Environmental Factors in Design and Operation of Waste Water Sludge Drying Beds

Principal Investigator: J. Charles Jennett
Student Assistant: Daniel J. Harris

MISSOURI WATER RESOURCES RESEARCH CENTER

University of Missouri-Rolla

Project No.: A-042-MO

Agreement No.: 14-31-0001-3225

Date: July 1, 1970 to June 30, 1971

COMPLETION REPORT

October 1971

The work on which this publication is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Act of 1964.

ABSTRACT

The dewatering characteristics of anaerobically digested primary and activated sludge were investigated under eight selected combinations of laboratory controlled air temperature and relative humidity using three open, drained model beds, as well as a closed, drained and an open, nondrained bed. The evaporation rate from a free water surface was also determined. Moisture content, drainage, evaporative weight loss, and sludge surface recession were measured and recorded periodically throughout the two week period of each of the eight experiments.

Relationships were shown to exist between sludge moisture content, evaporation rate from a free water surface, and the parameters ΔT (the difference between dry and wet bulb temperature) and ΔH (the difference between saturation and absolute humidity). It was found that moisture gradients developed within the dewatering sludge which generally increased with time and ΔT. An inverse relationship was noted between drainage and evaporation which was influenced by dry bulb temperature because of its effect upon water viscosity.

Keywords: sludge drying*, sludge*, sewage treatment*, sand filtration,
sludge waste disposal

ACKNOWLEDGEMENTS

The investigation on which this publication is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Act of 1964.

Table of Contents (continued) Page

APPENDICES

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

Government regulatory agencies at both the state and federal level, supported by a concerned public, are demanding that municipal and industrial waste treatment plants effect a higher degree of wastewater treatment and discharge to the receiving waters a better quality effluent. As treatment facilities expand and effluent qualities improve, the production of wastewater sludge will increase. McCarty (1) estimated the volume of sludge produced in 1970 from the secondary treatment of domestic wastewater alone at 120 mgd (455,000 cu m/day). Coupled with the need for more adequate treatment is an expanding population; together these two factors will produce even larger quantities of wastewater sludge.

The problems resulting from the need for sanitary, efficient, and economical disposal of wastewater sludge are increasing at an alarming rate and are compounded by the volumes produced. Sludge handling and disposal costs are high, representing 25 to 65 percent of primary and secondary plant capital and operating costs (2). Suitable land disposal sites are becoming more expensive and less accessible. Incineration with its heavy capital investment and operating costs, increased by the necessity of installing expensive air pollution control devices, has become prohibitive in some areas (3). Contributing to the dimensions of the problem is a growing realization on the part of a few individuals and concerned officials that ways and means must be found to utilize the sludge rather than destroy it (4).

In order to reduce the sludge volume, handling and transportation costs, sludge drying beds are still the most commonly used means for dewatering (5). Because of the large number of variables involved, these beds are often designed on a "rule-of-thumb" basis. Manual of Practice No. 20 of the Water Pollution Control Federation recommends an area of 1.75 to 2.5 sq ft/cap (0.16 to 0.23 sq m/cap) for digested primary and activated sludge on open beds (5, p.41). With the enormous quantities of sludge being produced, the large sums being spent on its handling and disposal, and the popularity of drying beds, it is desirable that a rational basis of design be developed for these beds.

The variables which affect the drying rates of sludge on open beds include the following: (a) climatic and atmospheric variations, (b) depth of application, (c) presence or absence of coagulants, (d) moisture content, (e) source and type of sludge, (f) extent of digestion, (g) age of sludge, (h) bed construction, and (i) grain size and depth of filter media. For a particular sludge applied to a bed at a given depth, drainage and climatic and atmospheric variations are major factors affecting drying rates.

A laboratory investigation of sludge drying under controlled conditions of air temperature, humidity, and wind velocity has been reported (6) on sludge which was not drained. As drainage is a factor of major importance influencing dewatering rates, more information is needed on the dewatering rates of drained, digested sludges under conditions where the operational variables of air temperature and relative humidity are controlled.

It was the purpose of this thesis to report the results of an investigation into the effects air temperature and relative humidity produce on the dewatering rate of anaerobically digested activated sludge, and to develop a mathematical model or set of curves which would be of use to both the treatment plant designer and operator. The designer, knowing the typical characteristics of a sludge and the average meteorological data of a region, would have a rational method for determining the required sludge drying bed area. The plant operator would be able to predict the drying time to reach a specific moisture content, as well as the number of sludge applications and removals per year. An additional objective of this investigation was the further understanding of the dewatering mechanisms of a drained sludge as affected by air temperature and relative humidity.

Model sludge drying beds were placed in environmental chambers under controlled air temperatures and relative humidities. The investigation consisted of eight experiments which were performed at three humidity levels and three air temperatures. Moisture content, drainage, evaporative weight loss, and sludge surface recession were measured and recorded periodically throughout the course of each run.

II. LITERATURE REVIEW

The objective of this literature review was the study of previous investigations pertaining to the dewatering of digested wastewater sludges on open drying beds. Particular attention was devoted to those investigations which studied drying rates as a function of air temperature and humidity.

Unless otherwise stated, the terms sludge and digested sludge refer to anaerobically digested sludge.

Haseltine (7), working with data from five activated sludge and trickling filter plants, developed empirical formulas which delimited the effects of sludge solids content on dewatering rates. The data included percent total solids of sludge as applied, dosing depth, number of days during which the sludge remained on the beds, and percent total solids of the sludge as removed from the beds. Haseltine developed a quantity which he termed "gross bed loading" and defined it as follows:

$$GBL = \frac{SD \times DD \times X \times 30}{DB}$$

Where: GBL = "gross bed loading," lb/30 days/sq ft

SD* = sludge density, lb/cu ft

DD = dosing depth, ft

X = total solids in applied sludge, percent

DB = number of days sludge is on bed

---

*Due to lack of data Haseltine used the density of water 62.5 lb/cu ft (1012.5 kg/cu m) in his formula instead of sludge density. It is assumed that the difference is slight.

An additional performance parameter used by Haseltine was the quantity "net bed loading" which he defined as the "gross bed loading" multiplied by the percent total solids in the dewatered sludge as removed from the bed. Using the above mentioned data, which was taken over a period of several years, Haseltine plotted "gross" and "net bed loading" versus percent total solids of the applied sludge. By fitting these data points with a straight line he developed two theoretical formulas for "gross" and "net bed loading" which were as follows:

$$GBL = 0.96X - 1.75$$

$$NBL = 0.35X - 0.5$$

Where: GBL = "gross bed loading," lb/30 days/sq ft

NBL = "net bed loading," lb/30 days/sq ft

X = total solids in applied sludge, percent

Haseltine was able to quantitatively determine the effects of other parameters upon drying rates by comparing the actual "gross" and "net bed loadings" to the theoretical values on a percentage basis. The formulas were used to determine optimum dosing depths at two different plants on both open and covered beds. Optimum depths were found to be 8-in. (20.3-cm) and 14-in. (35.5-cm), respectively. In addition the formulas were used to calculate the effects of seasonal variations upon bed performance as well as the effects of coagulants. However, after some field experimentation, Haseltine concluded that the theoretical formulas could not be used with old thoroughly digested sludges or with sludges containing excessive amounts of grit; he also concluded that, "next to temperature the solids content of sludge applied to the beds is the most important factor influencing bed performance." (7, p.1082)

Haseltine suggested that his theoretical formulas could be utilized to maximize the performance of any bed; however, it appears that the data points he plotted and fitted with a straight line to obtain the theoretical formulas, might just as easily have been fitted with a polynomial of some degree. For maximum bed performance at a particular plant one would probably want to develop one's own theoretical formulas from plant records. It is quite possible that a line of "best fit" would not necessarily give a linear relationship between bed loadings and percent total solids at all plants.

Haseltine found that a 14-in. (35.5-cm) dosing depth optimized bed loadings of a covered bed and that a 9-in. (22.8-cm) depth produced best results on an open bed. The greater depth of applied sludge on the covered bed was felt by Haseltine to be due, primarily, to the low solids content of the sludge at that particular plant. The optimum depths of the open and covered beds were found using sludges with solids contents of 9.14 and 3.5 percent, respectively.

Downes (8), in an early paper, illustrated the importance of dosing depth and percent solids of applied sludge in influencing drying time; Table I summarizes the results of his observations. Unfortunately Downes did not indicate to what moisture content the sludges were dried. It must be assumed that all applications were dried to the same moisture content.

Quon and Johnson (9) investigated the drainage characteristics of trickling filter sludge on drying beds under field and laboratory conditions. Basic parameters used for evaluation were drainage rate, ultimate drainage volume, and depth of sludge with time. Evaporation as well as heat transfer by radiation and convection were minimized.

TABLE I

DAYS REQUIRED TO DRY DIFFERENT DEPTHS OF SLUDGE OF VARYING SOLID CONTENTS*

Percent Solids	Dosing Depth, in.		
	8	9	10
	Drying Time, days		
4	5.5	6.0	6.0
5	6.5	8.5	10.0
6	9.0	12.0	13.0
7	12.0	14.0	16.0
8	14.0	18.0	23.0

*After Downes (8).

No attempt was made to control ambient temperature or humidity. The controlled variables included: (a) dosing depth, (b) cross-sectional area of beds to determine scale effects, (c) partial covering of sand beds to simulate paving, (d) depth of sand bed, and (e) ventilation of beds.

Using dosing depths of 4-, 8-, and 12-in. (10.2-, 20.3-, and 30.5-cm) it was found that 8 in. (20.3 cm) produced the greatest amount of drainage as a percentage of applied volume. Drainage rates and ultimate drainage volumes were not affected by model scale as long as the cross-sectional areas were greater than 0.09 sq ft (83 sq cm).

Part of Quon and Johnson's investigation was concerned with the characteristics of sludge drying on partially paved beds. The paving was simulated by blocking the drainage area with various geometric shapes of tin placed on the sand surface. Areas blocked represented 25, 50, and 75 percent of the gross cross-sectional drainage area. It was observed that coverage of 50 percent of the central portion of the drainage area did not appreciably affect drainage rate or the ultimate drainage volume. However, when blocking the perimeter of the same bed with a doughnut shaped cover, drainage rate and volume were reduced substantially; the investigators attributed this difference in drainage to variations in the ventilation of the beds produced by the two geometric shapes. The reason why ventilation varied as a result of different geometric shapes of the covers is not, however, clear to the author of this thesis.

Quon and Johnson noted two different drainage patterns based on the level of bed ventilation. Well ventilated drying beds exhibited maximum drainage rate on the first day with the rate decreasing monotonically with time thereafter. Poorly ventilated beds drained slowly on the first day with the rate gradually increasing and reaching a maximum on approximately the third day. The investigators attributed the latter drainage pattern to entrapped air in the bed which was not completely free to move and which decreased the porosity of the bed until absorbed by the liquid passing through. Ventilation of the sludge drying beds permitted air to be expelled as drainage proceeded. In this particular investigation, ventilation was accomplished by placing four ½-in. (1.27-cm) L-shaped glass tubes, which were open to the atmosphere, beneath the sand surface. The tubes were placed symmetrically at depths of 0.5 in. (1.2 cm) and 1.5 in. (3.8 cm) below the sludge-sand interface.

There was no significant difference in drainage rates or ultimate volumes of filtrate when applying 12 in. (30.5 cm) of sludge on model beds with sand depths of 3 in. (7.6 cm) and 6 in. (15.2 cm), respectively. Drainage rate and ultimate volume were reduced substantially using a 12-in. (30.5-cm) dosing depth on a 9-in. (22.8-cm) bed.

Quon and Johnson did not actually find an optimum dosing depth but observed that an 8-in. (20.3-cm) application gave the greatest drainage volume (percent of applied volume) of the three depths studied. Optimum dosing depths for their particular sludge, which had an average solids content of 6.1 percent, may have been anywhere from 6 in. (15.2 cm) to 10 in. (25.4 cm). In view of Haseltine's (7) and Quon and Johnson's (9) work, it would appear that initial solids content is a major factor in determining optimum dosing depth.

Randall and Koch (10), while studying the dewatering characteristics of aerobically digested sludge on partially paved beds under field conditions, found that paving reduced dewatering considerably. Seven days after applying a 4-in. (10.1-cm) layer of aerobically digested sludge to a partially paved bed with an oblong center drain, the moisture content of the sludge was still 90 percent. When applying the same sludge to the same depth on a nonpaved bed, the moisture content after seven days was less than 15 percent. The percentage of total area occupied by paving was not given. Quon and Johnson (9) also reported a reduction in drainage rate and volume when using annular rings to block drainage areas, however, they found that a 9-in. (22.8-cm) layer of sludge applied to beds with 50 and 75 percent of the total areas blocked produced utlimate drainage volumes of 43 and 24 percent, respectively.

Nebiker (11) conducted field investigations on sludge drying characteristics for parameterization of drying rates by comparison with evaporation from a free water surface. The sludge used included trickling filter and activated sludge from the secondary and primary digesters of five plants. The investigation took place in the middle of a large field under a glass pane roof which did not hinder air circulation but protected the sludge from rainfall.

Sludge containers, eighteen in all, were placed in a water-filled basin beneath the glass roof. The water-filled basin functioned as a heat reservoir, similar to a sludge drying bed or lagoon. The sludge containers were each 17.7 in. (45 cm) in diameter and were 7.1, 11.0, and 18.9 in. (18, 28, and 48 cm) in depth. The containers were dosed to depths of 3.9, 7.9, and 15.7 in. (10, 20, and 40 cm). Two containers, 11 in. (28 cm) deep and 9.8 in. (25 cm) and 17.7 in. (45 cm) in diameter were used to determine the evaporation rates of water and to check for scale effects. Both the water and sludge containers were so supported in the basin that the liquid levels in all the containers could be maintained at the same elevation as the water in the basin, thereby eliminating variances due to freeboard.

The investigation was performed on the two types of sludge each with a total solids content of 2.5, 5, and 10 percent. None of the sludges were permitted to drain and all weight losses were due to evaporation. The water and sludge containers were weighed at intervals of 7 days over a period of 7 wk.

Based on a statistical evaluation of water evaporation from the 9.8-in. (25-cm) and 17.7-in. (45-cm) containers Nebiker reported that, "In all tests a significance of less than 95 percent was found, demonstrating that the evaporation of water (and thus drying of sludge) from the containers probably was independent of container diameter, location, and water (thus supernatant) depth." (11, p.617) In addition, no difference in drying rates among well digested sludges differing in source, type of treatment, and stage of digestion was observed. Seasonal variations in temperature during the course of the experiment (May to December) were not found to affect relative drying rates, provided that freezing did not occur. The evaporation rates from the sludge surface during the constant rate drying period averaged about 5 percent more than the evaporation rate from a free water surface.

Nebiker's observations have contributed some understanding of the influence of dosing depth, type of sludge, and stage of digestion, upon dewatering rates. It would appear that evaporation, during the constant drying rate period, is not significantly affected by these factors. Based upon the investigations of Haseltine (7) and Quon and Johnson (9), it seems that these factors are of primary importance to drainage.

Quon and Tamblyn (12) studied the water losses of digested trickling filter sludge as a result of evaporation due to heat transfer from radiation on the sludge surface. Laboratory studies were conducted on both drained and nondrained sludges to determine the individual contributions of drainage and evaporation to sludge dewatering.

Radiation intensity was controlled from 0 to 1670 cal/min/sq ft (0 to 1.80 cal/min/sq cm). Heat transfer was limited to evaporation. The relative humidity, although recorded was not controlled. The evaporation rate of water under similar conditions was used as a reference.

In studying the individual effects of drainage and evaporation, Quon and Tamblyn observed that drainage prevented the formation of a free water surface and reduced the evaporation rate by 22 percent. With a radiant intensity of 929 cal/min/sq ft (1.00 cal/min/sq cm), the ultimate weight of drainage was 35 percent of the original applied weight of sludge. Ultimate drainage increased to 50 percent of the applied weight when the radiant intensity was reduced to zero.

Quon and Tamblyn observed that under similar conditions of temperature, relative humidity, and radiant intensity, the evaporation rates of water and sludge were essentially identical. Using a radiant intensity of 929 cal/min/sq ft (1.00 cal/min/sq cm), the evaporation rates from the water and sludge were found to be 1.86 and 1.82 lb/min/sq ft (0.91 and 0.89 gm/min/sq cm), respectively. The critical moisture content of the sludge varied from 66 to 84 percent, and the average critical moisture content of 13 observations was 77 percent.

Jennett and Santry (13), working in the field, investigated sludge drying rates on open, roofed, and wind protected beds. Additional studies included drying characteristics on open beds as affected by coagulants. The open, roofed, and wind protected beds were constructed by partitioning off a portion of an actual sludge drying bed into 12 smaller beds. Four of the beds were protected with wind breaks and another four were roofed. The remaining four beds were left open. Two beds in each of the three sets were sealed with plastic at the sand surface to prevent drainage. The other two beds in each set were drained by the existing underdrains. The major parameter used for evaluation of sludge drying was sludge moisture content. Samples were taken from the top, middle, and bottom of the sludge layers.

Jennett and Santry found that the drying rate on covered, non-drained beds was slightly better than on those beds not protected. Drained, roofed beds performed about the same as the drained, open beds for the first three weeks after the sludge was applied; however during the fourth week the open beds dried much faster. At the end of a 28-day period the mositure content of the open, drained beds decreased by 58 percent while during the same period the moisture content of the open, nondrained beds decreased by only 10 percent. The authors concluded that the better performance of the open, drained beds was due to the radiant energy on the sludge surface which was more readily absorbed when the sludge reached a solid state. It was also found that rainfall on the open, drained beds, did not appreciably retard drying rates once the sludge had cracked allowing precipitation to pass quickly through to the sand bed.

In general, polymers were found to be effective in increasing the dewatering rate. Little difference was observed in the dewatering rate when using 200 mg/l of the various polymers as opposed to 50 mg/l.

Jennett and Santry's work does not directly pertain to this investigation as the major portion of their study evaluated and compared the performance of various types of bed construction. However, their work clearly indicated the importance of drainage to the dewatering of sludge.

Quon and Ward (6) conducted laboratory investigations on digested sludge controlling the air temperature, humidity, and wind velocity. Their work was carried out in an environmental control chamber on digested sludge dosed in layers of 0.5, 1.5, and 2.5 in. (1.3, 3.8, and 6.4 cm). The sludge was not drained. The temperature ranged from 63 to 182 °F (16.7 to 83.3 °C) and the relative humidity from 7 to 54 percent, while air velocities were 4.2, 6.5, and 9.0 fps (1.3, 2.0, and 2.7 m/sec). The major paramter used for the evaluation of the results was sludge weight loss with time. The evaporation rate of water under similar atmospheric conditions was used as a reference.

The critical moisture content varied from 75 to 90 percent and within the range studied was found to be independent of the depth of sludge, temperature, humidity, and air velocity. The constant drying rate of the sludge was essentially equal to the evaporation rate of water for humidity differences greater than 0.03 lb moisture/lb of dry air (0.03 kg moisture/kg of dry air). For a given air velocity, the sludge drying rate varied linearly with humidity difference.*

---

*Humidity difference is the saturation humidity of the air at the wet bulb temperature minus the humidity of the air.

Variations in sludge drying rates for the three sludge depths were within 10 percent. Table II shows the results of their investigation.

