 4,000 coliforms per 100 ml. Although both lagoons effected practically a 100 per cent reduction in coliforms, it should be noted that the Warm Room Lagoon was more effective even though it was operating at half the detention period available in the Cold Room Lagoon. This indicated that the increased temperatures in the Warm Room Lagoon provided an environment more favorable for the aerobic bacteria while the reduced temperature of the Cold Room Lagoon helped preserve the coliforms.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

On the basis of the results of this study the following conclusions may be drawn:

1. Domestic sewage was effectively treated in a waste stabilization lagoon operating at a continuous low temperature.

2. The Cold Room Lagoon effected a BOD reduction of approximately 80 per cent when a loading of 11.3 pounds of BOD per acre per day was applied and a detention period of 110 days was provided. This unit was exposed to a continuous illumination of 550 to 600 foot candles and was maintained at a temperature of 5^{o} C.

3. The Warm Room Lagoon was considerably more efficient and resulted in a 94.0 per cent BOD reduction when loaded with 22.6 pounds of BOD per acre per day. This lagoon operated at the temperature range of 16 to 32^{o} C. and a detention period of 55 days and it was subjected continuously to an illumination of 550 to 600 foot candles.

4. Following the acclimatization period aerobic conditions were maintained in both lagoons with a dissolved oxygen content at or near the saturation value.

5. The suspended solids were effectively removed in both experimental units. The Warm Room Lagoon was more efficient and resulted in a 92.3 per cent reduction while the Cold Room Lagoon effected an 88.8 per cent removal.

6. The pH was maintained within the range of 7.9 to 9.5 in both experimental units throughout the study and was conducive to active bacterial and algal growth.

7. The coliform bacteria were effectively destroyed in both lagoons and a reduction of nearly 100 per cent was obtained.

B. RECOMMENDATIONS

On basis of the findings of this study the following recommendations may be made:

1. Waste stabilization lagoons can successfully function in areas where near freezing temperatures prevail and may be loaded up to 11.5 pounds of BOD per acre per day.

2. The effect of varying loadings was not completely investigated in this study and it is recommended that further investigation be undertaken to establish the maximum limit for effective operation.

3. Future studies should also be conducted to ascertain the effect of subjecting the lagoon to diurnal cycles of light and darkness. In addition the fate of coliform bacteria under low temperatures may also be investigated.

4. Lagoons can sucessfully operate under varying environmental conditions and are recommended for use in small communities, rural schools, resorts, motels, lodges, and other similar establishments. They are especially applicable to military installations because they can effectively operate under concentrated loadings applied during periods of the day.

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In June 1957, he began work at the Missouri School of Mines and Metallurgy and received a Bachelor of Science Degree in Civil Engineering in June 1959. Since that time the author has been continuously assigned to the R.O.T.C. Department of the Missouri School of Mines and at the same time, he has been enrolled for graduate study in the Civil Engineering Department.

In February 1952, the author was united in marriage with Miss Pearl Kelly of Republic, Pennsylvania. To this union three children were born.