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SOURCE CONTROL OF WATER TREATMENT WASTE SOLIDS

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SOURCE CONTROL OF WATER TREATMENT WASTE SOLIDS

Second Annual Report

By

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Federal Water Pollution Control Administration
Research Grant WP-01239

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PREFACE

The following report is the second of a series of progress reports prepared for the Federal Water Pollution Control Administration research grant WP-01239-02, "Source Control of Water Treatment Waste Solids." Last year's report was contained in one volume. This year's report is contained in four volumes: the first volume contains summary progress statements on each of several subjects of current research; the second volume, designated as Research Report No. 1, contains the original experimental and theoretical work on sludge dewatering which provided the inspiration for much of the current work; the third volume, designated as Research Report No. 2, contains a look at the centrifugation process of sludge dewatering; the fourth volume, designated as Research Report No. 3, contains reprints of the various papers which have been presented at conferences during the year.

The investigators have tried to involve a number of students in the research so as to increase the trained manpower pool which would be knowledgeable about the sludge handling process. Last year there were three undergraduate engineering students who assisted on the research. Of these, Ronald Michalski is now an M.S. candidate in Sanitary Engineering at Cornell University, Walter Bickford is an engineer with the Massachusetts Water Pollution Control Division, and Thomas Roule is a senior in Electrical Engineering at the University, but considering graduate work in Environmental Engineering.

Thus, in addition to the accomplishment of the primary purpose of this research project - the development of feasible solutions of the sludge handling problem - a valuable byproduct of trained manpower has been achieved.

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I. INTRODUCTION

by Donald D. Adrian

NEED FOR STUDY

The importance of engineering research on sludge dewatering and drying has been further recognized during the past year by those engaged in water pollution control activities. At conferences focused on waste treatment practice a higher fraction of papers are presented which discuss some aspect of sludge handling. Also, "Disposal of Wastes from Water Treatment Plants" was the topic selected as its first research project by the newly formed American Water Works Association Research Foundation (1).

The reason for the upswing of interest about sludge disposal is not hard to find. Higher levels of water and waste treatment produce more copious quantities of sludge, and the sludge which is produced is less amenable to dewatering than the sludge produced by lower standards of treatment. The future trend is definitely toward higher and higher levels of treatment. There is a concurrent trend toward evermore stringent receiving water standards. Thus, of a treatment plant's operating budget the fraction devoted to sludge handling and disposal operations can be expected to rise from the present range of 50-75% to even higher values. Indeed, while the dewatering, drying and disposal cost of $80 per ton of dry solids appeared extraordinarily high for wastewater sludge when reported a few years ago, recent calculations indicate an alum sludge from a water treatment plant may incur a cost of about $230. per ton of dry solids for vacuum filter dewatering alone (2). Clearly there is a need for research on alternative methods of sludge handling to try to reduce the disposal costs of sludge.

Land methods have been shown to be the most economical dewatering process. Yet there is no sound method available with which to design dewatering and drying beds. The absence of a sound design method for sludge dewatering and drying frequently results in the design engineer selecting an alternative process for which a rational design procedure is available, even though the alternative process is more costly.

There are enormous economic consequences of the design engineer's decision to avoid the uncharted paths of dewatering and drying bed design for alternative, more costly processes which have the advantage of clearcut design procedures. The consequences are especially important at this time when the vast majority of water treatment plants in the country are simultaneously faced with the necessity of upgrading and redesigning their waste disposal facilities to meet the new water quality standards. An annual savings of a few thousand dollars at each plant becomes a substantial sum when multiplied by all of the treatment plants in the country.

PURPOSE AND OBJECTIVES OF STUDY

As expressed in the 1968 progress report, the general objective of the study was to develop rational design formulations with which an engineer could design dewatering and drying beds for water treatment sludges.

Such an objective required progress on several fronts: study of the relevant physical properties of sludge, search of the technical literature, liason with manufacturers and treatment plant operators, design and fabrication of experimental equipment, formulation and testing of hypotheses, assembly and maintenance of an imaginative research team, synthesis of experimental results and mathematical models into practical engineering designs, and promulgation of the results to the engineering profession to form the basis for practical economic designs.

Specific objectives of the research project included:

1. To strengthen through the addition of selected new personnel the research team which had been successful during the first year of the research project, and to provide the intellectual stimulation and research environment in which to produce the most imaginative and useful results.
2. To review past literature and keep abreast of the current literature relating to the research program.
3. To continue investigating the physical properties of a variety of water treatment sludges produced by different water treatment processes, and to investigate for comparative purposes the analogous properties of other sludges such as wastewater sludges and benthic deposits.
4. To study the influence upon dewatering of the several sludge conditioning methods such as freezing and thawing, treatment with ferric chloride, addition of polyelectrolytes, and mixing with fly ash.
5. To develop mathematical models which would describe the dewatering and drying process.
6. To synthesize the output from all of the above objectives into the development of design procedures which will be useful to the engineering profession.
7. To promulgate the results of this research to interested members of other research teams; local, state and federal regulating agencies; and the engineering profession.

An examination of this progress report and the three accompanying research reports will indicate the considerable progress made toward achievement of these objectives. Items 1 and 2 have been achieved. Item 3 is a continuing process, but during the year the properties of the following sludges were investigated: lime softening sludge, raw primary sludge, digested primary and secondary sludge, benthic deposits and slum sludge. Item 4 has resulted in studies of the effect of freezing and thawing on altering the dewatering properties of sludge. Also, the influence of chemical conditioners upon sludge dewaterability was noted. In this regard the novel method proposed to evaluate the effect upon dewaterability of chemical conditioners should be pointed out. The method presented at the American Chemical Society National Symposium on Colloid and Surface Chemistry in Air and Water Pollution consisted of utilizing the gravity dewatering equation discussed in last year's report to select an optimum chemical dosage (2). This method permitted simple laboratory test results to be projected to full scale operating conditions. Current work on freezing and thawing is continuing, as well as work on modifying the properties of sludge by the addition of fly ash and diatomaceous earth. The work with the addition of fly ash is especially promising in that the disposal of both fly ash and sludge, now expensive separate processes, may be made less costly by their combination.

Progress on Item 5 has been noteworthy for dewatering and this report indicates the substantial progress achieved on modeling sludge drying. The accompanying Research Report No. 3 contains the developments on modeling the dewatering process. The paper presented at the Annual Meeting of the American Geophysical Union illustrated the applicability of the gravity dewatering model to materials other than fresh sludge. The paper presented at the Purdue Industrial Wastes Conference introduced the concept of the media factor to relate sludge dewatering characteristics to the properties of the supporting media. The paper presented at the Annual Meeting of the Solid Science Society of America meeting illustrated how to determine the rate at which sludge could be applied to land--an especially timely topic in view of the attention given to the use of sludge for land reclamation.

Item 6 has resulted in the most significant development of this research project. As indicated in Chapter III of this report the dewatering and drying models have been synthesized into a design procedure which results in the optimum economic design of a dewatering and drying bed. The design procedure incorporates the physical parameters of the sludge with the economics of any area to produce an optimum design. Should the designer be unable to use the optimum design the simulation procedure allows calculation of the economic penalty to be paid for non-optimum design.