A significant difference between the water and sludge evaporation rates during the constant rate drying period was unexpected and contrary to results reported by other investigators (11, 12). An examination of Table II would indicate that for a humidity difference of 0.01 lb moisture/lb of dry air (0.01 kg moisture/kg of dry air) or less the sludge drying rate was only half the free water surface evaporation rate. Quon and Ward did not give any explanation for this difference but stated that, "....the time required for the convective drying of sludge to some given moisture content cannot be estimated solely from our knowledge on the evaporation of water from a free surface." (6, p.319)

Of the two dewatering mechanisms (evaporation and drainage), drainage has been clearly indicated to be the more significant. It is felt that more information is needed on sludge dewatering rates when both evaporation and drainage are introduced as dewatering mechanisms under controlled conditions of air temperature and humidity.

TABLE II

SUMMARY OF SLUDGE DRYING RATES AND OPERATING VARIABLES*+

Series	Temp., °F		Humidity		Air Flow		Critical Moisture %	Rate of Drying lb/hr/sq ft	
	Dry Bulb	Wet Bulb	Relative %	ΔH lb/lb	fps	lb/sec		W_s	W_w
1A	165	105	15	0.042	8.97	3.00	77	0.64	--
2B	165	102	13	0.040	8.97	3.00	84	0.46	--
3B	182	108	11	0.050	9.22	3.00	86	0.53	--
4B	165	101	12	0.039	8.97	3.00	88	0.44	--
5B	145	93	15	0.029	8.92	3.08	81	0.41	--
6B	120	80	17	0.018	9.18	3.31	--	0.26	0.48
7B	120	89	30	0.021	9.05	3.26	--	0.27	0.37
8C	83	70	52	0.0076	8.60	3.31	--	0.092	0.21
Average					9.0	3.1			
9C	180	100	7	0.040	6.40	2.09	86	0.41	0.50
10B	165	98	11	0.036	6.35	2.12	84	0.37	0.40
11B	120	80	17	0.018	7.02	2.53	--	0.24	0.34
12B	120	80	17	0.018	6.23	2.25	85	0.27	0.32
13B	78	63	44	0.0068	6.36	2.47	--	0.062	0.15
14B	75	63	52	0.0058	6.32	2.47	--	0.072	0.13
Average					6.5	2.3			
15B	180	110	13	0.052	4.26	1.39	--	0.33	0.29
16B	165	96	9	0.035	4.18	1.40	86	0.35	0.38
17C	145	90	13	0.027	4.55	1.57	--	0.27	0.34
19B	120	85	25	0.020	4.19	1.51	--	0.14	0.15
20C	80	68	54	0.0066	3.74	1.45	--	0.055	0.11
Average					4.2	1.5			

*Values for series 1 to 5 represent the arithmetic average of 3 determinations. Values for series 6 to 20 represent the arithmetic average of 2 determinations.

+After Quon and Ward (6).

III. SLUDGE DEWATERING

Drainage and evaporation are the mechanisms which determine sludge dewatering rates on drying beds. Although an inverse relationship between the two has been reported by Quon and Tamblyn (12) who found that maximization of either mechanism retarded the other, drainage has been clearly indicated to be the more significant factor (13). Drainage is affected by solids content (7, 9) dosing depth (9), depth of supporting media (9), sand grain size (2), degree of paving (9, 10, 13), and the presence or absence of coagulants (13).

Sludge moisture loss by evaporation varies with the physical state of the sludge and the evaporative potential of the air, and would be expected to approximate the removal rate from a free water surface, provided that there is free sludge surface moisture (11). This similarity in evaporation rates has been observed under both laboratory (12) and field conditions (11). Nebiker has indicated (11) that sludge evaporative rates would be modified by the darker sludge surface which would absorb more radiant energy and increase moisture loss and by dissolved solids and oils and fats on the supernatant surface which would suppress evaporation losses.

Sludge dewatering by evaporation occurs in two distinct phases. The initial phase is known as the constant rate drying period. Evaporation loss at a constant rate continues until the free surface moisture is exhausted and can no longer be replenished by the internal transport of water to the sludge surface. Further evaporation then occurs at a decreasing rate during the period known as the falling rate drying period. The falling rate phase may or may not be a linear relationship with time and depends upon the nature of the dewatering material (14, p.279).

The critical moisture content which marks the transition from the constant to the falling rate drying period is influenced by the sludge transport rate and the dosing depth. A more intense drying condition requires a higher internal transport rate to maintain a constant moisture loss. Of two identical sludges dried under different conditions, the one dried under a more intense condition will exhibit a higher critical moisture content. Conversely, of two different sludges dried under the same conditions, the sludge having the lower internal transport rate will have a higher critical moisture content. The moisture content of the drying sludge surface is independent of depth at the instant of transition from the constant to the falling rate period (11). However, at this transition point a moisture gradient develops in the sludge layer, but the critical moisture content does not reflect this because it is an average measure of the moisture throughout the sludge depth. Therefore, if applying the same sludge at two different depths, the sludge of greater depth will have a higher critical moisture content.

Quon and Tamblyn have pointed out (12) that drainage prevents the formation of a free water surface and reduces the evaporation rate. Since the major portion of the total drainage is completed rather quickly in relationship to total dewatering time, it would appear that the constant rate drying period would be of short duration. It is probable that most of the total sludge moisture loss is the result of drainage and the falling rate period evaporation losses.

IV. EQUIPMENT, MATERIALS, AND PROCEDURE

A. INTRODUCTION

Relative humidities and temperatures were maintained in two incubators to create a controlled atmosphere for the investigation of sludge dewatering rates. The model sludge drying beds were designed and constructed to measure the drainage and evaporation from anaerobically digested activated sludge. The moisture contents of samples, which were periodically taken from the models, was the major parameter used for the evaluation of temperature and humidity effects.

B. EQUIPMENT AND APPARATUS

1. Incubators

Temperature control during the investigations was provided by two Labline Incubators. Incubator Model 704, which had no refrigeration capability, operated above ambient temperature. Model 704A, which was equipped with a refrigeration unit as well as heating elements, was operated over a wider temperature range. This unit had some oscillatory air circulation due to the fact that it was equipped with a blower. It would have been desirable to have carried out all investigations in one incubator; however, Model 704A was not available at the beginning of this research. Table III indicates the experimental conditions under which each run was performed. Specifications for the two incubators will be found in Appendix (A).

2. Temperature Monitoring

The incubators were self-regulating. No temperature recording devices were used, instead dry and wet bulb temperatures were read and recorded from two thermometers placed inside the incubators. The

TABLE III

SUMMARY OF EXPERIMENTAL CONDITIONS

Series	Run No.	Temperature		Relative Humidity %	Incubator Model	
		°F	°C		704	704A
1	1	95	35	42		X
	2	92	33	68	X	
	3	95	35	25	X	
2	4	50	10	40		X
	5	48	9	64		X
3	6	70	21	64		X
	7	70	21	28		X
	8	70	21	44		X

Type of Sludge: digested primary and activated

Dosing Depth: 8 in. (20.3 cm)

Approximate quantity of sludge in each model:

Models A, B, C, and D:	21.9 lb (10.0 kg)
Model E:	19.4 lb (8.8 kg)
Model F:	18.9 lb (8.6 kg)

wet bulb thermometer was made by placing a muslin wick over the mercury bulb and inserting the other end of the wick in a small beaker of distilled water.

To obtain temperature readings, the wet bulb wick was saturated and an air stream was directed across the thermometers. The two thermometers were read when the wet bulb reached the lowest temperature. (A small electric fan was used to create the draft in incubator Model 704. In the other incubator, the draft of the blower was sufficient for this purpose.) Temperatures were read and recorded to the nearest 0.5 °C (0.9 °F). Relative humidities were taken from psychrometric tables (15) using the difference between the wet and dry bulb temperatures and a barometric pressure of 30 in. (76.2 cm) of mercury. Atmospheric pressures were not observed or recorded. It was felt that the equipment used for temperature monitoring and humidity control was not sufficiently accurate to justify making adjustments as the result of the slight barometric variations which occur in the Rolla area.

A fan psychrometer* was used simultaneously with the thermometers for several of the runs. It produced wide variations in temperature readings by merely making a slight change in the orientation of the sensing unit during operation. Because of this, use of the instrument was discontinued. All temperatures and relative humidities were based upon the two thermometers.

---

*Atkins Thermistor Psychrometer, Model No. 3F01-F46, Serial No. 3269, Atkins Co., Gainesville, Florida.

3. Humidity Control

Humidity control in the incubators was maintained with an inexpensive portable dehumidifier* which was placed within the units. The manufacturer's indicated markings on the unit for humidity levels could not be relied upon over the temperature range desired. Although the humidistat on the unit was utilized for control, it was necessary that it be calibrated at the beginning of each run. Calibration of the dehumidifier was a "trial-and-error" procedure utilizing the wet and dry bulb temperature readings.

The dehumidifier was not designed to operate below 65 °F (18 °C); below this level the temperature of the air flowing across the condenser coils was too low to melt the ice which formed. Continued operation caused the coils to become completely blocked with ice, thus preventing air flow altogether. At this stage the dehumidifier was totally ineffective in maintaining a constant humidity. The study required that a number of runs be made at low temperatures and humidities. To accomplish this it was necessary to modify the dehumidifier in such a manner that the coils could automatically be deiced without appreciably interrupting the operation of the dehumidifier and without constant attention on the part of the investigator. An open insulated frame, which would not restrict air flow, was wound with a high-resistance Nichrome wire and was mounted between the condenser coils. A timer was built to turn on a relay every 3 hr. The relay, in turn, cut the power to the dehumidifier and

---

*Sears Coldspot Dehumidifier, Model No. 639200, Sears, Roebuck and Co., St. Louis, Missouri.

closed the circuit leading to the heating element for approximately 5 min. The melted ice was drained into a bottle which was emptied intermittently.

High and mid-range humidities in the incubators were created with an inexpensive room vaporizer* which merely threw a fine mist of cool water into the air. The vaporizer, which was filled with distilled water daily, was not equipped with a humidity sensing device and was run continuously, except at low humidities when it was turned off. To maintain a given humidity, the dehumidifier was operated against the vaporizer, condensing the excess moisture. The lower righthand corner of Figure 1 shows the location of the dehumidifier (foreground) and vaporizer (background) within the incubator.

It was planned that a total of nine runs be made, three runs in each series with the dry bulb temperature of all runs in a series the same. It can be seen in Table III that there was some variation in the data. The major factor causing this variation was the limitation of the equipment used. The higher temperature of Run 3 resulted from the almost continuous operation of the dehumidifier necessary to maintain the low humidity. The dehumidifier put more heat into the incubator than could be dissipated because of the absence of refrigeration equipment in that particular incubator. The low humidity of Run 7 represents the minimum humidity attainable at that temperature with the dehumidifier running 24 hr a day. The corresponding run in Series 2 is absent because the low relative humidity could not be achieved at that temperature. The temperatures and humidities shown in

---

*Hankscraft Cool-Vapor, Vapor Master, Hankscraft Co., Reedsburg, Wisconsin.

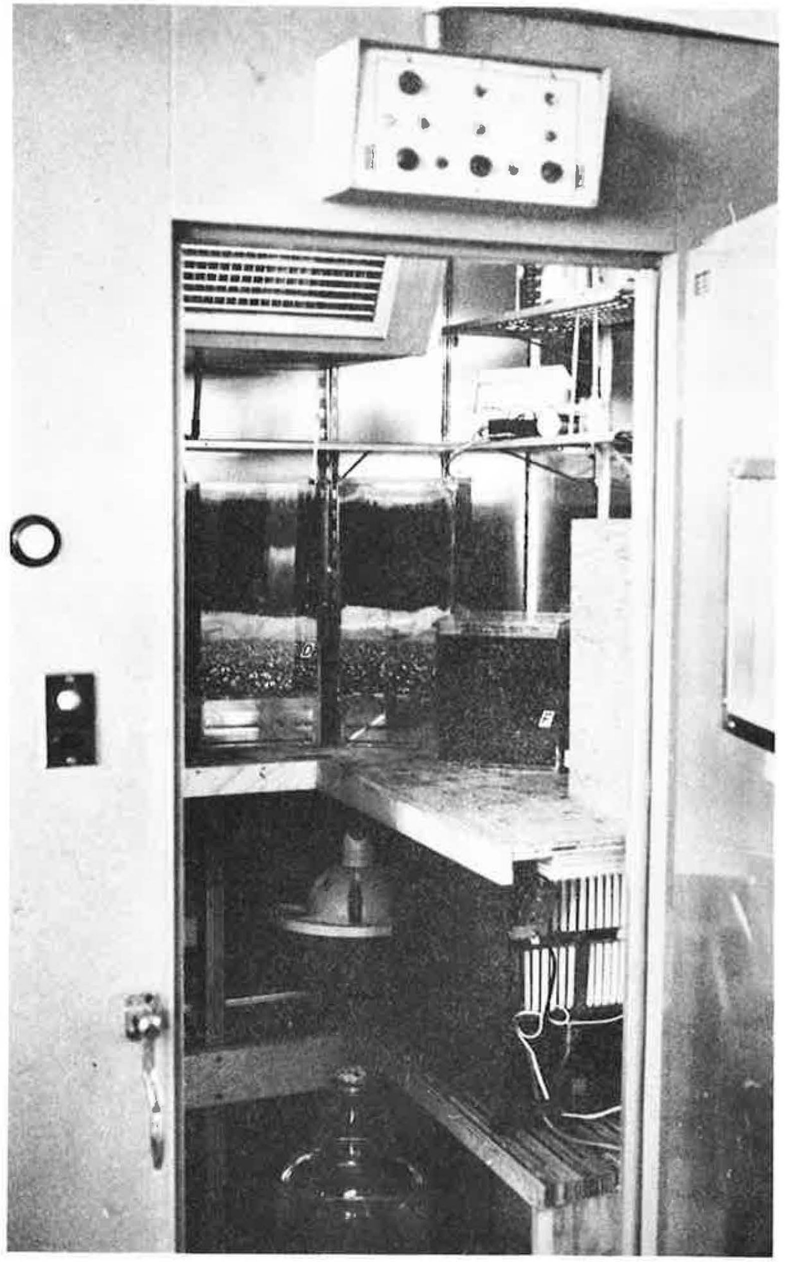

FIGURE 1. ENVIRONMENTAL CONTROL UNIT

Table III represent average values and are felt to be close enough for comparison.

4. Model Beds

Six models, A through F, of different design were built to investigate various aspects of sludge dewatering. Four of the models, A through D, were identical, had provisions for drainage and were open to the air to permit evaporation of moisture from the sludge surface. Three of these models were in use at any one time. The fourth model was kept in reserve in the event that leaks developed during a run. Figure 2 shows the dimensions and construction details of these four models. Models A through D had an inside cross-sectional area of 0.509 sq ft (0.047 sq m) and when initially filled with sludge to a depth of 8.0 in (20.3 cm) had 1 in. (2.5 cm) of freeboard. The overall depth of the sand bed and supporting media was about 6 in. (15.2 cm). The top-most layer was of white silica sand, about 2 in. (5.1 cm) in depth and had a uniformity coefficient of 2.9. The intermediate and bottom layers, each approximately 2 in. (5.1 cm) in depth, were of successively coarser material. Between the bottom gravel layer and the 0.50-in. (1.27-cm) perforated supporting plate, a piece of 18-mesh aluminum wire screen served to prevent any gravel from passing through the 0.25-in. (0.64-cm) diam drain holes. A tray with an inside cross-sectional area of 0.446 sq ft (0.042 sq m) was placed beneath the perforated supporting plate to catch and measure the amount of filtrate drained off. A thin plastic scale, graduated in 1/16-in. (0.158-cm) dimensions, was fixed to the inside of the tray to measure the depth of filtrate.

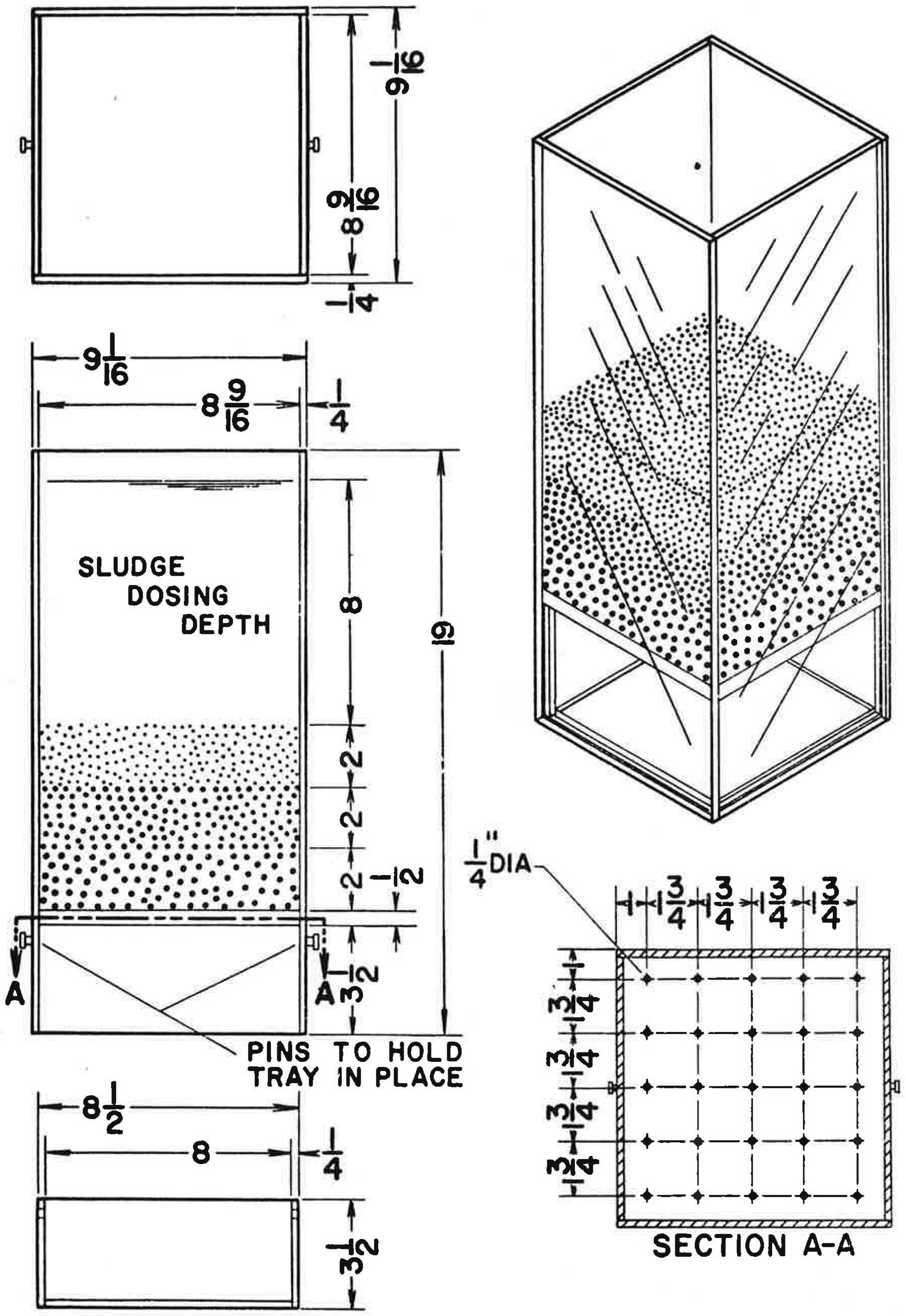

FIGURE 2.- DETAILS OF MODEL SLUDGE BEDS A, B, C, AND D.

Model E, which was provided with a cover to minimize evaporation, was similar to Models A through D. The inside cross-sectional areas of the model and drainage tray were slightly smaller, however, being 0.45 sq ft (0.041 sq m) and 0.391 sq ft (0.036 sq m), respectively. A 0.125-in. (0.318-cm) diam hole was drilled in the Plexiglas top to prevent formation of a vacuum while the sludge was draining. Model F, which was used to measure evaporation only, had an inside cross-sectional area of 0.445 sq ft (0.041 sq m), was sealed at the bottom, and had an inside depth of 9 in. (22.8 cm). Figure 3 shows Models B through F immediately after being dosed with sludge. At the beginning of each run a 1500-ml beaker was filled to the 1400-ml mark with water from the Rolla system and placed within the incubator to provide a comparison between the evaporation rate from sludge and the evaporation rate of water. The cross-sectional area and initial and final volumes of the beaker were used to determine the average evaporation rate of water.

5. Beam Balance

A beam balance with a capacity of 500 lb (228 kg) and capable of being read to 2 oz (57 g) was used to weigh the models for determination of evaporative weight losses.

C. MATERIALS

The anaerobically digested sludge used in this investigation was obtained from the Rolla Vichy Road Activated Sludge Treatment Plant. The sludge was taken from the digester between 4:00 and 5:00 PM on the day preceeding the run. The sludge was stored overnight, in the laboratory, at room temperature. Characterization of the sludge began the following morning.

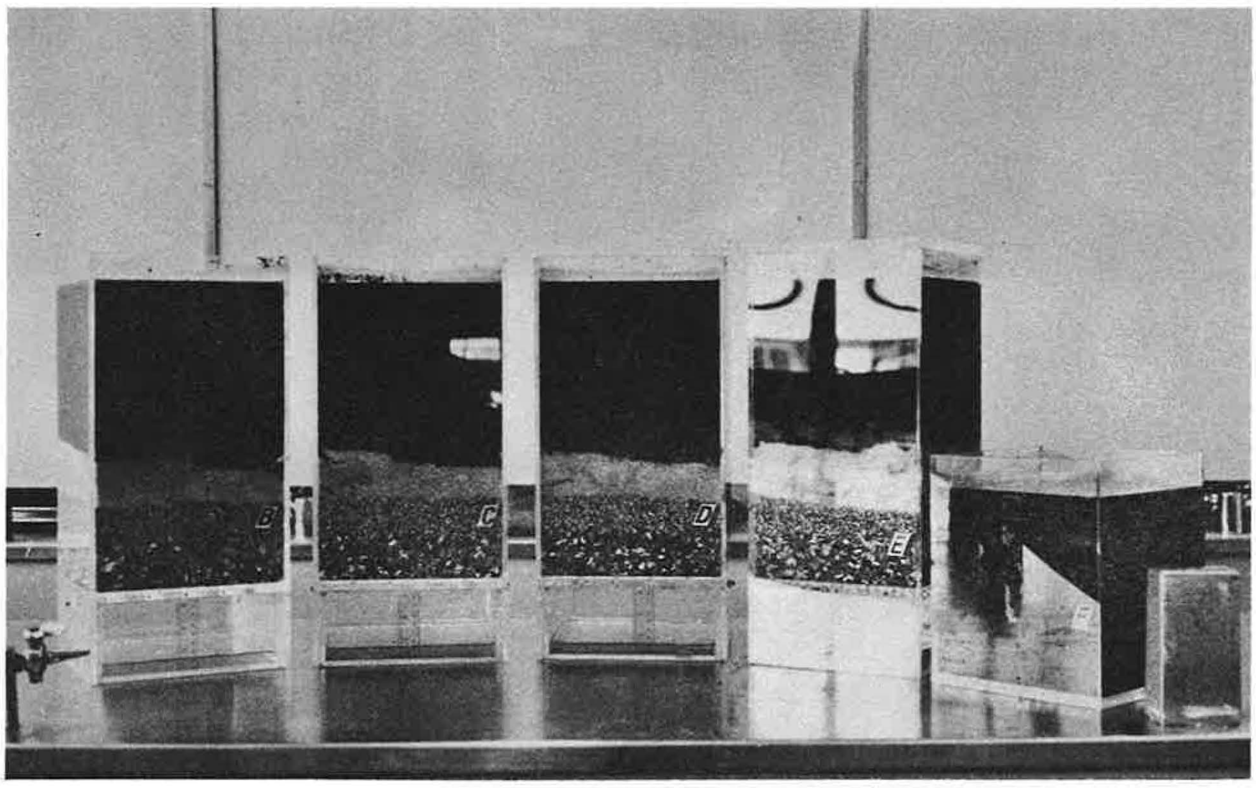

FIGURE 3. MODEL SLUDGE BEDS AFTER DOSING

D. SLUDGE CHARACTERIZATION

Gravimetric and chemical tests were performed to characterize the sludge and to establish a basis for comparison with sludge dewatering investigations reported in the literature.

The procedures outlined in Standard Methods (16), Part V, were used for the determination of pH, acidity, alkalinity, total solids, moisture content, volatile and fixed solids, and specific gravity. Chlorides were determined potentiometrically using the procedure described in Standard Methods (16, p.372).

Iron and aluminum were determined on an atomic absorption unit.* The sludge was digested with sulfuric acid using the procedure outlined in Standard Methods (16, p.468).

In addition to characterization of the sludge, samples were periodically removed from the models during a run and analyzed for moisture content to determine the dewatering rate of the sludge.

E. PROCEDURE

The investigation was conducted over approximately a 6-mo period, beginning in the latter part of October 1970, and ending in early April 1971.

The temperature and humidity were adjusted to desired levels the day preceding the start of each run and the environment of the incubator allowed to stabilize overnight.

The five models (three open and drained, one closed and drained, and one open and not drained) were tared to the nearest 2 oz (57 g),

---

*Perkin-Elmer Atomic Absorption Spectrophotometer, Model 303, Perkin-Elmer Corp., Norwalk, Connecticut.

filled with sludge to a depth of 8 in. (20.3 cm), weighed and placed in the incubator. Care was taken to disturb the sand as little as possible when pouring in the sludge.

Immediately after the models were placed in the incubator, the various chemical and gravimetric tests were begun. Initially it required about 3 days to complete these tests, however, with time and experience this was reduced to 1 day.

During the 2-wk of a run, sludge samples were periodically removed from the models (Model F excepted) for the determination of moisture content. Initially, while the sludge was still quite wet, a broken tip pipet was used to draw off sludge at various depths in the models in an attempt to obtain a representative sample. When the sludge became too thick to pipet, but was still liquid, a plastic spoon was used to remove samples. After the second or third day the sludge was thick enough to be cored. The procedure was to take a core out, 1-in. (2.54-cm) in diameter, weigh it, slice the thin layer of sand from the bottom, and then split the core between two evaporating dishes in order to determine moisture content at the top and bottom of the sludge layer. An additional core was removed for the determination of average moisture content throughout the sludge layer.

The sample weight of the two cores varied within a range of approximately 0.35 to 1.4 oz (20 to 80 g) depending upon the elapsed time. The three samples from each model were placed in tared evaporating dishes, weighed, and evaporated on a steam bath for several hours prior to drying overnight in an oven at 103 °C (217 °F).

Additional data recorded included the drainage as measured by depth of filtrate in the trays. These trays were insufficient to hold all the drainage and were emptied several times during the first few days of each run.

The depth of sludge with time was also determined by placing a straight edge across the top of each model and measuring the distance to the sludge surface.

The models were periodically removed from the incubators just long enough to weigh them on the beam balance to enable the determination of evaporation losses.

The date and time of day were recorded when the samples were removed, when the drainage was measured and/or discarded, when the sludge depth was determined, and when the models were weighed.

V. RESULTS

A. INTRODUCTION

The moisture content of sludge in three open, drained drying bed models and a closed, drained model was determined with time under a range of environmental conditions in eight experimental runs. The operational variables in this experiment included the dry bulb temperature, wet bulb temperature, and relative humidity. Data were also obtained on drainage rate and volume, total evaporative loss, and evaporative rates from a free water surface and a nondrained model sludge bed.

B. EXPERIMENTAL CONDITIONS

The chemical and physical characteristics of the anaerobically digested primary and activated sludge used in each run, as well as the arithmetic average for all eight runs, are summarized in Table IV. With the exception of initial moisture content, no attempt was made to correlate the results obtained in this investigation with the sludge characteristics.

For each run all models were loaded to the same 8-in. (20.3-cm) depth. However, on a weight basis there was more variation in model loading than could be explained by slight differences in dosing depth, sludge density, or cross-sectional area. The variation in weight of the applied sludge was largely attributed to drainage through the sand beds during loading. Model F, which was used to determine evaporation rates only, was sealed at the bottom and did not contain any sand. Models A through E, which were drained, had to be dosed slowly to keep sand bed disturbance at a minimum. Sand saturation and drainage often started before charging of the beds was complete,

TABLE IV

CHARACTERISTICS OF ANAEROBICALLY DIGESTED PRIMARY AND ACTIVATED SLUDGE

Characteristic	Run No.								avg
	1	2	3	4	5	6	7	8	
pH	--	6.4	6.5	6.4	6.4	6.3	6.4	6.3	6.4
Alkalinity, mg/l $CaCO_3$	--	865	890	670	660	655	700	595	719
Acidity, mg/l $CaCO_3$	--	672	692	443	480	563	614	485	564
Total solids, %	3.4	2.4	2.9	3.2	3.5	2.8	3.7	4.4	3.3
Moisture content, %	96.6	97.6	97.1	96.8	96.5	97.2	96.3	95.6	96.7
Fixed residue, %	--	42.9	44.9	41.3	38.0	35.3	35.9	39.8	39.7
Volatile matter, %	--	57.1	55.1	58.7	62.0	64.7	64.1	60.2	60.3
Specific Gravity	--	1.01	1.00	1.02	1.02	1.00	1.00	1.00	1.01
Turbidity, JTU	--	22,000	48,000	12,000	12,000	9,500	9,900	20,000	19,000
Iron, mg/l	--	430	1,030	640	--	--	--	--	700
Aluminum, mg/l	--	300	750	600	--	--	--	--	550

and consequently, more sludge had to be added to reach the 8-in. (20.3-cm) depth. Table V indicates the weight of sludge applied to each model, as well as the average weight of sludge for Models A through D. Because Models E and F had a smaller cross-sectional area than Models A through D, the applied weight of sludge in the models was converted to a loading expressed as weight per unit area of bed to facilitate comparison of results. An examination of Table V would indicate that the loading on Model F varied by a maximum of 1.0 psf (4.90 kg/sq m) throughout the eight runs. The loading on Model E varied by 8.6 psf (42.0 kg/sq m) while the variation of the average loading on Models A through D was 2.7 psf (13.2 kg/sq m).

Table VI presents the environmental conditions under which each run was performed. Based upon a study by Quon and Ward (6) who found a linear relationship between ΔT (the difference between wet and dry bulb temperature), ΔH (the difference between saturation and absolute humidity), and evaporation rate, it was decided to study these parameters in addition to temperature and relative humidity. The procedure followed for calculating the absolute and saturation humidities was as outlined by Faires (17, p.485).

C. SLUDGE MOISTURE CONTENT

The fate of the sludge moisture content with time is presented in Figures 4, 5, and 6. The curves shown on the graphs of the open, drained models were obtained by fitting the data points to a fourth degree polynomial using the method of least squares. Table VII indicates the polynomials obtained by this process. The data from these eight runs were also fitted with third and fifth degree polynomials. The fifth degree polynomials were discarded as the coefficient of

TABLE V

LOADING ON EXPERIMENTAL SLUDGE DRYING BEDS

Run No.	Applied Weight of Sludge									
	lb*							psf**of bed area#		
	Model									
	A	B	C	D	avg A,B,C, & D	E	F	avg A,B,C, & D	E	F
1		21.5	22.0	21.8	21.7	20.2	18.6	42.5	45.5	41.8
2		22.4	18.9	21.9	21.1	20.6	18.9	41.3	46.4	42.5
3		22.0	21.6	21.5	21.7	18.8	18.9	42.6	42.3	42.5
4	21.8		21.5	21.5	21.6	18.4	19.0	42.3	41.4	42.8
5		22.0	22.2	23.0	22.4	22.2	18.6	44.0	50.0	41.8
6		22.2	22.1	22.2	22.2	19.2	19.0	43.5	43.2	42.8
7		22.2	22.0	22.1	22.0	19.7	19.0	43.1	44.4	42.8
8		21.2	22.0	22.1	21.8	19.2	18.9	42.8	43.2	42.5

*Multiply by 0.454 to convert lb to kg.

**Multiply by 4.88 to convert psf to kg/sq m.

#The cross-sectional area of Models A through D was 73.25 sq in. (473 sq cm). The cross-sectional area of Models E and F was 64.00 sq in. (413 sq cm).

TABLE VI

ENVIRONMENTAL CONDITIONS

Series	Run No.	Temperature						Humidity			
		Dry Bulb		Wet Bulb		ΔT		Relative %	Absolute lb/lb*	Saturation lb/lb*	ΔH** lb/lb*
		°F	°C	°F	°C	°F	°C				
1	1	95.3	35.2	77.5	25.3	17.8	9.9	42	0.0162	0.0204	0.0042
	2	91.5	33.1	82.4	28.0	9.1	5.1	68	0.0218	0.0240	0.0022
	3	95.2	35.1	69.0	20.5	26.2	14.6	25	0.0092	0.0152	0.0060
2	4	49.6	9.8	39.9	4.4	9.7	5.4	39	0.0030	0.0052	0.0022
	5	47.7	8.7	42.5	5.8	5.2	2.9	64	0.0047	0.0057	0.0010
3	6	70.1	21.2	62.2	16.8	7.9	4.4	64	0.0101	0.0119	0.0018
	7	70.4	21.3	53.5	12.0	16.9	9.3	28	0.0048	0.0087	0.0039
	8	70.1	21.2	57.1	14.0	13.0	7.2	44	0.0069	0.0099	0.0030

*Units are lb of vapor/lb of dry air.
**Difference between saturation and absolute humidity.

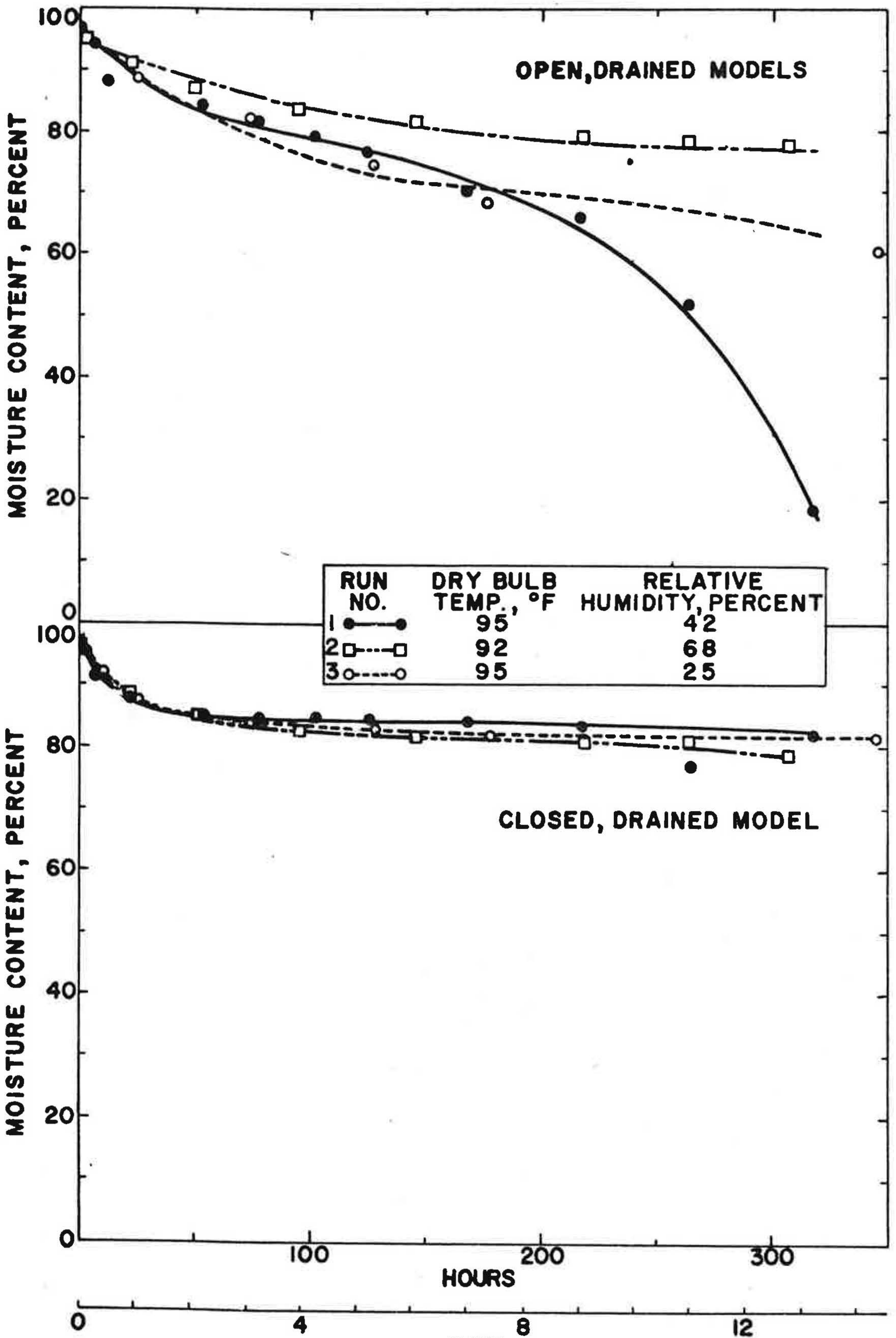

FIGURE 4.- MOISTURE CONTENT VERSUS TIME FOR RUNS 1, 2, AND 3.