Item 7 is the most difficult to assess. Both Principal Investigators continued their active participation in the ASCE-WPCF Subcommittee which is writing a new Manual of Practice on Sludge Dewatering. The manual is complete and has been prepared for publication. Presentations describing the progress of the research have been made at a number of technical meetings. Reprints of technical articles have been prepared for distribution to interested parties. Several articles have been prepared for submission to technical journals. Also, portions of the work are to be presented in the Short Course in Sanitary Engineering offered by the University of Massachusetts in June, 1969. Through all of these efforts it is anticipated the results of the research will be made available to interested persons.

SCOPE OF STUDY

The study reported in this volume and in the accompanying research reports was focused on the design of dewatering and drying beds for sludges. Related alternative processes were studied for insight into parameters which might be applicable to dewatering and drying bed designs.

The investigators have insisted upon working with sludges from water and waste treatment plants rather than studying the properties of an artificial material which might be aesthetically more pleasing, but physically less realistic. This insistence of working on the real problem rather than an artificial problem undoubtedly has resulted in a slight loss of statistical exactness in the results, but this loss is more than offset by the knowledge that the engineering profession needs solutions to real, not artificial, problems.

The types of sludges studied were increased during the present year to provide evermore stringent tests of the results. Also, work was started on the use of additives combined with sludge to determine whether more economical operation could be achieved.

The gravity dewatering equation developed last year has been tested under a wide variety of conditions. It continues to serve well and has been flexible in application to new situations.

Work on drying has continued apace. There is a continuing need to determine the influence on sludge drying properties of various additives and conditioning processes applied to increase dewaterability. For it would be a hollow victory to increase the dewaterability of sludge at a price of such a reduced evaporation rate that the total sludge handling costs would increase.

The successful combination of the dewatering and drying relationships together in the simulation model presented in Chapter 3 provides a useful tool with which to consider the overall economic consequences of use of additives, chemical conditioning agents and process changes. This system's viewpoint will be investigated further in the future.

ORGANIZATION FOR STUDY

There were a number of changes in the organization of the study in the year ensuing since the last progress report. Principal Investigator, Dr. D. D. Adrian and Co-principal Investigator, Dr. J. H. Nebiker, continued to devote a large fraction of their time and direction of the project during the past year. Research Associate, Philip A. Lutin, terminated his association with this project in September, 1968 but remained available for consultation while working on other research projects at the University. Mr. John F. Ramsay, who holds an M.S. degree in Sanitary Engineering, and who has several years consulting experience, joined the research project as a Research Associate in September, 1968.

Ph. D. Candidates Edward Clark and Kuang-Mei Lo, continued their appointments as Research Assistants while completing their course work and starting on their dissertation research. Mr. Thomas G. Sanders completed work on his master's thesis "Gravity Dewatering of Wastewater Sludge" in July, 1968, prior to beginning active duty with the U. S. Public Health Service, Division of Solid Wastes. Two other Ph. D. candidates, Donald Ray and Peter Meier, performed special project investigations although their dissertations are in other areas. Masters' candidate Nancy Lee served as a Research Assistant until November, 1968 when she withdrew from the University. Also, master's candidate Stephen Claughton began work in January, 1969 on his thesis which investigates the influence of additions of fly ash to sludge. Undergraduates Thomas Roule, a Senior Electrical Engineer, and Thomas Beliveau, a Senior Chemical Engineer, performed special project investigations. Also, Peter Rogers, an undergraduate Mechanical Engineer, worked as a machinist and fabricator of special equipment while George Andrikaidis, an undergraduate Civil Engineer, served as a research technician. Mrs. Susan Foudy carried out the drafting until her departure for the VISTA Program in February, 1969. Mrs. Marjorie Olanyk has served as the secretary and bookkeeper since August, 1968.

ACKNOWLEDGEMENTS

The writers are indebted to many persons and organizations who facilitated the study reported herein: Dr. Merit P. White, Chairman of the Civil Engineering Department, provided administrative support; Dr. Tsuan Hua Feng, Program Director of Environmental Engineering, provided continued support; the Chemical Engineering Department made available their pressure filter for testing; and the Research Computing Center was always a ready source of counsel on data handling. Also, personnel at water treatment plants in Billerica, Lowell, Lawrence, and Amesbury, Massachusetts; Albany, New York; Lebanon and Nashville, Tennessee; and Kankakee, Illinois, gladly provided sludge samples for analysis. Sewage sludge was obtained from Amherst and Pittsfield, Massachusetts. Dr. Robert B. Dean of the Cincinnati Water Research Laboratory and Professor Bernard B. Berger, Director of the Water Resources Center at the University and member of the Office of Science and Technology, made valuable suggestions about the role of freezing in assisting in sludge dewatering.

REFERENCES

(1) News Release, American Water Works Association Research Foundation, July 15, 1968.

(2) Adrian, D. D., and Nebiker, J. H., Consultants Final Report to the American Water Works Association Research Foundation, <u>Disposal of Water Treatment Wastes</u>, (in press).

II. THE DRYING OF WATER TREATMENT WASTE SOLIDS

by Edward E. Clark

INTRODUCTION

Drying by evaporation is of major importance in the removal of moisture from water treatment sludge by land disposal. Studies on alum sludges at the University of Massachusetts indicate that drainage alone produces at best a plastic mass, with about a 5% solids content. Drying is the only process which can further increase the solids content, and which can produce a cake capable of sustaining loads.

This Chapter is concerned with the last year's progress of the author toward further development of the theory of sludge drying, and toward determination of the major parameters controlling the drying rates. For background information the reader is referred to Chapter III, "Theory of Drying," of the 1968 Progress Report to FWPCA, Report EVE-7-68-1, (1).

THEORETICAL BACKGROUND

Chen and Johnson (2) have stated that the rate of drying depends upon the free moisture content of the material, with the rate law being

$$-\frac{d(U - U_p)}{dt} = -\frac{dU}{dt} = C(U - U_p)^m \qquad 2\text{-}1$$

with U = average moisture content (percent weight of water per weight of dry solids) at time t

U_p = equilibrium moisture content

C & m = empirical constants.

In the constant rateperiod the rate of change is constant and thus a zero-order kinetic reaction. Thus

$$-\frac{dU}{dt} = C, \text{ with } U \geq U_{CR} \qquad 2\text{-}2$$

where U_{CR} is the first critical moisture content. Equation 2-2 is analogous to Equation 3-14 of (1).

During a portion of the falling rate period if m can be considered equal to 1, Equation 2-1 becomes

$$-\frac{dU}{dt} = C(U-U_p) \qquad 2\text{-}3$$

By integration one obtains

$$\frac{U-U_p}{U_{ct}-U_p} = e^{-ct} \qquad 2\text{-}4$$

where U_{ct} is the second critical moisture content. Equation 2-4 is analogous to Equation 3-18 of (1) and a first order reaction.

During the falling rate period of drying a second critical moisture content is reached thus changing the value of m in Equation 2-1. Nebiker (3) states that the second critical moisture content does not appear to be of significance in wastewater sludge drying and that the entire falling rate curve can be well approximated by a straight line. Thus this would be a fractional-order reaction. This same approximation was made for water treatment sludge.

If the logarithm of Equation 1 is taken, we obtain

$$\log\ [-\frac{d(U-U_p)}{dt}] = \log C + m \log(U-U_p) \qquad 2\text{-}5$$

A plot of $(U-U_p)$ constructed from data versus $\frac{d(U-U_p)}{dt}$ as measured at several values of t, will yield a straight line with a slope of m, the order of the reaction.

Once m is determined, C can be obtained by separating the variables and integrating Equation 2-1 to obtain

$$\frac{(U-U_p)^{1-m}}{1-m} = -Ct + C_1 \qquad 2\text{-}6$$

or substituting the boundary conditions $U = U_{CR}$ at $t = 0$ to obtain

$$(U-U_p)^{1-m} = (m-1)Ct + (U_{CR}-U_p)^{1-m} \qquad 2\text{-}7$$

By substituting m into Equation 2-7, values of C can be determined for different sets of t and $(U-U_p)$; and a mean value of C can be obtained. Then taking the logarithm of both sides of Equation 2-7, one obtains

$$\log(U-U_p) = \frac{1}{1-m} \log \left[(m-1)Ct + (U_{CR}-U_p)^{1-m}\right] \qquad 2\text{-}8$$

By substituting values of m and C, a plot of log $(U-U_p)$ vs.

$$\log \left[(m-1)Ct + (U_{CR}-U_p)^{1-m}\right]$$

with the slope of $\frac{1}{1-m}$ can be constructed. Values of $(U-U_p)$ can then be predicted at different values of t, with the point U_{CR} taken as zero time.

Chen and Johnson (2) assumed a material isotropic and symmetric to the center, with a uniformly distributed initial moisture concentration. They developed the following equation for one sided drying of a slab:

$$\frac{U-U_p}{U_o-U_p} = \sum_{m=1}^{\infty} \frac{2L^2}{B_m^2\,(B_m^2 + L^2 + L)} \exp\left(-\frac{B_m^2\,Kt}{d^2}\right) \qquad 2\text{-}9$$

where L = $I_{S,C} \cdot d/k$, the Nusselt mass transfer number, a dimensionless parameter

d = mean thickness of the slab, an average of the initial and final thickness for a drying process.

k = mass transfer coefficient

$I_{S,C}$ = constant rate drying intensity

γ = weight density of water

B_m = eigenvalues, where B_m's are the positive roots of

$$B \tan B = L \tag{2-10}$$

This particular series converges rapidly: the higher terms are small in comparison with the first term and may be neglected. Therefore, equating Equations 2-4 and 2-9 for the case of m = 1, one obtains approximately

$$C = \frac{B_1^2 k}{d^2} \tag{2-11}$$

or

$$k = \frac{d^2 C}{B_1^2} \tag{2-12}$$

The parameter B_1 depends on $I_{S,C}$, and $I_{S,C}$ depends on the relative humidity and Reynolds number. Once C and B_1 have been determined from an experiment, then k can be evaluated from Equation 2-12, and considering k as a constant, C can be expressed as a function of d. The variation of C with temperature can be determined since k is proportional to C, and the relationship between C and k is expressed by the Arrhenius equation:

$$k = k_o e^{-\Delta H/RT} \tag{2-13}$$

where k_o = constant

R = gas constant

ΔH = energy of activation, and

T = absolute temperature.

The constants k_o and $\Delta H/R$ may be evaluated by determining k at two different temperatures. Chen and Johnson (4) assumed that their reaction order m was a function of humidity only, and that the rate constant C was a function of temperature only.

Drying rate studies for wastewater sludge have been performed by Nebiker as previously reported in (1) and (3). A relationship for the first critical moisture content was presented as

$$U_{CR} = u_h + \frac{100}{3} \frac{I_{S,C} \cdot d}{k\gamma_o} \qquad 2\text{-}14$$

where γ_o = weight of skeletal solids per initial volume

u_h = hygroscopic moisture content

The term u_h is temperature dependent. The moisture transfer coefficient varies with moisture content and depth. Both u_h and k as well as γ_o are characteristics of the sludge and under natural drying conditions were assumed to be constant giving rise to Equation 2-15 as:

$$U_{CR} = f(I_{S,C} \cdot W_{TS}/A). \qquad 2\text{-}15$$

For open air drying of wastewater sludge, Nebiker (3) found the following empirical equation for U_{CR}:

$$U_{CR} = 500(I_{S,C} \cdot W_{TS}/A)^{1/2} \qquad 2\text{-}16$$

A sludge drying in both constant and falling rate periods, according to Nebiker (3), will have a total drying duration as given by

$$t = \frac{W_{TS}}{100A\ I_{S,C}} [U_o - U_{CR} + U_{CR} \ln(U_{CR}/U_t)] \qquad 2\text{-}17$$

where t = time in hours

A = surface or drying area (sq m)

$I_{S,C}$ = drying intensity (kg/sq m/hr)

U_o = initial moisture content

U_{CR} = first critical moisture content

U_t = moisture content at time t.

EXAMPLE OF RESULTS

A drying rate curve for Sample 2 is shown in Figure 2-1 as $(\Delta U/\Delta t)_{avg.}$ versus t. The equilibrium temperature of the sludge was lower than the initial value causing a decrease in the evaporation rate until the initial adjustment occurred. It may be observed that the greater portion of the drying rate curve is in the constant rate drying region. The weight versus time, and the free moisture content $(U-U_p)$ versus time curves are shown in Figures 2-2 and 2-3.

The evaporation ratio is defined as the ratio of sludge weight loss by drying to the simultaneous evaporation of water (%). See Figure 2-4. In the constant rate drying region, the evaporation ratio averaged 90%. Nebiker (3) found the average evaporation ratio for wastewater sludge dried outdoors to be approximately 105%. This higher value is most likely due to infra-red radiation.

The average drying intensity for the constant rate period, $I_{S,C}$, was calculated to be 0.072 kg/m^2-hr (22°C and 40% relative humidity). This drying intensity is somewhat lower than values for open air drying of wastewater sludge presented by Adrian, Lutin and Nebiker (1) and Nebiker (3). The lower drying intensity is thought to be partly due to the absence of radiation effects in the controlled drying experiments. Using Equation 2-16, U_{CR} was calculated to be 116 and the corresponding total drying time from Equation 2-17 was 427 hr. This compared with experimental values of U_{CR} = 252 and t = 502 hr. Using the experimental value of U_{CR} = 252 from Figure 2-5, the total drying duration from Equation 2-17 was found to be 435 hr. or a difference of 13.4%.