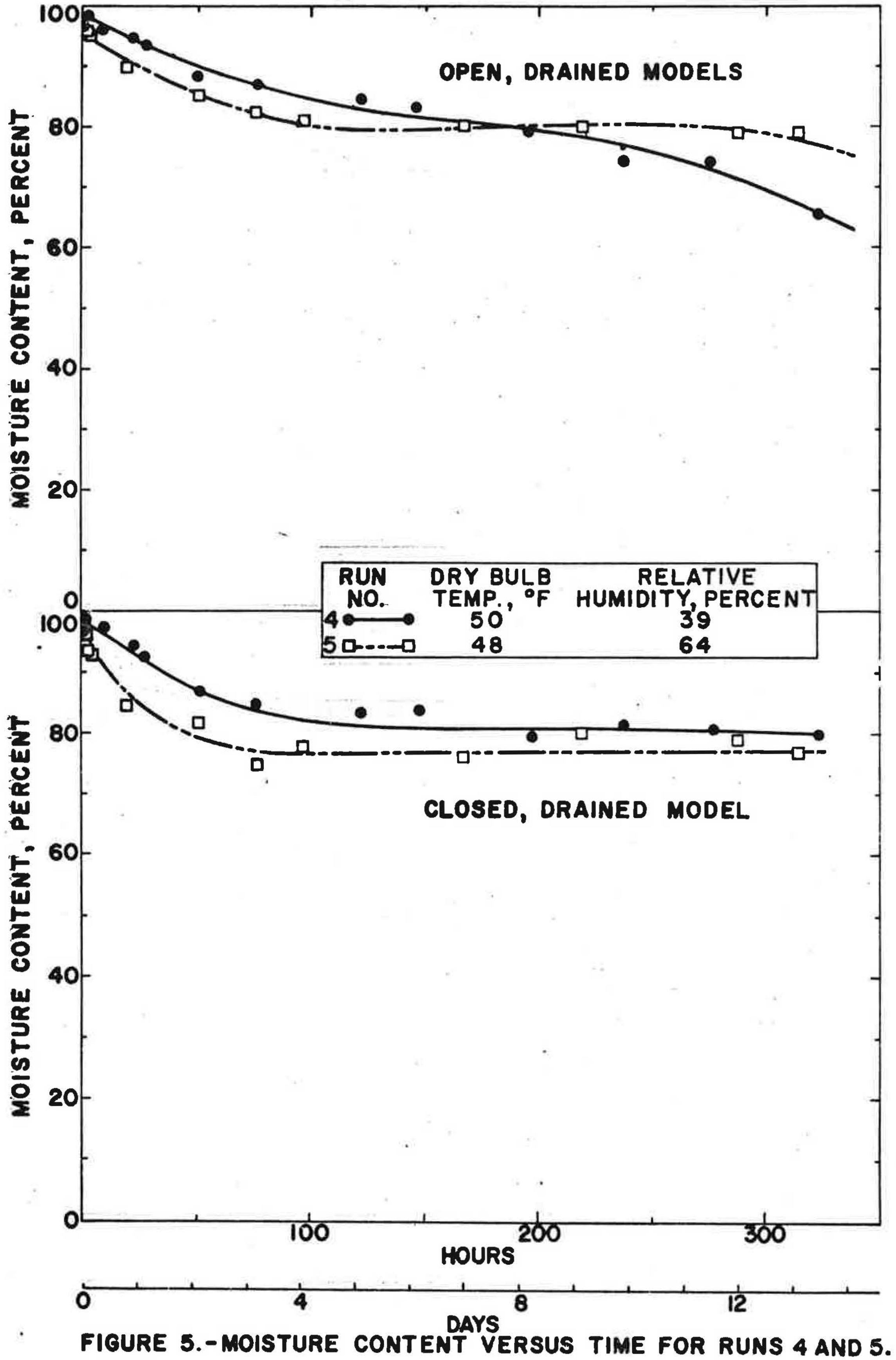

FIGURE 5.-MOISTURE CONTENT VERSUS TIME FOR RUNS 4 AND 5.

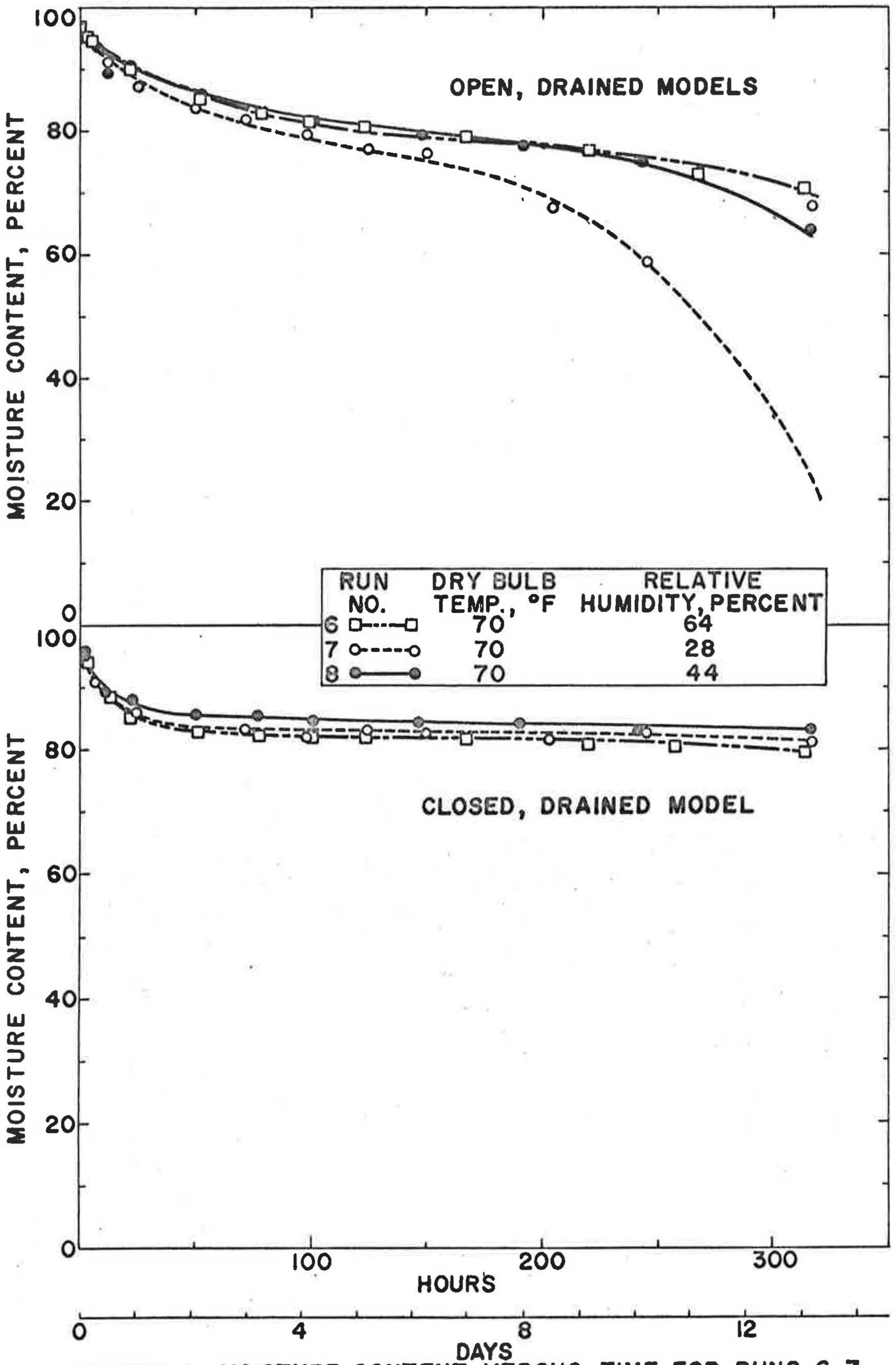

FIGURE 6.–MOISTURE CONTENT VERSUS TIME FOR RUNS 6,7 AND 8.

TABLE VII

MOISTURE CONTENT IN OPEN, DRAINED MODELS AS A FUNCTION OF TIME

Run No.	ΔT °F	4th Degree Polynomials Y = Moisture Content, percent X = Time, hr
1	17.8	$Y = 95.94 - 0.33X + 0.0022X^2 - 0.0000059X^3$
2	9.1	$Y = 95.71 - 0.16X + 0.00050X^2 - 0.0000005X^3$
3	26.2	$Y = 97.21 - 0.34X + 0.0015X^2 - 0.0000024X^3$
4	9.7	$Y = 98.13 - 0.20X + 0.00085X^2 - 0.0000017X^3$
5	5.2	$Y = 96.21 - 0.28X + 0.0015X^2 - 0.0000025X^3$
6	7.9	$Y = 96.26 - 0.25X + 0.0012X^2 - 0.0000021X^3$
7	16.9	$Y = 95.14 - 0.32X + 0.0021X^2 - 0.0000056X^3$
8	13.0	$Y = 94.82 - 0.21X + 0.0011X^2 - 0.0000023X^3$

the X^4 term was zero for most of the runs. After visually comparing the plots of the third and fourth degree polynomials, it was decided that the latter set of polynomials gave the best fit. The data for these graphs can be found in Tables B-1 and B-2, Appendix B.

The moisture content of the sludge in the closed, drained model (Model E) was not significantly affected by the imposed environmental conditions. The final moisture content of Model E varied from a high of 82.9 percent for Run 8 to a low of 76.4 percent for Run 5. The moisture content of the sludge in the open, drained models varied considerably with time over the range of the environmental conditions imposed. It will be noted that the last data point of Run 7 in the open, drained models (Figure 6) is drastically off the curve. This point, 67.8 percent moisture, represents an increase of approximately 9 percent over the preceding point. Although irregularities can be expected when working with a nonhomogeneous material such as sludge, an increase of this amount is not reasonable. This point, as well as all the other points of the open drained models, represents an arithmetic average of values from three models. All three models showed a similar increase in moisture content. No reasonable explanation is available to justify this increase. This data point was, therefore, disregarded when fitting the remaining points to a polynomial.

On the basis of Figures 4, 5, and 6 it would appear that the sludge dewatering was not a function of relative humidity as had been originally assumed. Other parameters were therefore examined in an attempt to find a relationship between environmental conditions and sludge dewatering. Table VIII is a partial summary of the results from the runs in the open, drained models. The sludge to water

TABLE VIII

SELECTED RESULTS OF DEWATERING EXPERIMENTS

Run No.	Moisture Content, % avg A,B,C, & D		Evaporation Rate psf/hr*		Ratio	Total Drainage avg A,B,C, & D		Final Sludge Depth in.
	Initial	Final	Model F	Free Water Surface	$\frac{\text{Sludge}}{\text{Water}}$	psf**	% of H_2O Applied	
1	96.6	19.2	0.1100	0.0708	1.55	31.0	75.6	1.6
2	97.6	75.8	0.0127	0.0147	0.86	31.9	79.0	1.1
3	97.1	60.5	0.0334	0.0413	0.81	33.4	80.7	1.1
4	96.8	65.3	0.0445	0.0353	1.25	24.4	59.5	1.6
5	96.5	78.7	0.0089	0.0060	1.47	39.5	93.0	1.0
6	97.2	70.6	0.0446	0.0335	1.33	34.5	81.5	1.3
7	96.3	58.7#	0.0648	0.0437	1.48	30.6	73.7	1.5
8	95.6	63.7	0.0518	0.0392	1.32	28.3	69.0	1.8

*Multiply by 4.88 to convert psf/hr to kg/hr/sq m.
**Multiply by 4.88 to convert psf to kg/sq m.
#Moisture content at 245.8 hr rather than at end of run.

evaporation ratio shown in this table is the evaporation rate of moisture from the sludge in Model F divided by the evaporation rate of moisture from a free water surface. The data on total drainage in this table were calculated as a percentage of the initial moisture content of the applied sludge loading in psf. This procedure was felt to eliminate variations in initial applied weight of sludge and percent moisture and to enable to results of the eight runs to be compared. In order to correlate the results in this table with the imposed environmental conditions, Table IX was constructed. Table IX shows the experimental results and the environmental conditions (Table VI) ranked by increasing or decreasing order of magnitude. A study of this table initially yielded no relationship between sludge dewatering and environmental conditions. However, a closer examination of this table along with the data shown in Table VIII revealed that Runs 2 and 3 were inconsistent with the other runs. The sludge to water evaporation ratios of Runs 2 and 3 differed considerably from the others, indicating that environmental conditions were somewhat different for these two runs. These two experiments were performed in a different incubator than were the others (Table III, p.20). When this investigation began, it was not believed that utilization of both incubators would have caused any measurable difference in results; however, it is apparent this assumption was erroneous.

After disregarding Runs 2 and 3, the remaining six runs were reranked as shown in Table X. This table indicates that a relationship exists between final moisture content (column 9), evaporation rate from a free water surface (column 11), ΔT (column 3), and ΔH (column 7).

TABLE IX

RUNS 1 THROUGH 8 RANKED* ON THE BASIS OF ENVIRONMENTAL CONDITIONS AND APPLICABLE RESULTS

Temperature			Humidity				Moisture, %		Evaporation			Drainage	
Dry Bulb ↑ (1)	Wet Bulb ↑ (2)	ΔT ↑ (3)	Rel. ↓ (4)	Abs. ↓ (5)	Sat. ↓ (6)	ΔH ↑ (7)	Init. ↓ (8)	Final ↓ (9)	Sludge ↑ (10)	Water ↑ (11)	Ratio ↑ (12)	Total ↓ (13)	% Applied ↓ (14)
1	2	3	3	4	4	3	8	1	1	1	1	4	4
3	1	1	7	5	5	1	7	7	7	7	7	8	8
2	3	7	4	7	7	7	5	3	8	3	5	7	7
7	6	8	1	8	8	8	1	8	6	8	6	1	1
6, 8	8	4	8	3	6	2, 4	4	4	4	4	8	2	2
8, 6	7	2	5, 6	6	3	4, 2	3	6	3	6	4	3	3
4	5	6	6, 5	1	1	6	6	2	2	2	2	6	6
5	4	5	2	2	2	5	2	5	5	5	3	5	5

*↓- Indicates increasing order of magnitude.
↑- Indicates decreasing order of magnitude.

TABLE X

RUNS 1, 4, 5, 6, 7, AND 8 RANKED* ON THE BASIS OF ENVIRONMENTAL CONDITIONS AND APPLICABLE RESULTS

Temperature			Humidity				Moisture, %		Evaporation			Drainage	
Dry Bulb ↑ (1)	Wet Bulb ↑ (2)	ΔT ↑ (3)	Rel. ↓ (4)	Abs. ↓ (5)	Sat. ↓ (6)	ΔH ↑ (7)	Init. ↓ (8)	Final ↓ (9)	Sludge ↑ (10)	Water ↑ (11)	Ratio ↑ (12)	Total ↓ (13)	% Applied ↓ (14)
1	1	1	7	4	4	1	8	1	1	1	1	4	4
7	6	7	4	5	5	7	7	7	7	7	7	8	8
6, 8	8	8	1	7	7	8	5	8	8	8	5	7	7
8, 6	7	4	8	8	8	4	1	4	6	4	6	1	1
4	5	6	5, 6	6	6	6	4	6	4	6	8	6	6
5	4	5	6, 5	1	1	5	6	5	5	5	4	5	5

*↓ - Indicates increasing order of magnitude.
↑ - Indicates decreasing order of magnitude.

Why the evaporation rates for sludge and water are reversed for Runs 4 and 6 in columns 10 and 11 is not clear. It seems reasonable to suppose that these two columns should rank in the same manner.

After disregarding Runs 2 and 3, a reasonable family of curves showing the relationship of moisture content with time was obtained (Figure 7). Beyond the 240-hr point, these curves were in the same order as ranked in Table X. The changing order of the curves prior to 240 hr can probably be attributed to differences in initial moisture content and drainage rates. If sludge were a homogeneous material with a uniform moisture content, one would expect a smooth family of curves which would all diverge from a single point on the Y axis; however, it is not a homogeneous material nor does it have a uniform moisture content and irregularities in results are to be expected.

Although ΔT is felt to be a reliable operational variable affecting sludge moisture content, it would have been desirable to have extended the runs over a longer period of time in order to determine the shape of each curve out to equilibrium conditions. However, the experiment was not structured to allow for longer dewatering periods. Had the runs been conducted for a longer period of time, one would probably have obtained a series of curves similar to those of Runs 1 and 7 with each curve dropping off sequentially as ΔT decreased. Had the runs been extended to equilibrium conditions, each run should have developed a reverse curve and then leveled off and stabilized at some moisture content based upon ΔT.

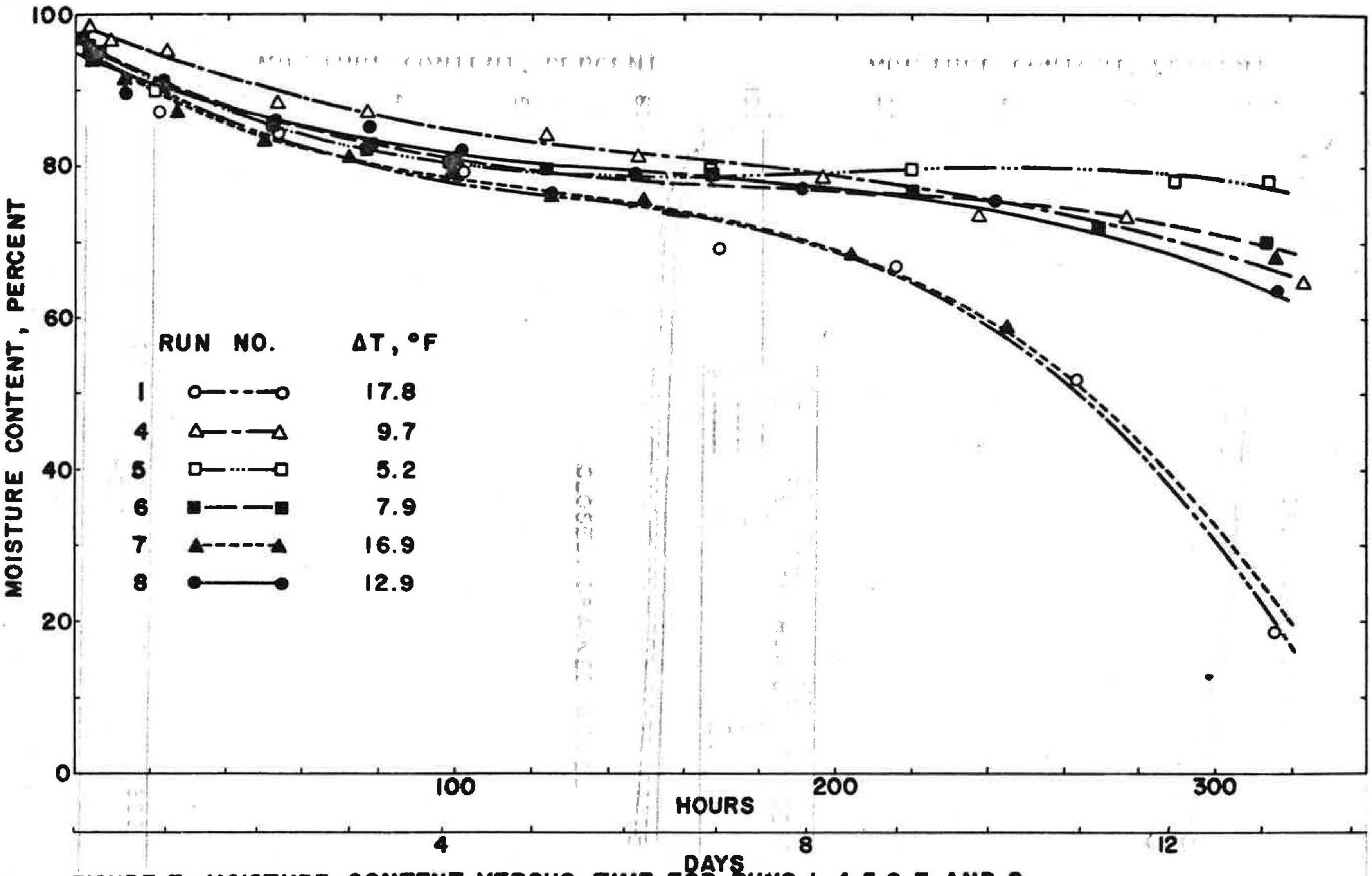

FIGURE 7.-MOISTURE CONTENT VERSUS TIME FOR RUNS 1, 4, 5, 6, 7, AND 8.