Using an equation of the form

$$U_{CR} = K(I_{S,C} \cdot W_{TS}/A)^n \qquad 2\text{-}18$$

and taking the logarithm of both sides one obtains

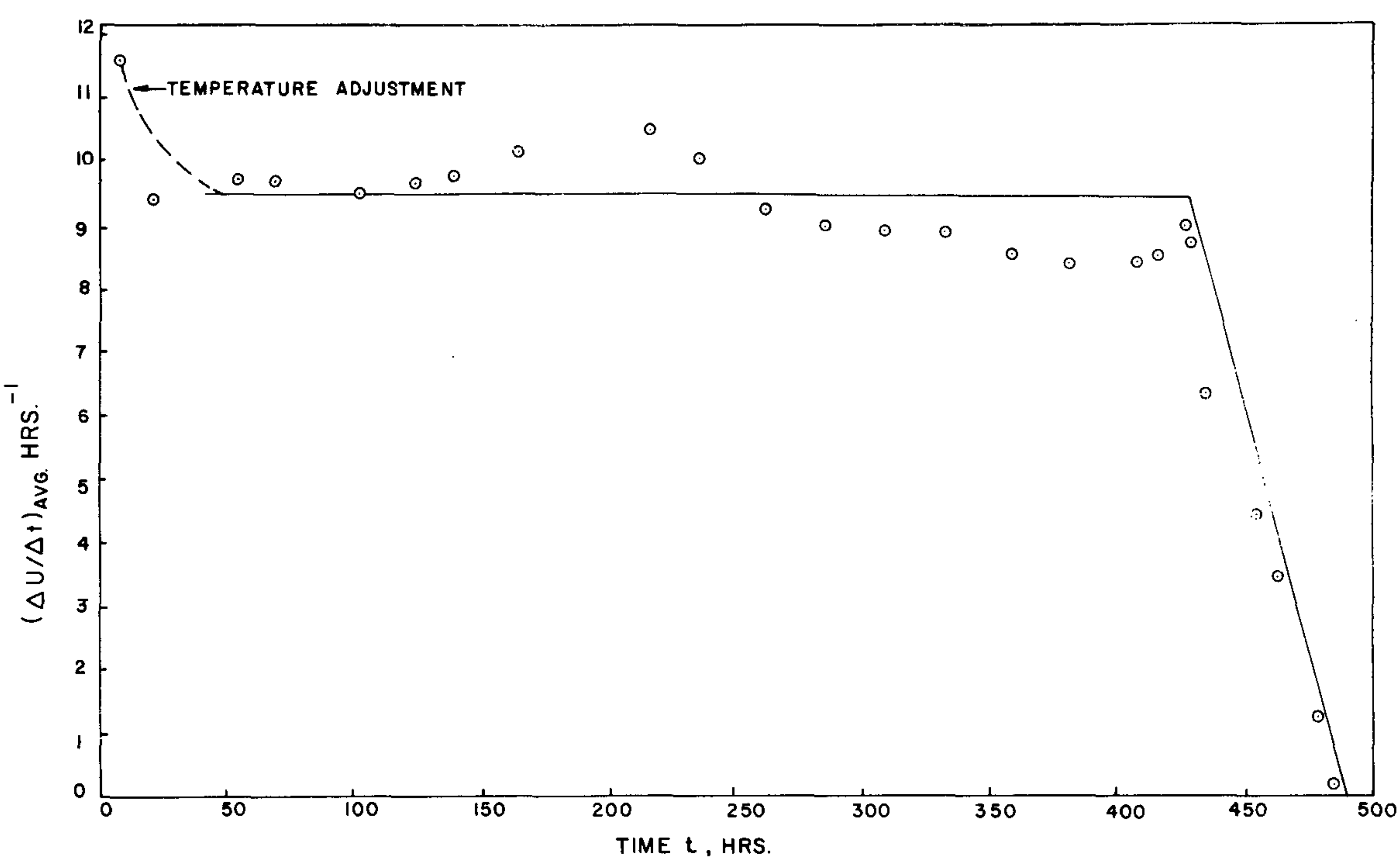

Figure 2-1. Drying rate for alum sludge with 2.3% solids content as a function of time at 22.2° C and 40% relative humidity.

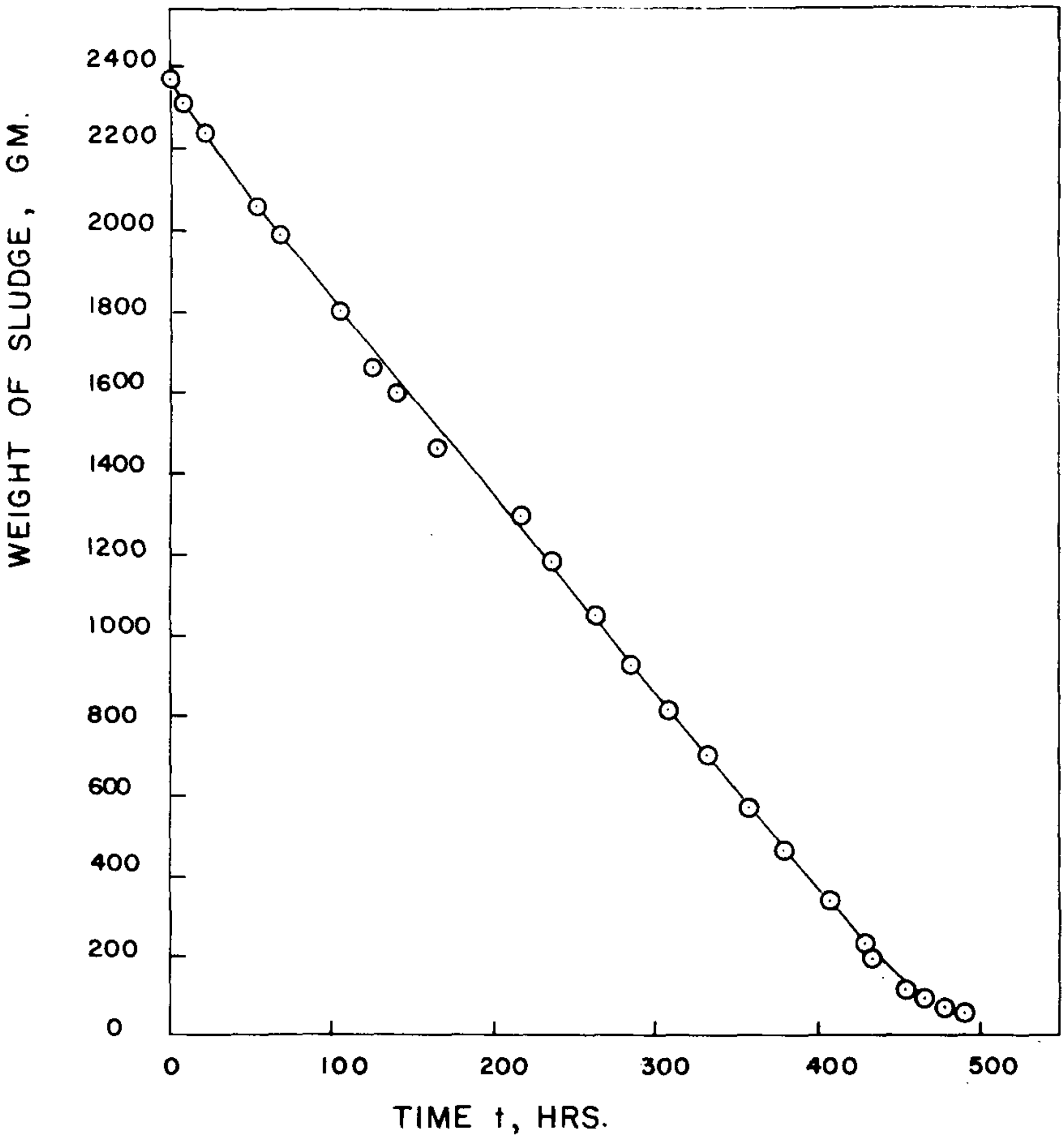

Figure 2-2. Weight of alum sludge with 2.3% solids content as a function of time at 22.2° C and 40% relative humidity.