D. SLUDGE MOISTURE GRADIENT

An attempt was made to determine the moisture content of the top and bottom of the sludge. The moisture gradient, which is the moisture content of the top layer minus the moisture content of the bottom layer, is shown plotted against time in Figure 8 for Runs 1, 4, 5, 6, 7, and 8. It can be seen that the moisture gradient of the runs was generally ordered with respect to ΔT and generally increased with time. The indefinite order of Runs 4 and 6 is believed to be due to the small difference in ΔT values (9.7 and 7.9 ^{o}F, respectively) and to differences in drainage. A negative gradient developed during Run 5 indicating that the top of the sludge was wetter than the bottom. This negative gradient was attributed to the combination of a low ΔT and a high initial drainage rate. Referring to Table B-3, Appendix B, it can be seen that Run 5 had the highest initial drainage rate, 35 psf/hr (171 kg/hr/sq m) between 0.0 and 0.2 hr after dosing. Apparently the sludge liquid was drained off at a faster rate than could be maintained by the liquid passing from top to bottom through the sludge. It is thought that some liquid remained trapped within the upper layer and was not evaporated because of the small ΔT. The reason for the high drainage values of Run 5 is not clearly understood. The moisture gradients of Model E, the closed, drained model, were found to vary from negative to positive and did not exhibit a relationship with time or ΔT.

The data showing sludge moisture content of the top and bottom portions of the sludge layer for Models A through E can be found in Tables B-1 and B-2, Appendix B.

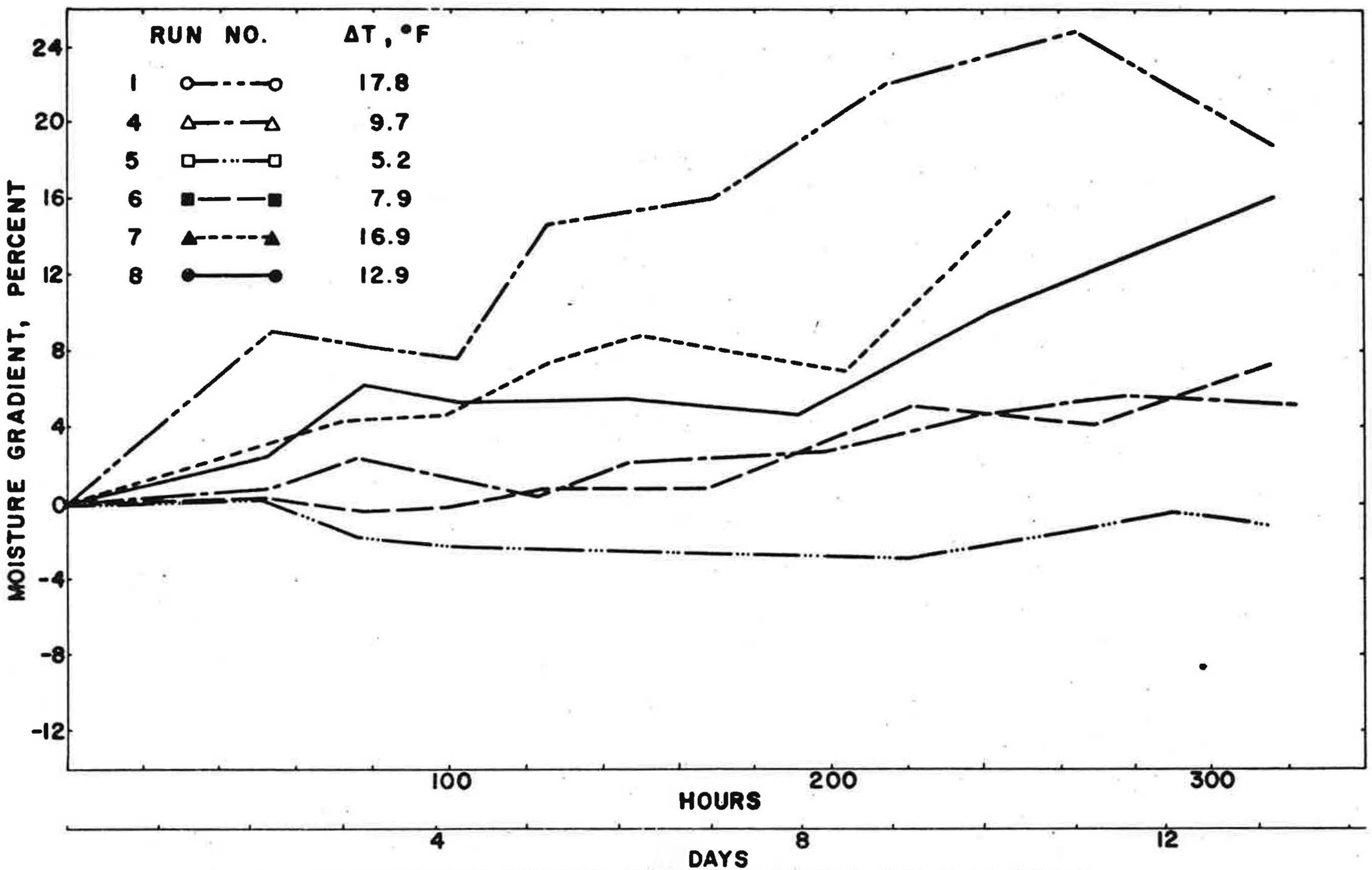

FIGURE 8.- MOISTURE GRADIENT VERSUS TIME FOR RUNS 1, 4, 5, 6, 7, AND 8.

E. DRAINAGE

Figure 9 presents the drainage patterns which occurred in the open, drained models up to 40 hr after dosing. It can be seen that only the drainage rate of Run 5 decreased smoothly with time. For Runs 1, 2, and 3 the maximum drainage rate did not occur immediately after dosing but rather a few hours later. For Runs 4, 6, 7, and 8 the drainage rate was at a maximum immediately after dosing, then fell off, climbed again slightly, and finally declined. This variation in drainage patterns is felt to be due to air blocking. Additional drainage data can be found in Tables B-3 and B-4, Appendix B. Ninety percent or more of the total drainage in the open, drained models was completed in 77 hr or less and total drainage was completed in 240 hr or less (Table B-3).

F. SLUDGE SURFACE RECESSION

The ultimate depth of sludge from the eight runs is listed below.

Run No	Ultimate Depth, in.	
	Open, Drained Models	Closed, Drained Model
1	1.6	2.1
2	1.1	1.1
3	1.1	1.8
4	1.6	2.5
5	1.0	0.8
6	1.3	1.6
7	1.5	2.2
8	1.8	2.2

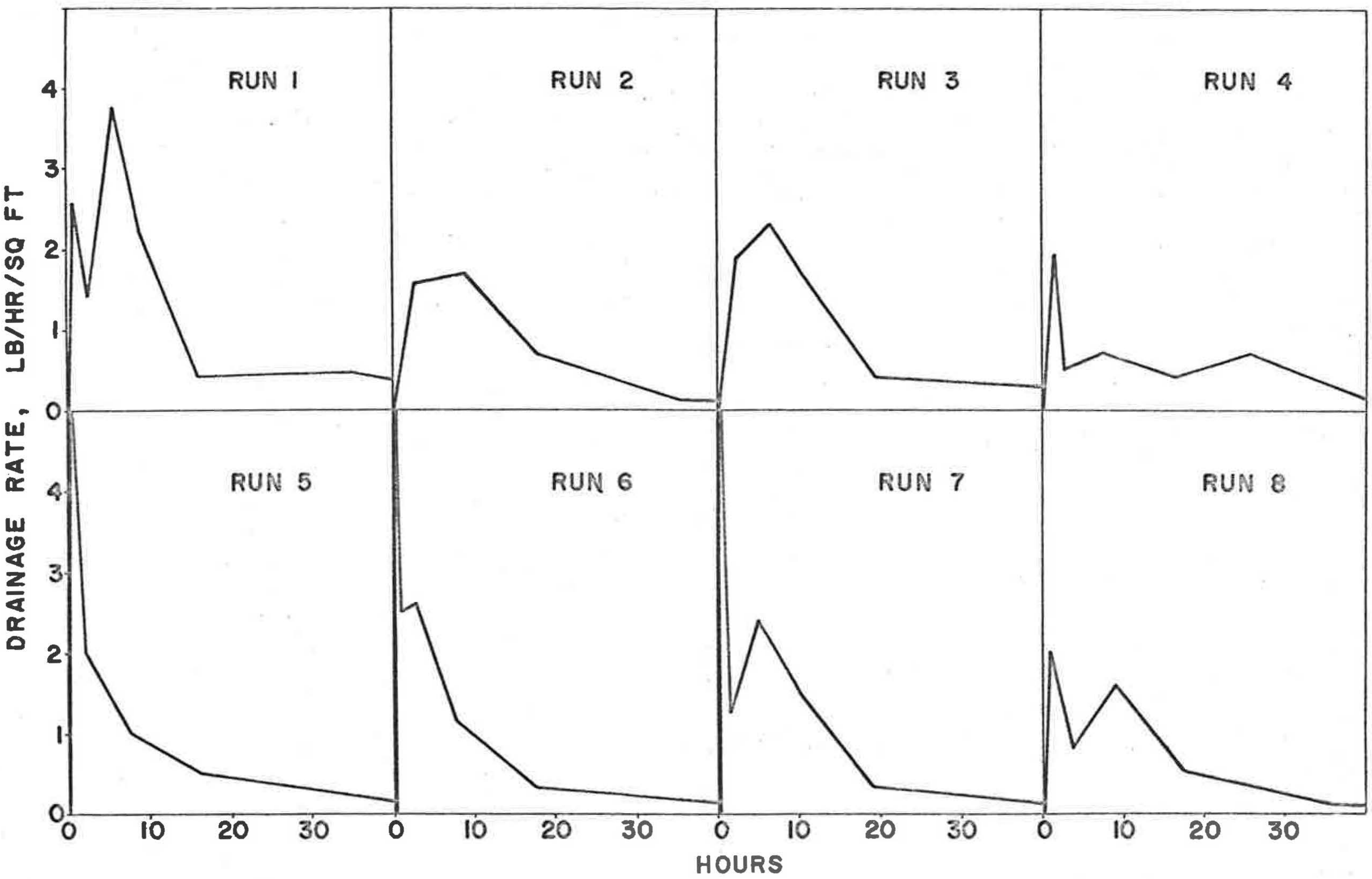

FIGURE 9. DRAINAGE RATE VERSUS TIME FOR OPEN, DRAINED MODELS

The measurement of sludge surface recession was not found to be of any particular value. After disregarding the values for Runs 2 and 3 due to differences in environmental conditions, it was found that the ultimate depth of sludge was not directly determined by initial or final moisture content, ultimate drainage, total evaporative loss, or ΔT. More detailed information covering sludge surface recession may be found in Tables B-5 and B-6, Appendix B.

VI. DISCUSSION

The evaporation loss from the free water surface did not approximate the loss from Model F, the open, nondrained model (Table VIII, p.42). The sludge to water evaporation ratio for Runs 1 and 4 through 8 averaged 1.40 while the ratio for Runs 2 and 3, which were conducted under different conditions, averaged 0.84. A sludge to water evaporation ratio significantly differing from unity is not in agreement with values reported in the literature (11, 12), except by Quon and Ward (6). It is felt that scale effects could, at least partially, have been involved in producing these ratios. The beaker used to determine evaporation losses from a free water surface had an inside cross-sectional area of 16.6 sq in. (107 sq cm) compared to an inside cross-sectional area of 64 sq in. (413 sq cm) for Model F. An additional interference could have been caused by the fact that the free water surface was not at the same elevation in the incubator as the sludge surface in Model F. Based upon Quon and Ward's study (6), it seems likely that the change in environmental conditions for each run may also have affected the sludge to water evaporation ratios. Using their data shown in Table II (p.16), the author found that their sludge to water evaporation ratio varied from 0.34 to 1.14. As was true in this investigation, the author did not find a relationship between the ratios calculated from their data and the parameter ΔT.

It was not possible to determine the intermediate evaporation rates from the open, drained models which occurred during the runs. This was due, primarily, to two factors. The sensitivity of the beam balance was inadequate for determining the day to day evaporative weight losses of the sludge as moisture content decreased; this was particularly true with runs performed under humid conditions. The second factor was the necessity of accounting for the drained water which was periodically discarded as it accumulated in the drainage trays. The drainage was determined volumetrically by reading a scale placed within the tray. An error in reading the depth of the drained liquid of 1/32 in. (0.09 cm) would have produced an evaporative weight error of approximately 2.2 oz (64.4 g) for Models A through D. This small amount is insignificant in relation to drainage, but under humid conditions with low evaporative potentials would represent a major error in the determination of evaporative loss. The removal of sludge samples from the models, even though this loss was theoretically accounted for by weighing the samples, could possibly have introduced an additional source of error. It is believed that reliable evaporation data could have been obtained if the drainage trays had been constructed deep enough to contain all the drainage which occurred during any run. This would have eliminated any chance for evaporative weight errors due to misreading drainage levels. To determine day to day evaporation rates under humid conditions, a more sensitive balance would be required.

Table XI summarizes the total drainage and evaporation losses from the open, drained models. In order to compare the results of the eight runs, these moisture losses are calculated as a percentage of the initial sludge moisture content in psf to eliminate variation due to differences in applied weight of sludge and initial percent moisture. Tables XII and XIII show total drainage losses from the closed, drained model (Model E) and total evaporative losses from the open, nondrained model (Model F) and a free water surface

TABLE XI

TOTAL MOISTURE LOSSES FROM THE OPEN, DRAINED MODELS

Run No.	Average Applied Weight of Sludge psf*	Initial Moisture Content %	Initial Water Content psf*	Drainage		Evaporation		Dewatering	
				Total psf*	% of Initial Water Content	Total psf*	% of Initial Water Content	Drainage + Evap. psf*	% of Initial Water Content
1	42.5	96.6	41.0	31.0	75.6	10.2	24.9	41.2	100.4
2	41.3	97.6	40.4	31.9	79.0	2.9	7.2	34.8	86.2
3	42.6	97.1	41.4	33.4	81.0	5.5	13.3	38.9	94.0
4	42.3	96.8	41.0	24.4	59.5	9.5	23.2	33.9	82.7
5	44.0	96.5	42.5	39.5	93.0	0.3	0.7	39.8	93.7
6	43.5	97.2	42.3	34.5	81.5	4.8	11.4	39.3	93.0
7	43.1	96.3	41.5	30.6	73.7	8.2	19.8	38.8	93.5
8	42.8	95.6	41.0	28.3	69.0	7.8	19.0	36.1	88.0

*Multiply by 4.88 to convert psf to kg/sq m.

TABLE XII

TOTAL DRAINAGE LOSS FROM THE CLOSED, DRAINED MODEL

Run No.	Applied Weight of Sludge psf*	Initial Moisture Content %	Initial Water Content psf*	Drainage	
				Total psf*	% of Initial Water Content
1	45.5	96.6	44.0	34.8	79.1
2	46.4	97.6	45.3	29.2	64.5
3	42.3	97.1	41.1	24.6	59.9
4	41.4	96.8	40.0	22.0	55.0
5	50.0	96.5	48.2	46.6	96.6
6	43.2	97.2	42.0	26.3	62.6
7	44.4	96.3	42.7	34.2	75.5
8	43.2	95.6	41.4	31.0	75.0

*Multiply by 4.88 to convert psf to kg/sq m.

TABLE XIII

TOTAL EVAPORATIVE LOSS FROM SLUDGE AND A FREE WATER SURFACE

Run No.	Open, Nondrained Model (Model F)					Free Water Surface		
	Applied Weight of Sludge psf*	Initial Moisture Content %	Initial Water Content psf*	Evaporation		Initial Weight of Water psf*	Evaporation	
				Total psf*	% of Initial Water Content		Total psf*	% of Initial Weight of Water
1	41.8	96.6	40.4	34.7	86.0	22.9	22.3	97.5
2	42.5	97.6	41.5	6.8	16.4	22.9	7.6	33.2
3	42.5	97.1	41.3	11.7	28.3	22.9	14.3	62.5
4	42.8	96.8	41.4	15.2	36.7	22.9	11.6	51.6
5	41.8	96.5	40.4	2.8	6.9	22.9	1.9	8.3
6	42.8	97.2	41.6	14.1	33.9	22.9	10.6	46.3
7	42.8	96.3	41.2	15.3	37.1	22.9	13.8	60.2
8	42.5	95.6	40.6	16.3	40.1	22.9	12.4	54.1

*Multiply by 4.88 to convert psf to kg/sq m.

calculated in the same manner. The evaporative loss shown in Table XI represents the average net loss from the three models after accounting for the weight of drainage and the sludge samples which were removed. This method was used to diminish the effects of errors in reading drainage. The total amounts of drainage shown are considered to be slightly low since any drainage which remained in the sand bed was not accounted for. However, all measurements of moisture loss were made in the same manner and the relationship of the runs to each other is felt to be reliable.

Columns 13 and 14 of Table X (p.45) which rank cumulative drainage and cumulative drainage as a percent of initial sludge moisture content by increasing order of magnitude, indicate that no direct relationship was found between total drainage from the open, drained models and the imposed environmental conditions shown. This was thought to be due to an interrelationship between drainage and evaporation and to the unintentional introduction of an additional variable, water viscosity, into the experiment. As the result of a widely varying dry bulb temperature during these studies, it appears that water viscosity could have been a significant factor affecting drainage and therefore evaporation.