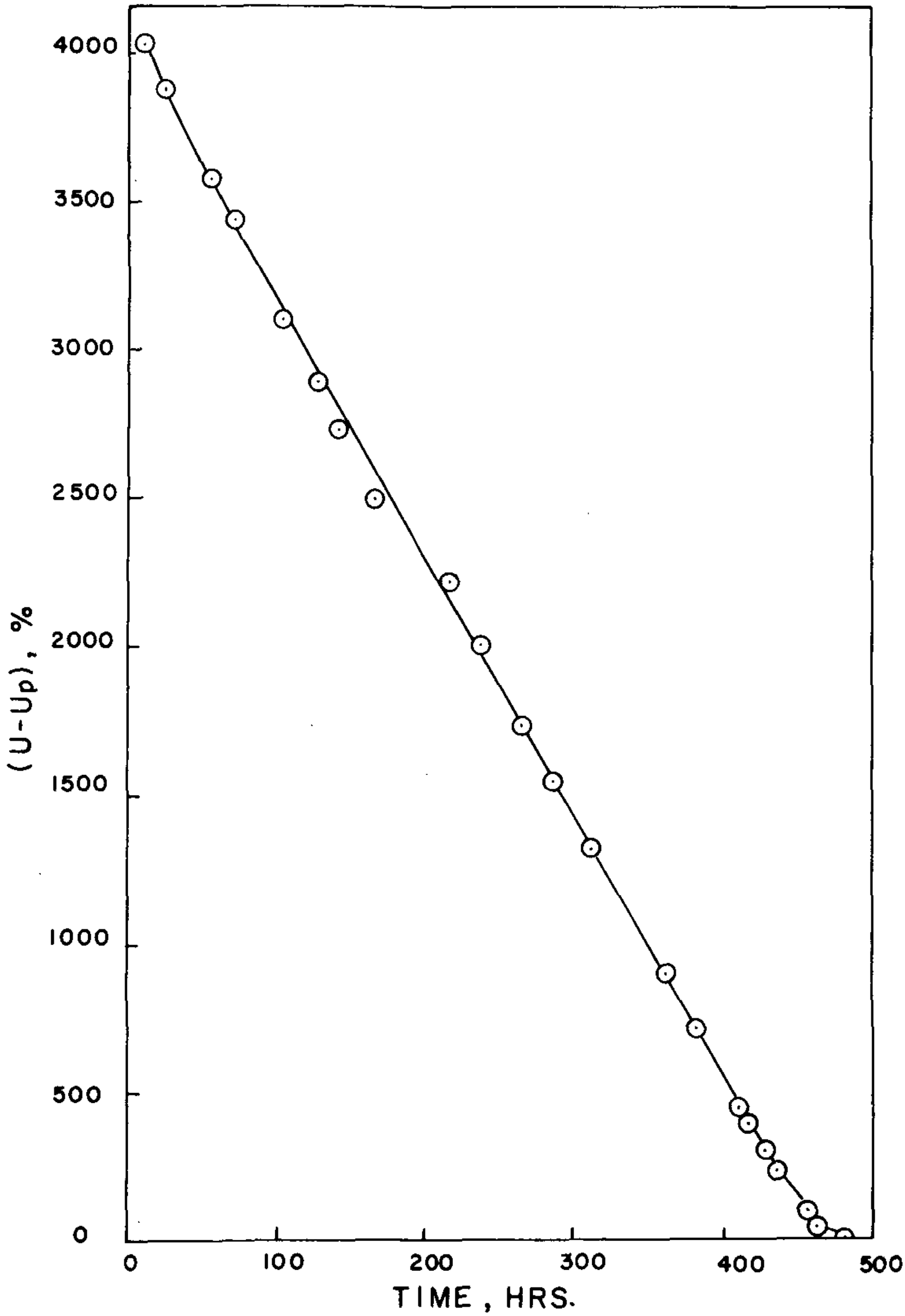

Figure 2-3. Free mositure content for alum sludge with 2.3% solids as a function of time at 22.2° C and 40% relative humidity.

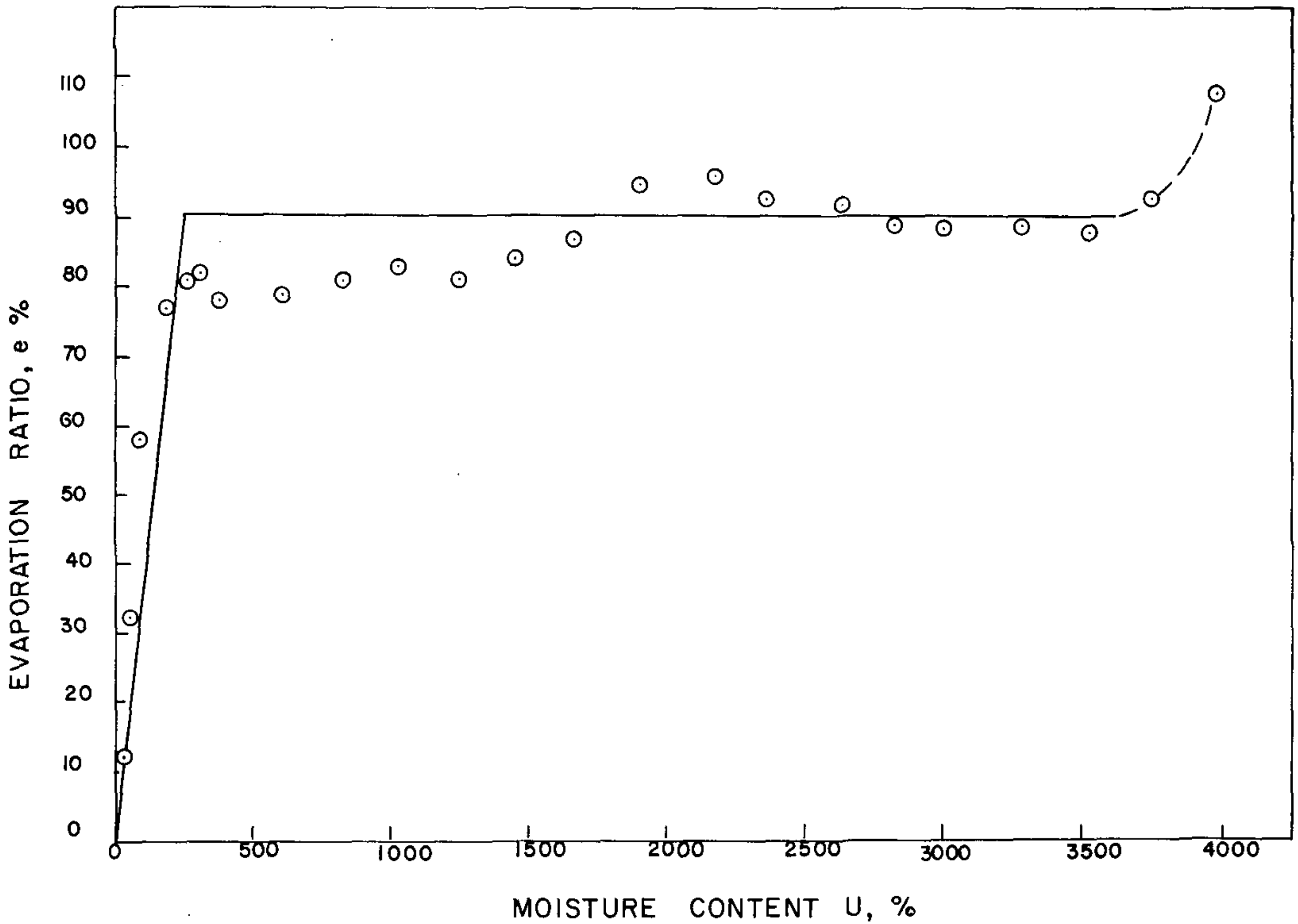

Figure 2-4. Evaporation ratio for alum sludge with 2.3% solids content as a function of time at 22.2° C and 40% relative humidity.

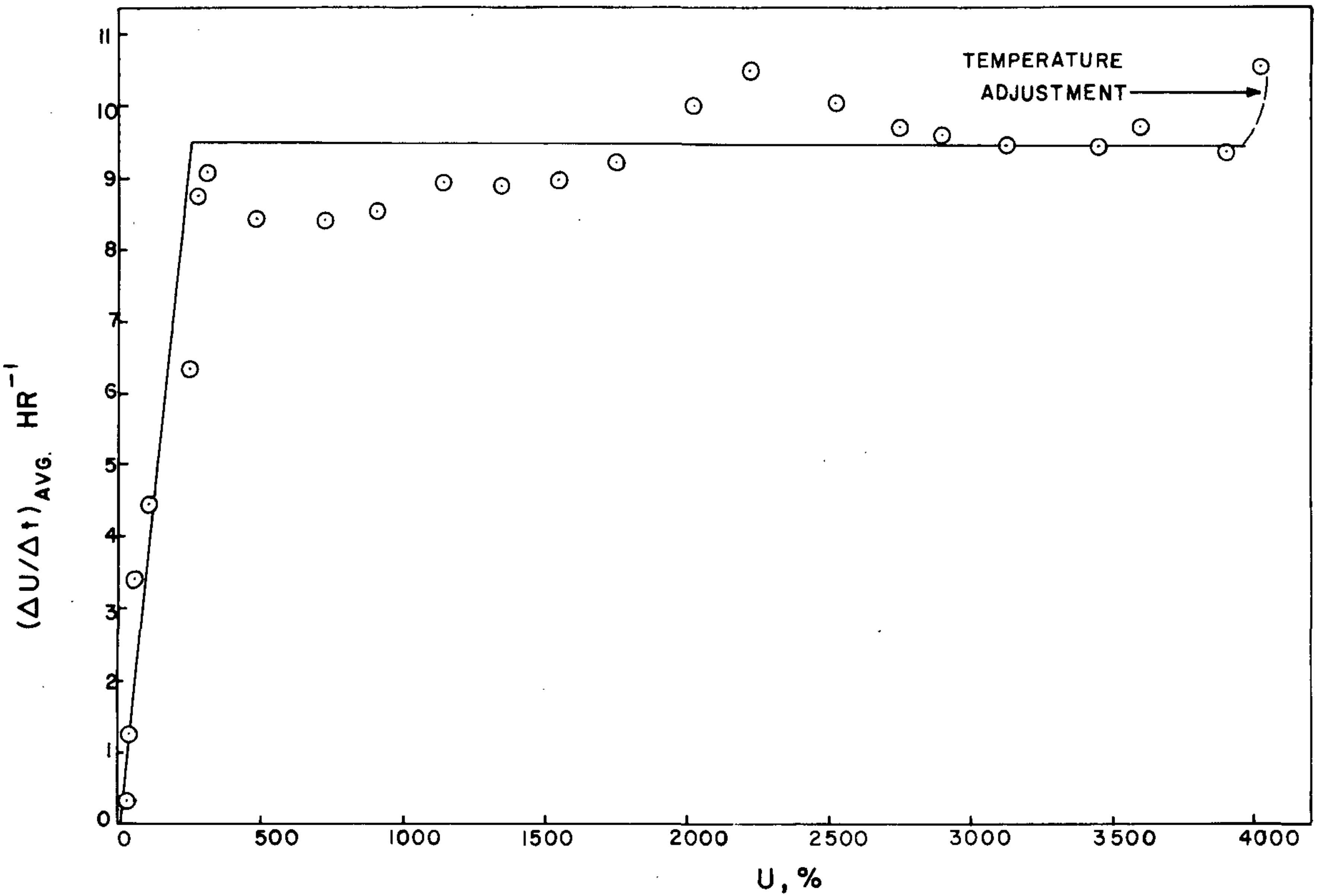

Figure 2-5. Drying rate of alum sludge with 2.3% solids as a function of moisture content at 22.2° C and 40% relative humidity.

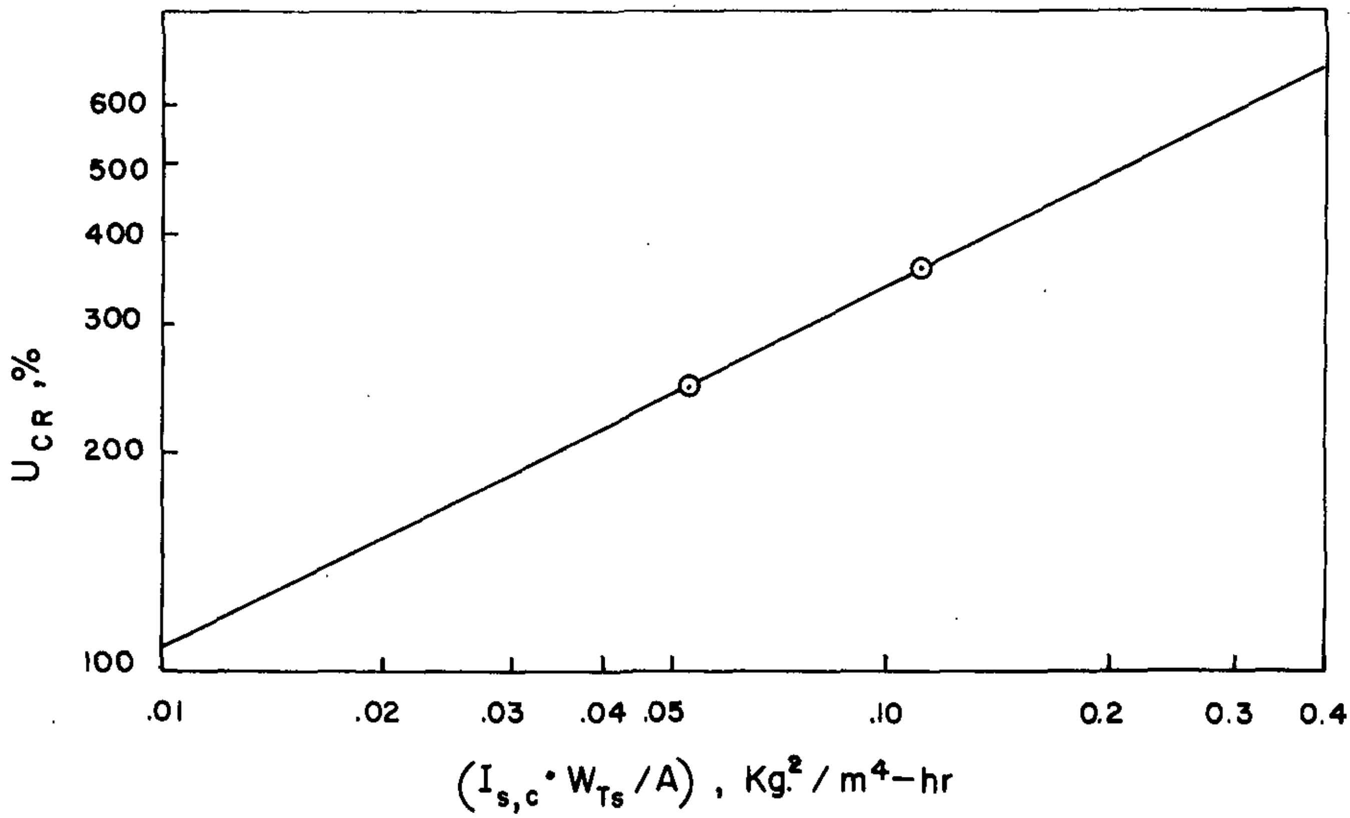

Figure 2-6. Critical moisture content for alum sludges as a function of drying solids per area at 22.2° C and 40% relative humidity.