Figure 10 shows the percentage moisture losses of the various models and the free water surface for Runs 1, 4, 5, 6, 7, and 8 plotted against ΔT. It will be noted that the total percentage dewatering of the open, drained models was relatively constant throughout the experiment while both drainage and evaporation from these same models varied widely and were inversely related. Water viscosity, which could be at least partially responsible for this relationship

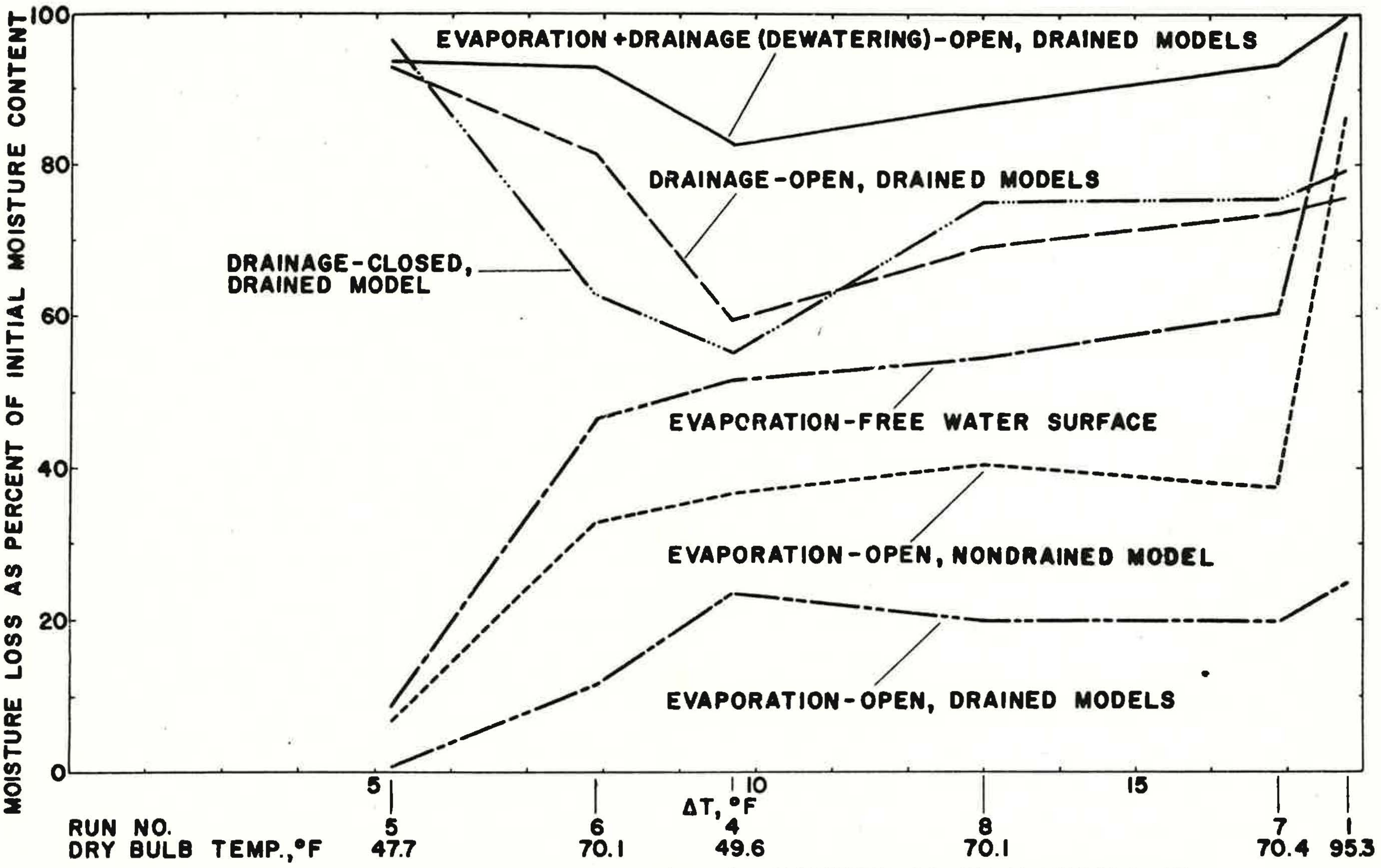

FIGURE 10. - MOISTURE LOSS AS PERCENT OF INITIAL MOISTURE CONTENT VERSUS ΔT.

between drainage and evaporation, varied from a high of 1.36 centipoises for Run 5 47.7 °F (8.7 °C) to a low of 0.71 centipoises for Run 1 95.3 °F (35.2 °C) (18, p.1652). The high drainage value for Run 5, which occurred even though this run had the highest viscosity, was probably due to the low evaporative potential of that run. Run 6 with its higher temperature and ΔT displayed decreased drainage and greater evaporation which would indicate that evaporative potential was of more significance than the decreased viscosity under the combination of conditions imposed. That evaporative potential is of greater significance than viscosity would seem to be confirmed by Runs 7 and 8 which were performed at about the same temperature as Run 6 and which had approximately the same amount of drainage. The drainage for Runs 6, 7, and 8 was 81.5, 73.7, and 69.0 percent, respectively. The greater drainage for Run 6 was probably due to the lower evaporative potential of that run. Run 4 which had the least drainage, had evaporative losses approaching that of Run 1. This can be explained by the low temperature of Run 4 which so hindered drainage as to allow for a considerable amount of evaporation at a ΔT of 9.7 °F (5.4 °C). It can be seen from Figure 10 that the combination of a large ΔT in conjunction with a high dry bulb temperature, as was the case with Run 1, provided for the greatest amount of dewatering although neither drainage nor evaporation considered separately was significantly greater than the values obtained from some of the other runs.

The effect of viscosity upon drainage is further indicated by the values obtained from the closed, drained model (Model E). The cover on this model effectively eliminated evaporation as a dewatering factor. Figure 10 indicates that the drainage from Model E varied directly with dry bulb temperature, except for Run 5. The high value obtained from Run 5 is not clearly understood but is felt to be a "freak" of the experiment which may have been caused by some undetermined physical or chemical property of the sludge used for this run. It should also be remembered that the data from Model E can not be considered as reliable as the average values obtained from the three open, drained models.

The literature review preceding this investigation did not indicate that previous investigators had considered viscosity when studying dewatering of sludge on drying beds where both drainage and evaporation were permitted. However, as nearly as can be determined, previous laboratory investigations of this nature have not been conducted over a wide temperature range. A narrow dry bulb temperature range would, of course, eliminate viscosity as a variable. Field investigations are not desirable for studying viscosity because of diurnal and seasonal temperature and climatic variations which would tend to mask viscosity effects.

Within the range of the environmental conditions imposed, sludge moisture content was not directly related to relative humidity as had been originally assumed. However, a nonlinear relationship was found to exist between sludge moisture content, time, ΔT, and ΔH. A nonlinear relationship was also found between the evaporation rates from a free water surface and the parameter ΔT. It is believed that a relationship also existed between ΔT and the evaporation rate of moisture from a sludge surface although Table X (p.45) did not definitely indicate a relationship for all six runs.

The experimental procedures used in this investigation are felt to be reliable, capable of giving reproducible results, and were relatively inexpensive. Although this experiment was performed in laboratory incubators, a less elaborate environmental control chamber could have been used if provisions for a controlled heat source were made. However, if it were necessary to extend the range of operational variables beyond the limits obtained in this investigation, more sophisticated and expensive equipment would be required.

Although the calculations used in this investigation to eliminate the variation in weight of applied sludge are considered to give reliable and comparable results, more accurate quantitative data could have been obtained if the model beds had been loaded on a weight or volume basis rather than on the basis of depth.

The moisture gradients of the open, drained models which developed within the sludge layers of the various runs were generally found to vary directly with time and ΔT over the 2-wk periods studied. If the runs had been extended in time until equilibrium conditions were reached, the moisture gradient for each run should have reached a maximum and then have tapered off to zero as evaporation losses from the sludge ceased. If present theory (11) concerning the establishment of a positive moisture gradient at the critical moisture content is correct, the continuous monitoring of a dewatering sludge to determine when this gradient begins may be of value in field investigations in determining when the falling rate drying period starts.

Although the investigation was not structured to include wind as an operational variable, it can only be concluded that wind did have a significant affect upon the sludge moisture content. Run 1 with a

ΔT of 17.8 °F had a final moisture content of 19.2 percent compared to Run 3 which had a ΔT of 26.2 °F and a final moisture content of 60.5 percent. Since both runs were performed at nearly the same dry bulb temperature it must be assumed that the absence of wind in the case of Run 3 was responsible for the difference in moisture content.

The dewatering curve (the sum of drainage and evaporation) from the open, drained models was found to be relatively flat (Figure 10). Although this curve did not cover the entire temperature and relative humidity range under which sludge might be dewatered on open beds, it did span a significant range. The shape of this curve may partially explain why the present "rule-of-thumb" design for sludge drying beds has been found to be adequate.

The interrelationship observed between drainage, evaporation, and viscosity raises some question as to the applicability of laboratory studies in which only one of the dewatering mechanisms is considered. Laboratory investigations should study drainage and evaporation simultaneously, if they are to adequately describe sludge behavior on drying beds in field situations.

VII. CONCLUSIONS

Within the range of environmental conditions studied in this investigation, the following conclusions are made:

1. The sludge moisture content was not directly related to relative humidity.
2. A relationship existed between the sludge moisture content, the evaporation rate from a free water surface, and the operational variables ΔT and ΔH.
3. Under a specific set of conditions, the sludge moisture content can be described as a function of time.
4. A relationship existed between the moisture gradient which developed within the sludge layer and ΔT and time.
5. Scale effects and/or environmental conditions affected the relationship between the rate of evaporation of moisture from a sludge surface and from a free water surface.
6. Wind significantly affected the removal of sludge moisture with time.
7. A relationship existed between drainage and evaporation which was affected by viscosity when the dry bulb temperature was variable.
8. Laboratory investigations should study drainage and evaporation simultaneously if they are to adequately describe sludge behavior on drying beds in field situations.

VIII. RECOMMENDATIONS FOR ADDITIONAL RESEARCH

It is felt that the computer can be an effective tool for the mathematical analysis of sludge dewatering data. With the aid of the computer, the researcher is free to enter as many controlled variables into his investigation as he has the time or desire to study.

Although ΔT has been shown to be an effective parameter controlling dewatering rates, more research is required to determine the influence of ΔT over greater time spans. Future investigations should be structured to obtain a wide range of ΔT at several dry bulb temperatures.

Future investigations on sludge dewatering should be preceded by an investigation into the suitability of soil moisture meters for measuring sludge moisture content.

Model beds should be dosed on a volume or weight basis rather than on the basis of depth to increase quantitative accuracy and to eliminate some calculations.

Additional operational variables which the author feels would be desirable to include in future research include initial moisture content, radiant energy, and wind velocity. Specific resistance should be included as an additional sludge characteristic and as a measure of viscosity with the test being performed at the same dry bulb temperature as the particular sludge dewatering experiment or run.

BIBLIOGRAPHY

1. McCarty, P. L., "Sludge Concentration--Needs, Accomplishments, and Future Goals," Jour. Water Poll. Control Fed., 38, 493 (1966).

2. Nebiker, J. H., Sanders, T. G., and Adrian, D. D., "An Investigation of Sludge Dewatering Rates," Jour. Water Poll. Control Fed., 41, R255 (1969).

3. Dalton, F. E., Stein, J. E., and Lynam, B. T., "Land Reclamation--A Complete Solution of the Sludge and Solids Disposal Problem," Jour. Water Poll. Control Fed., 40, 748 (1968).

4. Hinesly, T. D., and Sosewitz, B., "Digested Sludge Disposal on Crop Lands," Jour. Water Poll. Control Fed., 41, 470 (1969).

5. "Sludge Dewatering," Manual of Practice No. 20, Water Pollution Control Federation, Washington, D. C. (1969).

6. Quon, J. E., and Ward, G. B., "Convective Drying of Sewage Sludge," International Jour. Air and Water Poll., 9, 311 (1965).

7. Haseltine, T. R., "Measurement of Sludge Drying Bed Performance," Sew. and Ind. Wastes, 23, 1065 (1951).

8. Downes, J. R., "The Separation, Digestion, and Disposal of Sewage Solids," Sew. Works Jour., 3, 237 (1931).

9. Quon, J. E., and Johnson, G. M., "Drainage Characteristics of Digested Sludge," Jour. San. Eng. Div., Proc. Amer. Soc. Civil Engr., 92, SA2, 67 (1966).

10. Randall, C. W., and Koch, T. C., "Dewatering Characteristics of Aerobically Digested Sludge," Jour. Water Poll. Control Fed., 41, R215 (1969).

11. Nebiker, J. H., "Drying of Waste Water Sludge in the Open Air," Jour. Water Poll. Control Fed., 39, 608 (1967).

12. Quon, J. E., and Tamblyn, T. A., "Intensity of Radiation and Rate of Sludge Drying," Jour. San. Eng. Div., Proc. Amer. Soc. Civil Engr., 91, SA2, 17 (1965).

13. Jennett, J. C., and Santry, I. W., "Characteristics of Sludge Drying," Jour. San. Engr. Div., Proc. Amer. Soc. Civil Engr., 95, SA5, 849 (1969).

14. Rich. L. G., "Unit Operations of Sanitary Engineering," Wiley, New York (1961).

15. Marvin, C. F., "Psychrometric Tables for Obtaining the Vapor Pressure, Relative Humidity, and Temperature of the Dew Point," U. S. Dept. of Commerce, Weather Bureau (1941).

16. "Standard Methods for the Examination of Water and Wastewater," 12th Ed., Amer. Pub. Health Assn., New York, N. Y. (1965).

17. Faires, V. M., "Thermodynamics," Macmillian, 4th Ed., New York (1962).

18. "Handbook of Chemistry and Physics," 27th Ed., Chemical Rubber Publishing Co., Cleveland, Ohio (1943).

APPENDIX A

SPECIFICATION OF THE ENVIRONMENTAL CHAMBERS

TABLE A-1

INCUBATOR* SPECIFICATIONS

Incubator Model No.	Temperature Range	Width ft	Depth ft	Height ft	Wattage
704	ambient to 140 °F	4	4	7	925
704A	40 to 140 °F	4	4	7	1,150

*Lab-line Instruments, Inc., Melrose Park, Illinois.

APPENDIX B

DRYING PARAMETERS

TABLE B-1

PERCENT MOISTURE OF OPEN, DRAINED MODELS

Time hr	Sample Point								Composite			
	Top Layer				Bottom Layer							
	Models											
	B	C	D	avg	B	C	D	avg	B	C	D	avg
Run 1												
0.0												96.6
3.2									94.1	95.5	95.1	94.9
6.2									95.3	94.1	93.4	94.3
21.8									86.7	87.1	87.0	86.7
53.0	75.8	76.9	78.8	77.2	85.8	87.3	86.5	86.5	84.5	84.3	84.7	84.6
77.0	72.4	81.3	77.1	76.9	83.9	84.4	87.0	85.1	80.9	82.3	84.3	82.5
102.0	71.6	74.6	75.7	74.1	80.5	81.8	82.9	81.7	77.4	78.4	82.6	79.4
125.0	66.2	59.4	69.8	65.2	80.8	79.8	79.2	79.9	78.0	75.3	76.6	76.6
168.0	58.6	59.9	59.0	59.2	75.6	75.6	74.2	75.2	68.4	69.4	71.1	69.6
216.1	42.0	54.2	46.3	47.5	67.4	71.1	71.6	70.0	66.1	64.1	70.1	66.8
264.0	14.5	45.6	46.0	35.4	51.5	57.4	71.7	60.2	37.6	53.8	64.2	51.9
316.5	13.2	26.7	7.5	15.8	35.4	60.3	7.4	34.4	16.4	33.2	8.0	19.2
Run 2												
0.0												97.6
22.6									90.2	91.5	91.4	91.1
49.8									86.8	87.0	88.4	87.3
94.8	83.9	83.1	84.7	83.9	83.2	82.5	84.0	83.2	83.6	82.8	84.6	83.7
146.3	82.4	82.4	83.0	82.6	82.1	79.9	81.0	81.0	82.7	81.8	82.2	82.2
218.8	78.7	78.7	79.8	79.1	78.8	76.2	76.2	77.1	79.6	77.3	80.4	79.1
264.9	77.2	77.0	78.8	77.7	78.0	76.9	78.0	77.6	79.0	77.1	78.2	78.1
307.6	76.3	74.8	78.0	75.7	77.4	75.3	79.2	77.4	76.4	76.1	78.1	76.9
383.1	72.8	72.8	76.3	74.0	73.7	72.8	76.1	74.2	78.1	73.1	76.2	75.8

TABLE B-1, CONTINUED

PERCENT MOISTURE OF OPEN, DRAINED MODELS

Time hr	Sample Point								Composite			
	Top Layer				Bottom Layer							
	Models											
	B	C	D	avg	B	C	D	avg	B	C	D	avg
Run 3												
0.0												97.1
10.0									95.1	91.4	95.7	94.0
25.0									89.4	85.6	89.6	88.2
73.8	83.6	79.1	83.6	82.1	83.2	80.4	83.0	82.2	83.4	80.6	82.9	82.3
128.1	71.4	69.7	74.5	71.9	77.0	74.0	77.6	76.2	76.1	73.5	72.2	73.9
177.8	67.2	57.0	65.4	63.2	72.1	70.2	72.8	71.7	71.1	64.2	68.5	67.9
346.3	56.8	51.1	55.4	54.4	66.2	64.6	68.9	66.6	58.8	60.6	62.0	60.5
Run 4												
	Models											
	A	C	D	avg	A	C	D	avg	A	C	D	avg
0.0												96.8
3.5									99.2	97.8	99.2	98.7
9.5									97.5	95.9	95.1	76.2
23.5									95.4	95.8	94.0	95.1
27.5									94.0	94.6	93.0	93.8
51.7	86.6	87.2	87.9	87.2	87.2	88.6	88.2	87.9	86.7	88.7	88.4	87.9
76.0	84.6	87.7	85.8	84.4	84.0	88.9	87.0	86.7	84.9	87.8	87.2	86.6
123.5	76.6*	85.1	82.9	84.0	82.4	86.0	84.5	84.3	82.3	85.8	85.4	84.5
147.5	80.4	84.5	82.8	82.6	83.1	84.8	82.9	83.6	81.0	84.1	84.3	83.1
197.0	56.9*	77.9	71.7	74.8	53.2*	78.7	76.0	77.3	70.6*	79.0	78.9	79.0
238.5	73.0	75.9	70.9	73.3	77.4	79.5	76.6	77.8	78.0	76.4	68.3*	77.2
277.0	69.6	74.8	68.8	71.1	75.8	77.9	76.6	76.8	75.1	73.8	74.2	74.4
324.3	66.3	68.5	63.7	66.2	69.5	74.2	69.9	71.2	34.9*	73.2	57.4	65.3

*Indicates values not used to determine arithmetic avg.

TABLE B-1, CONTINUED

PERCENT MOISTURE OF OPEN, DRAINED MODELS

Time hr	Sample Point								Composite			
	Top Layer				Bottom Layer							
	Models											
	B	C	D	avg	B	C	D	avg	B	C	D	avg
Run 5												
0.0												96.5
2.7									95.4	97.0	93.8	95.4
5.2									96.0	96.4	95.3	95.9
20.2									92.9	94.6	81.2	89.6
51.3	87.2	87.8	83.0	86.0	88.3	89.4	81.6	86.5	88.0	88.6	78.9	85.2
76.2	84.6	86.0	80.6	83.7	79.1	84.6	65.6*	81.8	83.7	85.8	77.3	82.3
97.9	82.7	83.4	78.0	81.3	81.4	81.5	74.4	79.1	82.0	82.2	79.2	81.1
166.9	81.8	81.2	80.5	81.2	78.0	80.6	77.2	78.6	80.9	81.5	76.8	79.8
220.4	81.2	82.7	78.5	80.8	81.0	77.7	75.1	77.9	81.2	81.6	77.0	80.0
289.8	79.8	80.3	78.6	79.6	79.0	78.8	79.9	79.2	79.2	80.1	76.3	78.6
315.9	78.4	79.9	78.6	78.9	78.6	78.9	74.4	77.4	79.0	79.6	77.4	78.7
Run 6												
0.0												97.2
3.5									95.7	94.6	96.1	95.5
5.8									93.9	95.6	95.1	94.9
22.6									87.3	90.2	93.6	90.4
51.5	82.4	84.4	87.4	84.8	83.0	83.8	88.4	85.0	82.6	84.9	88.6	85.4
77.5	81.6	82.3	85.8	83.3	80.9	81.0	86.2	82.7	81.0	81.4	86.1	82.9
99.7	80.5	81.0	83.2	81.6	80.3	80.0	83.8	81.4	79.9	81.0	83.5	81.6
124.2	78.7	80.7	81.1	80.2	79.9	80.4	82.1	80.8	79.4	79.3	81.9	80.2
167.2	77.4	78.7	80.9	79.0	78.4	80.0	80.5	79.7	76.2	77.6	82.9	78.9
220.2	67.4	74.8	75.1	72.4	75.2	77.5	79.7	77.5	73.9	77.3	78.8	76.7
268.2	69.7	70.0	78.0	72.6	75.3	74.6	80.0	76.6	72.4	73.3	72.3	72.7
314.7	62.2	64.7	72.6	66.2	71.6	72.6	76.7	73.6	67.6	68.6	75.5	70.6

*Indicates values not used to determine arithmetic avg.