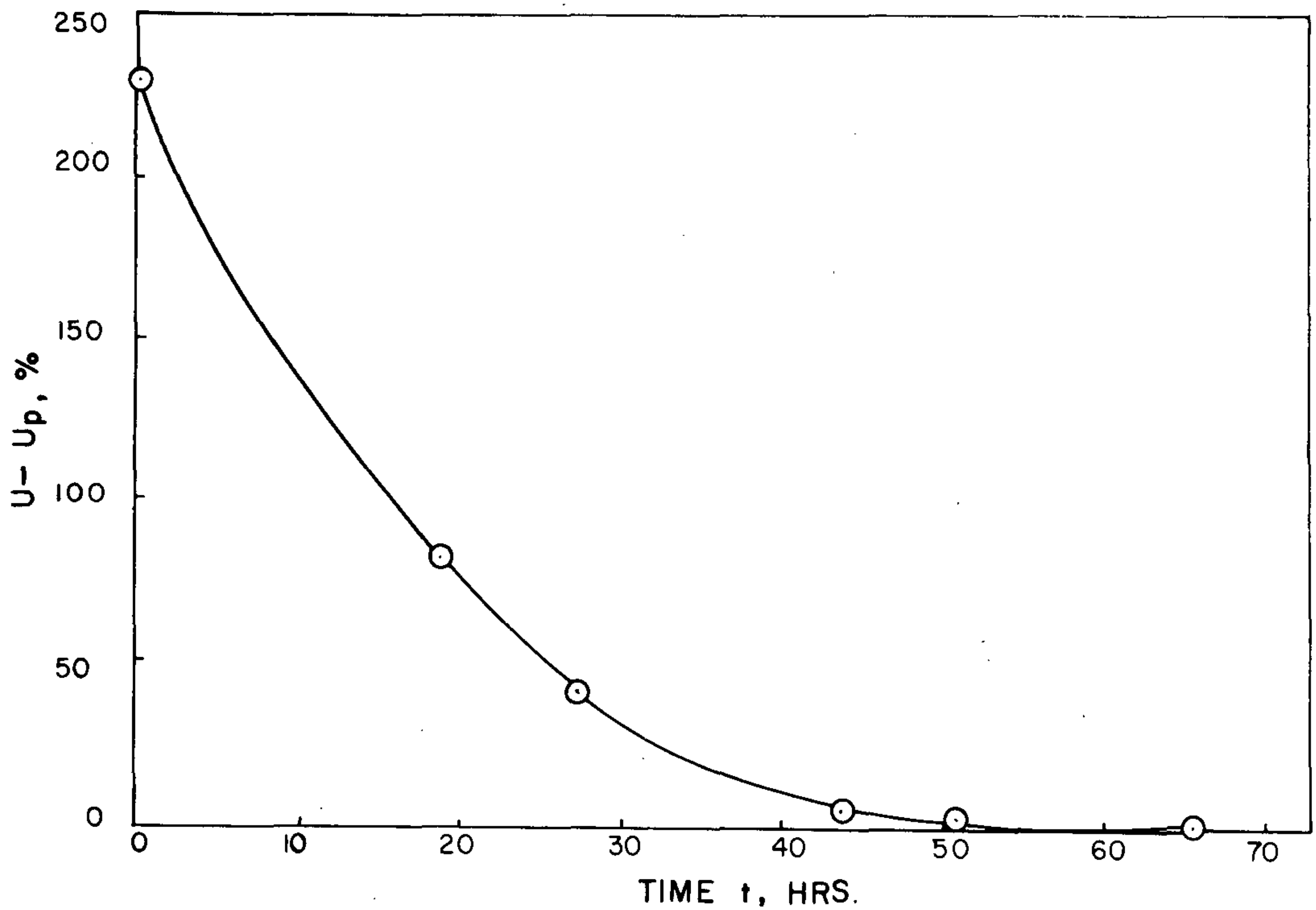

Figure 2-7. Free moisture content of alum sludge with 2.3% solids as a function of time for falling rate period at 22.2° C and 40% relative humidity.