TABLE B-1, CONTINUED

PERCENT MOISTURE OF OPEN, DRAINED MODELS

Time hr	Sample Point								Composite			
	Top Layer				Bottom Layer							
	Models											
	B	C	D	avg	B	C	D	avg	B	C	D	avg
Run 7												
0.0												96.3
6.8									93.8	92.2	92.6	92.9
12.1									93.2	89.1	90.8	91.1
25.8									86.1	88.0	87.5	87.2
49.0	84.5	84.2	82.7	83.8	85.1	84.7	84.1	84.7	84.1	84.7	82.9	83.9
71.4	78.6	79.0	75.2	77.6	82.6	81.3	81.6	81.8	81.8	81.7	81.2	81.6
98.8	78.0	78.7	71.4	76.0	80.0	81.0	80.5	80.5	78.6	81.0	78.0	79.2
125.9	64.9*	75.1	66.1	70.6	77.9	80.6	75.1	77.9	76.1	73.3	77.9	75.8
149.6	72.6	73.2	62.7	69.5	79.1	79.2	76.2	78.2	78.0	78.4	72.1	76.2
204.3	--	64.8	52.5	58.6	75.7	77.3	73.6	75.5	65.3	68.7	68.9	67.7
245.8	58.0	57.0	54.4	56.5	69.9	72.8	72.6	71.8	62.5	60.4	53.3	58.7
317.2	--	--	--	--	--	--	--	--	69.6	65.6	68.1	67.8
Run 8												
0.0												95.6
3.2									94.6	95.3	96.2	95.4
12.5									89.0	88.9	89.6	89.2
22.8									92.4	89.5	91.3	91.1
51.8	84.5	82.6	85.8	84.3	86.8	85.2	89.0	87.0	86.7	--	85.8	86.3
77.2	82.4	79.3	82.1	81.3	87.6	87.2	87.7	87.5	84.2	84.6	86.4	85.0
101.5	80.1	76.7	78.6	78.5	83.7	83.8	83.3	83.6	82.5	81.6	82.7	82.2
146.7	78.3	73.6	74.4	75.4	81.4	81.0	80.1	80.8	81.6	80.9	75.2	79.3
191.2	77.8	71.6	75.5	75.0	80.4	77.5	80.2	79.4	80.4	75.7	76.4	77.5
241.8	72.4	68.4	64.5	68.4	79.2	78.9	77.4	78.5	74.8	75.4	75.1	75.1
316.7	58.2	59.7	56.1	58.1	75.0	74.8	73.0	74.3	59.9	64.8	66.5	63.7

*Indicates value not used to determine arithmetic avg.

TABLE B-2

PERCENT MOISTURE OF CLOSED, DRAINED MODEL E

RUN 1

Time hr	Sample Point		Composite
	Top Layer	Bottom Layer	
0.0			96.6
3.2			95.7
6.2			91.6
21.8			87.2
53.0	84.6	85.1	85.3
77.0	85.0	85.6	84.8
102.0	84.6	84.5	85.1
125.0	84.3	84.3	84.4
168.0	83.9	81.4	84.0
216.1	82.5	83.8	83.5
264.0	82.3	81.3	76.8
316.5	78.3	81.1	81.8

RUN 2

Time hr	Sample Point		Composite
	Top Layer	Bottom Layer	
0.0			97.6
22.6			88.5
49.8			84.9
94.8	83.5	82.7	83.0
146.3	82.3	80.8	81.8
218.8	80.8	80.1	81.2
264.9	80.8	79.4	80.9
307.6	79.9	78.7	78.7
383.1	79.1	78.2	79.5

RUN 3

Time hr	Top Layer	Bottom Layer	Composite
0.0			97.1
10.0			91.5
25.0			87.1
73.8	83.6	83.7	84.3
128.1	83.9	82.3	83.1
177.8	83.0	82.2	82.3
346.3	82.7	80.6	81.6

RUN 4

Time hr	Top Layer	Bottom Layer	Composite
0.0			96.8
3.5			99.2
9.5			96.4
23.5			94.1
27.5			92.1
51.7	86.3	86.4	86.7
76.0	85.6	86.0	84.7
123.5	84.2	83.6	83.5
147.5	83.8	83.0	83.8
197.0	77.4	77.0	79.4
238.5	83.0	81.4	81.9
277.0	81.9	80.4	80.7
324.3	79.4	80.2	79.8

RUN 5

Time hr	Top Layer	Bottom Layer	Composite
0.0			96.5
2.7			93.5
5.2			93.1
20.2			84.6
51.3	83.4	81.9	81.8
76.2	80.8	75.6	73.4
97.9	--	88.9	77.7
166.9	80.2	65.3	75.9
220.4	80.7	80.2	80.1
289.8	76.8	76.3	79.1
315.9	80.3	73.8	76.4

RUN 6

Time hr	Top Layer	Bottom Layer	Composite
0.0			97.2
3.5			94.9
5.8			93.5
22.6			84.7
51.5	83.8	81.5	82.9
77.5	83.5	81.4	82.3
99.7	82.3	80.9	81.8
124.2	82.9	80.8	81.6
167.7	82.1	81.1	81.3
220.2	81.4	79.6	81.0
268.2	81.3	79.0	80.7
314.7	79.9	78.4	79.7

TABLE B-2, CONTINUED

PERCENT MOISTURE OF CLOSED, DRAINED MODEL E

RUN 7			
Time hr	Sample Point		Composite
	Top Layer	Bottom Layer	
0.0			96.3
6.8			90.6
12.1			88.5
25.8			85.8
49.0	84.9	83.3	84.8
71.4	84.9	82.8	83.3
98.8	84.5	81.4	81.8
125.9	--	82.5	83.1
149.6	83.8	81.7	82.7
204.3	83.0	79.5	81.5
245.8	83.4	82.8	82.7
317.2	--	--	81.3

RUN 8			
Time hr	Sample Point		Composite
	Top Layer	Bottom Layer	
0.0			95.6
3.2			96.3
12.5			88.9
22.8			88.3
51.8	85.6	86.0	85.7
77.2	85.7	86.4	85.4
101.5	85.1	85.1	84.8
146.7	84.4	83.8	84.3
191.2	83.3	84.1	84.3
241.8	82.8	82.0	82.8
316.7	83.1	81.7	82.9

TABLE B-3

DRAINAGE OF OPEN, DRAINED MODELS

Time hr		Cumulative Drainage psf				Drainage as Percent of Total Drainage				Drainage Rates psf/hr			
Elapsed	Interval	Models											
		A	C	D	avg	A	C	D	avg	A	C	D	avg
RUN 1													
0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
	1.3									2.4	2.6	2.8	2.6
1.3		3.1	3.4	3.7	3.4	10.3	10.9	11.9	11.0				
	2.8									1.5	1.1	1.6	1.4
4.1		7.4	6.5	8.3	7.4	24.4	22.7	26.6	24.6				
	2.2									3.6	3.5	4.4	3.8
6.3		15.4	14.1	17.9	15.8	50.7	44.5	57.8	51.0				
	3.7									2.2	2.9	1.8	2.2
10.0		23.4	24.5	24.5	24.1	77.0	78.2	78.9	78.0				
	12.2									0.4	0.4	0.3	0.4
22.2		28.2	29.1	28.2	28.5	93.0	92.7	90.8	92.2				
	31.6									0.06	0.06	0.06	0.5
53.8		30.0	30.4	30.3	30.2	99.1	97.3	97.2	97.9				
	23.7									0.02	0.02	0.02	0.02
77.5		30.4	31.1	30.7	30.7	100.0	99.1	98.6	99.2				
	25.0									0.00	0.01	0.02	0.01
102.5		30.4	31.4	31.1	31.0		100.0	100.0	100.0				

TABLE B-3, CONTINUED

DRAINAGE OF OPEN, DRAINED MODELS

Time hr		Cumulative Drainage psf				Drainage as Percent of Total Drainage				Drainage Rates psf/hr			
Elapsed	Interval	Models											
		B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 2													
0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
	5.2									1.8	1.5	1.4	1.6
5.2		9.1	7.9	7.4	8.1	29.6	25.5	22.0	25.7				
	7.9									1.9	1.4	1.7	1.7
13.1		24.4	18.8	21.1	21.4	75.9	60.0	62.7	66.2				
	9.5									0.3	0.8	0.9	0.7
22.6		27.9	26.2	29.6	27.9	90.7	83.6	88.1	87.5				
	29.9									0.06	0.2	0.1	0.1
52.5		29.6	31.1	32.8	31.2	96.3	99.1	97.5	97.6				
	43.7									0.01	0.00	0.009	0.007
96.2		30.2	31.1	33.2	31.5	98.1	99.1	98.7	98.6				
	48.8									0.002	0.000	0.008	0.002
145.0		30.3	31.1	33.6	31.6	98.6	99.1	100.0	99.2				
	75.9									0.007	0.004	0.000	0.004
220.9		30.8	31.4	33.6	31.9	100.0	100.0		100.0				

TABLE B-3, CONTINUED

DRAINAGE OF OPEN, DRAINED MODELS

Time hr		Cumulative Drainage psf				Drainage as Percent of Total Drainage				Drainage Rates psf/hr			
Elapsed	Interval	Models											
		B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 3													
0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
	5.0									1.7	2.6	1.5	1.9
5.0		8.5	13.1	7.4	9.7	22.2	42.6	23.6	29.5				
	3.4									2.0	2.5	2.4	2.3
8.4		15.4	21.6	15.4	17.5	40.0	70.4	49.1	53.2				
	4.6									2.0	1.1	2.0	1.6
13.0		24.5	26.8	24.4	25.2	63.7	87.0	79.1	76.6				
	11.5									0.5	0.2	0.4	0.4
24.5		29.9	29.3	29.0	29.4	77.8	95.4	92.7	88.6				
	49.0									0.03	0.03	0.03	0.03
73.5		31.3	30.7	30.7	30.9	81.5	100.0	98.2	93.2				
	55.9									0.1	0.00	0.01	0.04
129.4		38.3	30.7	31.3	33.4	100.0		100.0	100.0				

TABLE B-3, CONTINUED

DRAINAGE OF OPEN, DRAINED MODELS

Time hr		Cumulative Drainage psf				Drainage as Percent of Total Drainage				Drainage Rates psf/hr			
		Models											
Elapsed	Interval	B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 4													
0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
	3.2									1.8	1.8	2.1	1.9
3.2		5.7	5.7	6.8	6.1	23.5	23.0	28.2	24.9				
	2.3									0.7	0.5	0.4	0.5
5.5		7.4	6.8	7.7	7.3	30.6	27.6	31.8	30.0				
	4.0									0.8	0.4	0.8	0.7
9.5		10.5	8.5	11.1	10.0	43.5	34.5	45.9	41.3				
	14.5									0.6	0.2	0.2	0.4
24.0		19.1	12.0	14.5	15.2	78.8	48.3	60.0	62.4				
	4.1									0.3	1.2	0.5	0.7
28.1		20.2	16.9	16.5	17.9	83.5	54.0	68.2	68.6				
	24.9									0.1	0.1	0.2	0.1
53.0		23.4	19.4	21.6	21.5	96.5	78.2	89.4	88.0				
	24.5									0.02	0.1	0.08	0.08
77.5		23.9	22.8	23.6	23.4	98.9	92.0	97.6	96.1				
	47.0									0.006	0.4	0.000	0.01
124.5		24.2	24.5	23.6	24.1	100.0	98.8	97.6	98.8				
	24.0									0.000	0.000	0.02	0.008
148.5		24.2	24.5	24.2	24.3		98.8	100.0	99.6				
	91.0									0.000	0.003	0.000	0.001
239.5		24.2	24.8	24.2	24.4		100.0		100.0				

TABLE B-3, CONTINUED

DRAINAGE OF OPEN, DRAINED MODELS

Time hr		Cumulative Drainage psf				Drainage as Percent of Total Drainage				Drainage Rates psf/hr			
Elapsed	Interval	Models											
		B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 5													
0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
	0.2									28.5	25.5	50.5	35.0
0.2		5.7	5.1	10.1	7.0	15.2	13.7	24.2	17.7				
	0.2									11.5	8.5	25.0	15.0
0.4		8.0	6.8	15.1	10.0	21.2	18.3	34.6	24.7				
	0.5									5.0	5.2	6.8	5.6
0.9		10.5	9.4	18.5	12.8	28.0	25.1	42.5	31.9				
	3.3									1.6	1.7	2.3	2.0
4.2		15.7	15.1	26.2	19.3	41.7	40.3	60.1	47.4				
	7.0									1.3	1.0	0.9	1.0
11.2		24.5	22.2	32.8	26.5	65.2	59.3	75.2	66.6				
	10.2									0.6	0.4	0.6	0.5
21.4		30.2	26.0	38.8	31.7	80.3	69.2	88.9	74.4				
	31.0									0.2	0.2	0.08	0.2
52.4		36.5	33.0	41.2	36.9	97.0	88.2	94.8	93.3				
	43.9									0.01	0.08	0.04	0.04
96.3		37.1	36.5	43.0	38.8	98.5	97.3	98.7	98.2				
	70.6									0.007	0.01	0.000	0.007
166.9		37.6	37.4	43.0	39.3	100.0	100.0	98.7	99.6				
	53.5									0.000	0.000	0.01	0.004
220.4		37.6	37.4	43.6	39.5			100.0	100.0				

TABLE B-3, CONTINUED

DRAINAGE OF OPEN, DRAINED MODELS

Time hr		Cumulative Drainage psf				Drainage as Percent of Total Drainage				Drainage Rates psf/hr			
		Models											
Elapsed	Interval	B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 6													
0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
	0.3									18.0	18.0	20.0	19.0
0.3		5.4	5.4	6.0	5.6	16.5	15.8	18.6	17.0				
	1.0									3.2	1.2	3.1	2.5
1.3		8.6	6.6	9.1	8.1	26.1	19.1	28.3	24.5				
	3.0									2.7	2.5	2.5	2.6
4.3		16.8	14.0	16.5	15.8	51.3	40.7	51.3	47.8				
	8.9									1.5	1.1	0.8	1.1
13.2		30.4	24.2	23.3	26.0	93.0	70.5	72.6	78.7				
	9.7									0.2	0.4	0.4	0.3
22.9		32.1	27.9	26.8	28.9	98.2	81.3	83.2	87.6				
	29.3									0.0	0.2	0.2	0.2
52.2		32.1	32.6	32.2	32.3	98.2	95.0	88.1	93.7				
	26.1									0.01	0.05	0.10	0.05
78.3		32.5	33.8	34.7	33.7	99.1	98.3	95.0	96.8				
	22.1									0.00	0.00	0.04	0.01
100.4		32.5	33.8	35.5	33.9	99.1	98.3	97.3	97.9				
	24.5									0.00	0.01	0.02	0.01
124.9		32.5	34.1	36.1	34.2	99.1	99.2	98.9	99.1				
	43.5									0.002	0.002	0.005	0.003
168.4		32.6	34.2	36.3	34.3	99.6	99.6	99.4	99.5				
	52.1									0.002	0.002	0.004	0.003
220.5		32.7	34.3	36.5	34.5	100.0	100.0	100.0	100.0				

TABLE B-3, CONTINUED

DRAINAGE OF OPEN, DRAINED MODELS

Time hr		Cumulative Drainage psf				Drainage as Percent of Total Drainage				Drainage Rates psf/hr			
		Models											
Elapsed	Interval	B	C	D	avg	B	C	D	avg	B	C	D	avg
						RUN 7							
0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
	0.6									5.2	5.7	5.2	5.3
0.6		3.1	3.4	3.1	3.2	11.0	10.8	9.9	10.6				
	2.4									1.3	1.2	1.1	1.2
3.0		6.3	6.3	5.7	6.1	21.9	19.8	17.9	19.9				
	4.1									2.1	2.8	2.2	2.4
7.1		14.8	17.9	14.8	15.8	51.7	56.7	46.6	51.7				
	4.8									1.3	1.6	1.5	1.5
11.9		21.1	25.6	22.2	23.3	73.6	81.1	70.0	74.9				
	14.3									0.3	0.3	0.5	0.3
26.2		25.4	29.4	29.0	27.9	88.6	92.8	91.5	91.0				
	24.7									0.1	0.06	0.09	0.09
50.9		27.9	30.8	31.3	30.0	97.5	97.3	98.7	97.8				
	22.6									0.01	0.01	0.00	0.009
73.5		28.2	31.1	31.3	30.2	98.5	98.2	98.7	98.5				
	25.7									0.004	0.01	0.008	0.008
99.2		28.3	31.4	31.5	30.4	99.0	98.6	99.1	98.9				
	50.6									0.000	0.004	0.002	0.002
149.8		28.3	31.6	31.6	30.5	99.0	100.0	99.6	99.5				
	55.0									0.005	0.000	0.002	0.002
204.8		28.6	31.6	31.7	30.6	100.0		100.0	100.0				

TABLE B-3, CONTINUED

DRAINAGE OF OPEN, DRAINED MODELS

Time hr		Cumulative Drainage psf				Drainage as Percent of Total Drainage				Drainage Rates psf/hr			
		Models											
Elapsed	Interval	B	C	C	avg	B	C	D	avg	B	C	D	avg
RUN 8													
0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
	1.5									1.3	2.3	2.5	2.0
1.5		2.0	3.4	3.7	3.0	8.9	11.8	12.2	11.0				
	4.8									1.1	1.0	1.1	1.1
6.3		7.3	8.1	8.8	8.1	28.4	28.1	29.0	28.8				
	5.9									0.9	1.9	1.9	1.6
12.2		12.6	19.1	20.1	17.3	49.1	66.3	66.1	60.5				
	11.0									0.5	0.5	0.5	0.5
23.2		17.6	24.5	26.0	22.7	68.5	85.0	85.6	79.6				
	29.6									0.2	0.1	0.09	0.1
52.8		23.9	27.4	28.6	26.6	93.0	95.1	94.2	94.1				
	25.7									0.04	0.03	0.03	0.03
78.5		25.0	28.2	29.5	27.6	97.4	97.9	97.1	97.5				
	13.8									0.01	0.00	0.007	0.007
92.3		25.2	28.2	29.6	27.5	98.1	97.9	97.5	97.8				
	57.0									0.004	0.005	0.005	0.005
149.3		25.4	28.5	29.9	28.0	98.9	98.9	98.4	98.7				
	42.5									0.007	0.007	0.01	0.007
191.8		25.7	28.8	30.4	28.3	100.0	100.0	100.0	100.0				

TABLE B-4

DRAINAGE OF CLOSED, DRAINED MODEL E

Time hr		Cumulative Drainage psf	Drainage as Percent of Total Drainage	Drainage Rates psf/hr
Elapsed	Interval			
RUN 1				
0.0		0.0	0.0	
	1.3			5.1
1.3		6.6	19.0	
	2.8			1.3
4.1		10.3	29.6	
	2.2			5.4
6.3		22.2	63.7	
	3.7			1.2
10.0		26.6	76.4	
	12.2			0.3
22.2		30.6	87.8	
	31.6			0.07
53.8		32.7	93.9	
	23.7			0.05
77.5		33.4	95.9	
	25.0			0.05
102.5		34.2	98.2	
	23.5			0.008
126.0		34.4	98.7	
	42.5			0.007
168.5		34.7	99.6	
	48.0			0.002
216.5		34.8	100.0	
RUN 2				
0.0		0.0	0.0	
	5.2			2.2
5.2		11.1	39.0	
	7.8			1.8
13.0		24.8	85.0	
	9.6			0.2
22.6		26.8	91.9	
	29.9			0.08
52.5		29.2	100.0	

TABLE B-4, CONTINUED

DRAINAGE OF CLOSED, DRAINED MODEL E

Time hr		Cumulative Drainage psf	Drainage as Percent of Total Drainage	Drainage Rates psf/hr
Elapsed	Interval			
RUN 3				
0.0		0.0	0.0	
	5.1			1.9
5.1		9.7	39.4	
	3.6			3.3
8.7		21.7	88.2	
	4.3			0.07
13.0		22.0	89.5	
	12.5			0.2
25.5		24.0	97.5	
	103.9			0.002
129.4		24.2	98.4	
	49.9			0.008
179.3		24.6	100.0	
RUN 4				
0.0		0.0	0.0	
	3.2			2.7
3.2		8.6	39.1	
	2.3			0.8
5.5		10.5	47.7	
	3.5			0.2
9.0		11.1	50.5	
	16.0			0.06
25.0		12.0	54.5	
	28.0			0.2
53.0		18.6	84.5	
	24.5			0.04
77.5		19.7	89.5	
	47.0			0.03
124.5		21.2	96.3	
	24.0			0.008
148.5		21.4	97.2	
	91.0			0.003
239.5		21.7	98.5	
	58.7			0.005
298.2		22.0	100.0	

TABLE B-4, CONTINUED

DRAINAGE OF CLOSED, DRAINED MODEL E

Time hr		Cumulative Drainage psf	Drainage as Percent of Total Drainage	Drainage Rates psf/hr
Elapsed	Interval			
RUN 5				
0.0		0.0	0.0	
	0.2			65.5
0.2		13.1	28.1	
	0.2			34.5
0.4		20.0	43.0	
	0.5			8.0
0.9		24.0	51.5	
	3.3			2.9
4.2		33.7	72.3	
	2.6			3.0
6.8		41.5	89.0	
	4.5			0.6
11.3		44.0	94.4	
	10.1			0.1
21.4		45.5	97.5	
	31.0			0.04
52.4		46.6	100.0	
RUN 6				
0.0		0.0	0.0	
	0.3			11.3
0.3		3.4	12.9	
	1.0			4.3
1.3		7.7	29.2	
	3.0			3.2
4.3		17.4	66.1	
	8.9			0.7
13.2		23.8	90.5	
	9.7			0.1
22.9		24.8	94.3	
	29.3			0.03
52.2		25.7	97.6	
	26.1			0.02
78.3		25.8	98.1	
	22.1			0.02
100.4		25.9	98.5	
	24.5			0.00
124.9		25.9	98.5	
	43.5			0.007
168.4		26.2	99.6	
	52.1			0.002
220.5		26.3	100.0	

TABLE B-4, CONTINUED

DRAINAGE OF CLOSED, DRAINED MODEL E

Time hr		Cumulative Drainage psf	Drainage as Percent of Total Drainage	Drainage Rates psf/hr
Elapsed	Interval			
RUN 7				
0.0		0.0	0.0	
	0.6			10.0
0.6		6.0	17.5	
	2.4			1.7
3.0		10.0	29.2	
	4.1			3.3
7.1		23.7	69.2	
	4.8			1.1
11.9		29.2	85.3	
	14.3			0.1
26.2		31.2	91.1	
	24.7			0.07
50.9		33.0	96.4	
	22.6			0.009
73.5		33.2	97.0	
	25.7			0.008
99.2		33.4	97.5	
	50.6			0.006
149.8		33.7	98.5	
	55.0			0.005
204.8		34.0	99.4	
	41.0			0.005
245.8		34.2	100.0	
RUN 8				
0.0		0.0	0.0	
	1.5			3.6
1.5		5.4	17.4	
	4.8			1.0
6.3		10.3	33.2	
	5.9			2.1
12.2		22.5	72.5	
	11.0			0.4
23.2		26.5	85.5	
	29.6			0.07
52.8		28.6	92.2	
	25.7			0.05
78.5		30.0	96.7	
	13.8			0.00
92.3		30.0	96.7	
	57.0			0.004
149.3		30.2	97.4	
	42.5			0.02
191.8		31.0	100.0	

TABLE B-5

SLUDGE SURFACE RECESSION OF OPEN, DRAINED MODELS

Time hr		Depth of Sludge in.				Surface Recession as Percent of Total Recession				Recession Rates in./hr			
		Models											
Elapsed	Interval	B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 1													
0.0		8.0	8.0	8.0	8.0	0.0	0.0	0.0	0.0				
	4.0									0.2	0.2	0.2	0.2
4.0		7.0	7.2	7.2	7.1	15.9	12.3	12.7	14.1				
	18.2									0.2	0.2	0.2	0.2
22.2		3.4	3.1	3.6	3.4	73.0	75.4	69.8	71.9				
	31.6									0.03	0.02	0.02	0.02
53.8		2.6	2.4	3.0	2.7	85.6	86.1	79.4	82.8				
	24.3									0.01	0.01	0.02	0.02
78.1		2.3	2.1	2.5	2.3	90.5	90.7	87.3	89.0				
	25.0									0.004	0.000	0.01	0.008
103.1		2.2	2.1	2.1	2.1	92.0	90.7	93.5	92.2				
	23.5									0.01	0.008	0.004	0.008
126.6		1.9	1.9	2.0	1.9	96.8	93.7	95.2	95.3				
	42.5									0.005	0.009	0.007	0.007
169.1		1.7	1.5	1.7	1.6	100.0	100.0	100.0	100.0				

TABLE B-5, CONTINUED

SLUDGE SURFACE RECESSION OF OPEN, DRAINED MODELS

Time hr		Depth of Sludge in.				Surface Recession as Percent of Total Recession				Recession Rates in./hr			
Elapsed	Interval	Models											
		B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 2													
0.0		8.0	8.0	8.0	8.0	0.0	0.0	0.0	0.0				
	5.2									0.3	0.3	0.3	0.3
5.2		6.4	6.6	6.6	6.5	22.9	20.3	20.6	21.7				
	17.4									0.2	0.2	0.2	0.2
22.6		2.2	3.0	2.8	2.7	82.9	75.5	76.5	76.9				
	29.9									0.02	0.04	0.04	0.03
52.5		1.6	1.7	1.7	1.7	91.5	91.4	92.6	91.3				
	43.7									0.007	0.005	0.005	0.007
96.2		1.3	1.5	1.5	1.4	95.7	94.2	95.6	95.6				
	48.8									0.000	0.000	0.005	0.000
145.0		1.3	1.5	1.4	1.4	95.7	94.2	97.1	95.6				
	75.9									0.003	0.003	0.001	0.003
220.9		1.1	1.3	1.3	1.2	98.6	97.0	98.5	98.5				
	112.2									0.0009	0.002	0.0009	0.0009
333.1		1.0	1.1	1.2	1.1	100.0	100.0	100.0	100.0				

TABLE B-5, CONTINUED

SLUDGE SURFACE RECESSION OF OPEN, DRAINED MODELS

Time hr		Depth of Sludge in.				Surface Recession as Percent of Total Recession				Recession Rates in./hr			
Elapsed	Interval	Models											
		B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 3													
0.0		8.0	8.0	8.0	8.0	0.0	0.0	0.0	0.0				
	5.1									0.3	0.5	0.3	0.4
5.1		6.3	5.7	6.4	6.1	24.3	34.8	22.9	27.8				
	3.3									0.4	0.4	0.4	0.4
8.4		4.9	4.4	5.0	4.8	44.3	54.5	42.9	46.4				
	4.6									0.4	0.2	0.3	0.3
13.0		3.2	3.5	3.4	3.4	68.5	68.1	65.7	66.7				
	11.5									0.1	0.07	0.1	0.1
24.5		2.0	2.7	2.2	2.3	85.7	80.2	82.9	82.6				
	49.0									0.01	0.02	0.01	0.01
73.5		1.4	1.9	1.5	1.6	94.3	92.4	92.9	92.8				
	55.9									0.007	0.005	0.007	0.007
129.4		1.0	1.6	1.1	1.2	100.0	97.0	98.5	98.5				
	49.9									0.000	0.004	0.002	0.002
179.3		1.0	1.4	1.0	1.1		100.0	100.0	100.0				

TABLE B-5, CONTINUED

SLUDGE SURFACE RECESSION OF OPEN, DRAINED MODELS

Time hr		Depth of Sludge in.				Surface Recession as Percent of Total Recession				Recession Rates in./hr			
		Models											
Elapsed	Interval	A	C	D	avg	A	C	D	avg	A	C	D	avg
RUN 4													
0.0		8.0	8.0	8.0	8.0	0.0	0.0	0.0	0.0				
	3.2									0.3	0.3	0.5	0.4
3.2		7.0	6.9	6.5	6.8	15.6	17.2	23.4	18.8				
	5.8									0.2	0.1	0.2	0.2
9.0		6.1	6.1	5.1	5.8	29.7	29.7	45.4	34.4				
	15.0									0.08	0.07	0.07	0.07
24.0		4.9	5.0	4.1	4.7	48.5	46.9	61.0	51.6				
	4.1									0.2	0.02	0.01	0.01
28.1		4.2	4.9	3.7	4.3	59.4	48.5	67.2	57.8				
	24.9									0.03	0.06	0.03	0.04
53.0		3.5	3.4	2.9	3.3	70.4	71.9	79.6	73.5				
	24.5									0.02	0.02	0.01	0.02
77.5		2.9	2.9	2.6	2.8	79.7	79.7	84.4	81.2				
	47.0									0.01	0.01	0.01	0.01
124.5		2.2	2.4	1.9	2.2	90.6	87.5	95.4	90.6				
	24.0									0.004	0.004	0.000	0.004
148.5		2.1	2.3	1.9	2.1	92.2	89.1	95.4	92.1				
	91.0									0.002	0.007	0.002	0.003
239.5		1.9	1.7	1.7	1.8	95.3	98.5	98.5	96.9				
	58.7									0.003	0.002	0.002	0.003
298.2		1.7	1.6	1.6	1.6	98.5	100.0	100.0	100.0				
	43.3									0.002	0.000	0.000	0.000
341.5		1.6	1.6	1.6	1.6	100.0							

TABLE B-5, CONTINUED

SLUDGE SURFACE RECESSION OF OPEN, DRAINED MODELS

Time hr		Depth of Sludge in.				Surface Recession as Percent of Total Recession				Recession Rates in./hr			
Elapsed	Interval	Models											
		B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 5													
0.0		8.0	8.0	8.0	8.0	0.0	0.0	0.0	0.0				
	0.9									1.9	1.7	3.0	2.2
0.9		6.3	6.5	5.3	6.0	24.7	22.1	37.5	28.6				
	3.3									0.2	0.3	0.4	0.3
4.2		5.6	5.5	4.0	5.0	34.8	36.8	55.5	43.0				
	17.2									0.2	0.1	0.1	0.1
21.4		3.0	3.5	1.9	2.8	58.0	66.2	84.6	74.3				
	31.0									0.03	0.03	0.006	0.02
52.4		2.2	2.5	1.7	2.1	84.0	80.9	87.5	84.3				
	43.9									0.02	0.02	0.005	0.01
96.3		1.5	1.6	1.5	1.5	94.2	94.1	90.2	92.9				
	71.9									0.003	0.004	0.006	0.004
168.2		1.3	1.3	1.1	1.2	97.1	98.5	95.7	97.2				
	52.9									0.005	0.003	0.008	0.005
221.1		1.1	1.2	0.8	1.0	100.0	100.0	100.0	100.0				

TABLE B-5, CONTINUED

SLUDGE SURFACE RECESSION OF OPEN, DRAINED MODELS

Time hr		Depth of Sludge in.				Surface Recession as Percent of Total Recession				Recession Rates in./hr			
		Models											
Elapsed	Interval	B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 6													
0.0		8.0	8.0	8.0	8.0	0.0	0.0	0.0	0.0				
	0.3									2.0	1.3	2.0	1.7
0.3		7.4	7.6	7.4	7.5	8.7	6.2	9.0	7.5				
	3.8									0.5	0.4	0.4	0.5
4.1		5.5	6.0	5.7	5.7	36.2	31.2	34.3	34.3				
	19.0									0.2	0.1	0.1	0.1
23.1		2.2	3.7	3.8	3.2	84.1	67.2	62.7	71.6				
	29.4									0.02	0.04	0.03	0.03
52.5		1.7	2.4	2.8	2.3	91.3	87.5	77.6	85.0				
	26.0									0.004	0.01	0.03	0.02
78.5		1.6	2.1	2.1	1.9	92.8	92.2	88.0	91.0				
	22.1									0.005	0.005	0.009	0.005
100.6		1.5	2.0	1.9	1.8	94.2	93.8	91.1	92.5				
	24.5									0.004	0.004	0.008	0.004
125.1		1.4	1.9	1.7	1.7	95.6	95.3	94.0	94.0				
	43.5									0.000	0.005	0.002	0.002
168.6		1.4	1.7	1.6	1.6	95.6	98.5	95.5	95.5				
	52.1									0.004	0.002	0.006	0.004
220.7		1.2	1.6	1.3	1.4	98.5	100.0	100.0	98.5				
	48.6									0.002	0.000	0.000	0.002
269.3		1.1	1.6	1.3	1.3	100.0			100.0				

TABLE B-5, CONTINUED

SLUDGE SURFACE RECESSION OF OPEN, DRAINED MODELS

Time hr		Depth of Sludge in.				Surface Recession as Percent of Total Recession				Recession Rates in./hr			
Elapsed	Interval	Models											
		B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 7													
0.0		8.0	8.0	8.0	8.0	0.0	0.0	0.0	0.0				
	3.0									0.07	0.07	0.2	0.1
3.0		7.8	7.8	7.4	7.7	3.0	3.1	9.2	4.6				
	8.9									0.3	0.4	0.3	0.4
11.9		4.8	4.1	4.6	4.5	47.8	61.0	52.3	53.8				
	14.6									0.1	0.06	0.09	0.08
26.5		3.4	3.2	3.3	3.3	68.6	75.0	72.3	72.3				
	47.0									0.03	0.02	0.02	0.02
73.5		2.2	2.3	2.2	2.2	86.5	89.1	89.2	89.2				
	25.7									0.008	0.008	0.008	0.008
99.2		2.0	2.1	2.0	2.0	89.5	92.2	92.3	92.3				
	27.0									0.000	0.007	0.004	0.004
126.2		2.0	1.9	1.9	1.9	89.5	95.3	93.9	93.9				
	23.6									0.008	0.000	0.008	0.004
149.8		1.8	1.9	1.7	1.8	92.5	95.3	96.9	95.5				
	55.0									0.004	0.004	0.000	0.002
204.8		1.6	1.7	1.7	1.7	95.5	98.5	96.9	96.9				
	41.0									0.007	0.002	0.005	0.005
245.8		1.3	1.6	1.5	1.5	100.0	100.0	100.0	100.0				

TABLE B-5, CONTINUED

SLUDGE SURFACE RECESSION OF OPEN, DRAINED MODELS

Time hr		Depth of Sludge in.				Surface Recession as Percent of Total Recession				Recession Rates in./hr			
		Models											
Elapsed	Interval	B	C	D	avg	B	C	D	avg	B	C	D	avg
RUN 8													
0.0		8.0	8.0	8.0	8.0	0.0	0.0	0.0	0.0				
	6.3									0.2	0.1	0.2	0.2
6.3		6.7	7.2	6.6	6.8	20.6	13.3	21.9	19.4				
	16.7									0.1	0.2	0.1	0.2
23.0		4.5	4.0	4.1	4.2	55.5	66.7	61.0	61.4				
	29.5									0.04	0.02	0.03	0.03
52.5		3.4	3.4	3.0	3.3	73.0	76.6	78.1	75.9				
	25.0									0.02	0.02	0.02	0.02
77.5		2.9	3.0	2.5	2.8	81.0	83.4	86.0	83.9				
	21.8									0.005	0.005	0.000	0.005
99.3		2.8	2.9	2.5	2.7	82.5	85.0	86.0	85.5				
	50.0									0.008	0.01	0.006	0.008
149.3		2.4	2.4	2.2	2.3	88.9	93.3	90.6	92.0				
	42.5									0.01	0.005	0.005	0.007
191.8		1.9	2.2	2.0	2.0	96.8	96.6	93.7	96.8				
	50.7									0.000	0.002	0.004	0.002
242.5		1.9	2.1	1.8	1.9	96.8	98.4	96.9	98.5				
	74.2									0.003	0.001	0.003	0.001
316.7		1.7	2.0	1.6	1.8	100.0	100.0	100.0	100.0				

TABLE B-6

SLUDGE SURFACE RECESSION OF CLOSED, DRAINED MODEL E

Time hr		Depth of Sludge in.	Recession as Percent of Total	Recession Rates in./hr
Elapsed	Interval			
RUN 1				
0.0		8.0	0.0	
	4.0			0.2
4.0		7.1	15.2	
	18.2			0.2
22.2		3.5	76.3	
	31.6			0.02
53.8		2.9	86.5	
	24.3			0.008
78.1		2.7	89.9	
	25.0			0.01
103.1		2.4	94.9	
	23.5			0.01
126.6		2.1	100.0	
RUN 2				
0.0		8.0	0.0	
	5.2			0.4
5.2		6.0	29.0	
	17.4			0.2
22.6		3.0	58.0	
	29.9			0.04
52.5		1.9	88.5	
	43.7			0.01
96.2		1.4	95.7	
	48.8			0.004
145.0		1.3	97.1	
	75.9			0.001
220.9		1.2	98.6	
	112.2			0.0009
333.1		1.1	100.0	

TABLE B-6, CONTINUED

SLUDGE SURFACE RECESSION OF CLOSED, DRAINED MODEL E

Time hr		Depth of Sludge in.	Recession as Percent of Total	Recession Rates in./hr
Elapsed	Interval			
RUN 3				
0.0		8.0	0.0	
	5.1			0.3
5.1		6.6	22.6	
	8.1			0.4
13.0		3.6	71.0	
	11.5			0.06
24.5		2.9	82.2	
	49.0			0.02
73.5		2.1	95.1	
	55.9			0.00
129.4		2.1	95.1	
	50.4			0.006
179.8		1.8	100.0	
RUN 4				
0.0		8.0	0.0	
	3.2			0.3
3.2		7.0	18.2	
	5.8			0.2
9.0		6.1	34.6	
	15.0			0.02
24.0		5.2	50.9	
	4.1			0.02
28.1		5.1	52.7	
	24.9			0.04
53.0		4.1	70.9	
	24.5			0.03
77.5		3.4	83.6	
	47.0			0.004
124.5		3.2	87.3	
	24.0			0.008
148.5		3.1	89.1	
	91.0			0.003
239.5		2.8	94.6	
	58.7			0.005
298.2		2.5	100.0	

TABLE B-6, CONTINUED

SLUDGE SURFACE RECESSION OF CLOSED, DRAINED MODEL E

Time hr		Depth of Sludge in.	Recession as Percent of Total	Recession Rates in./hr
Elapsed	Interval			
RUN 5				
0.0		8.0	0.0	
	0.9			3.2
0.9		5.1	40.3	
	3.3			0.6
4.2		3.2	66.6	
	17.2			0.1
21.4		1.4	91.6	
	31.0			0.01
52.4		1.1	95.9	
	43.9			0.00
96.3		1.1	95.9	
	71.9			0.001
168.2		1.0	92.2	
	52.9			0.004
221.1		0.8	100.0	
RUN 6				
0.0		8.0	0.0	
	0.3			2.3
0.3		7.3	10.9	
	3.8			0.6
4.1		5.2	43.8	
	19.0			0.1
23.1		2.4	87.5	
	29.4			0.02
52.5		1.8	96.9	
	26.0			0.004
78.5		1.7	98.5	
	22.1			0.005
100.6		1.6	100.0	