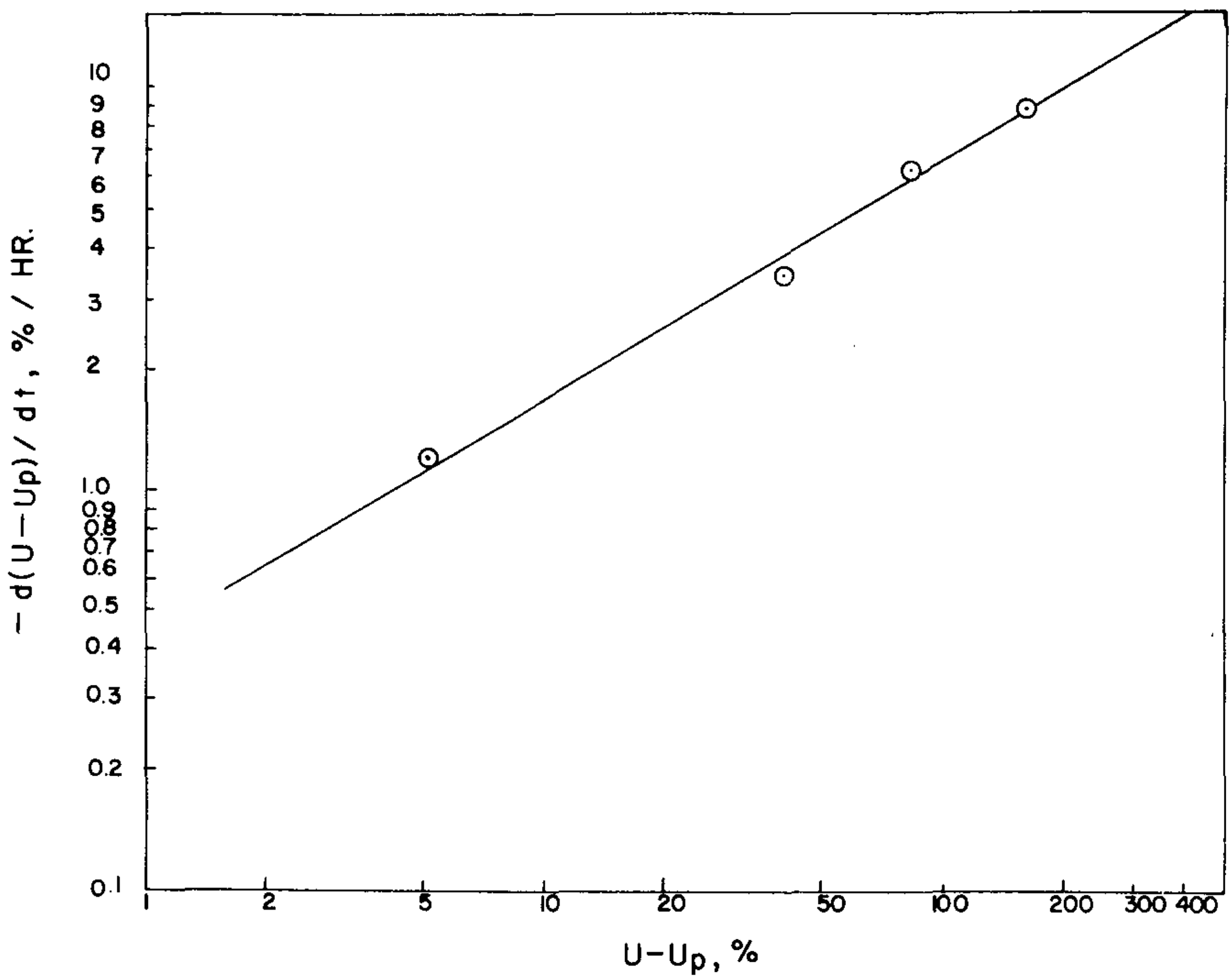

Figure 2-8. Log of rate of drying of alum sludge with 2.3% solids versus log of free moisture content for determination of order n at 22.2° C and 40% relative humidity.

$$\log U_{CR} = \log K + n \log(I_{S,C} \cdot W_{TS}/A) \qquad 2\text{-}19$$

A plot of log U_{CR} versus log $(I_{CS} \cdot W_{TS}/A)$ was drawn (Figure 2-6). The slope of the resulting line is n, which was found to be approximately 0.3. Also, K was then calculated to be 700 giving rise to

$$U_{CR} = 700(I_{S,C} \cdot W_{TS}/A)^{0.3} \qquad 2\text{-}20$$

In the constant rate period, the value C from Equation 2-2 was found to be 9.5 hr^{-1}. Since no distinct change could be determined during the falling rate period, it was approximated by a straight line. A plot of $(U-U_p)$ was constructed from the original data with the point U_{CR} taken as zero time. This plot is shown as Figure 2-7. Values of $d(U-U_p)/dt$ were measured at several values of t, and plotted versus the corresponding values of $(U-U_p)$ as shown in Figure 2-8. The slope of the reaction was found to be 0.64. Having determined m, particular values of C were determined from Equation 2-7 and a mean value of 0.322 was obtained. Then constructing a plot of $\log(U-U_p)$ vs. $\log[(m-1)\,Ct + (U_t-U_p)^{1-m}]$ with a slope of $\frac{1}{1-m}$, as shown in Figure 2-9, values of $(U-U_p)$ can then be predicted for different values of t.

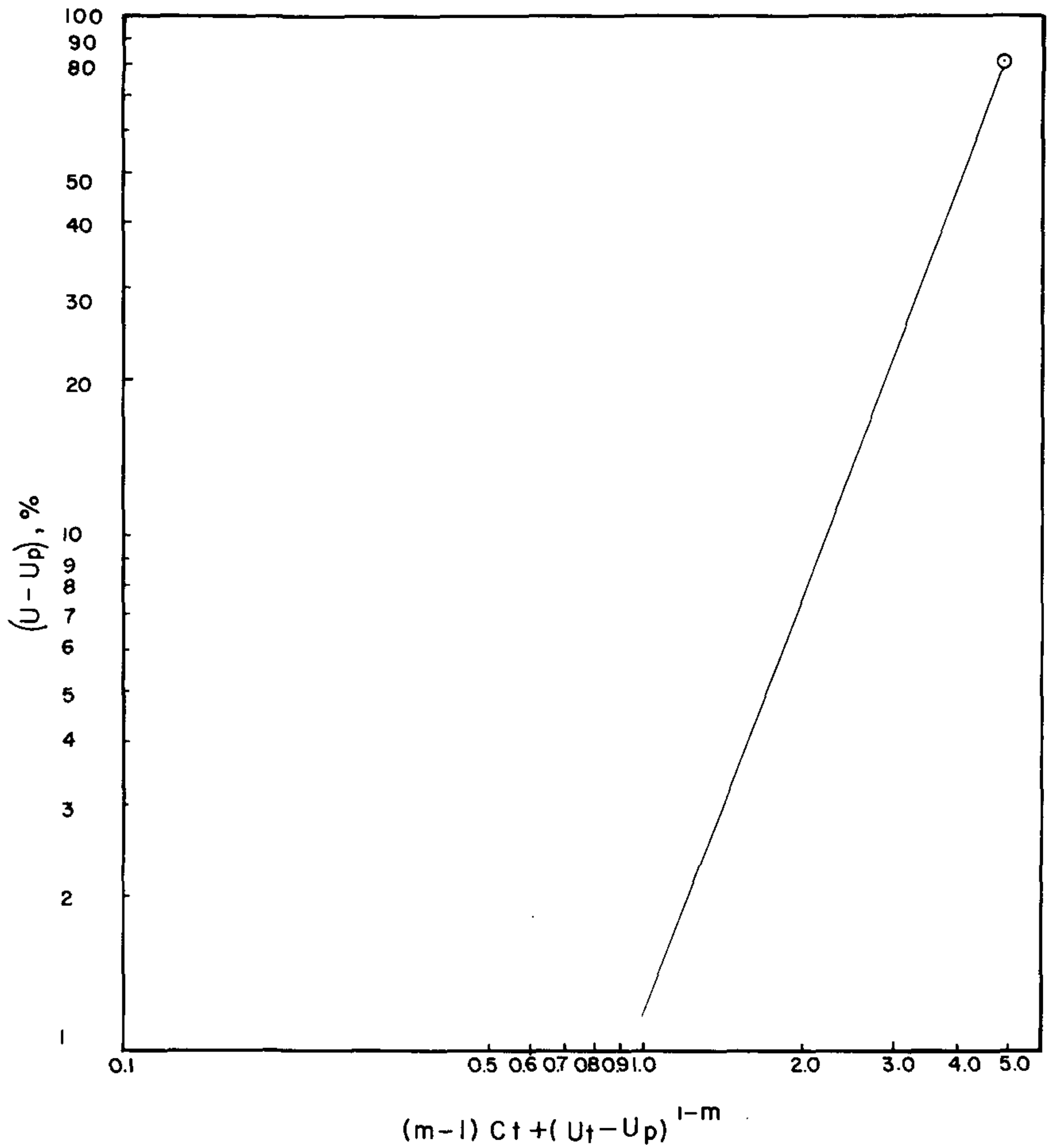

Figure 2-9. Log-log plot of $(U-U_p)$ as a function of $[(m-1)\ Ct + (U-U_p)^{1-m}]$.

EXPERIMENTAL PROCEDURE

In order to conduct experiments on the rates of removal of moisture from water treatment waste solids, an environmental chamber was constructed. The chamber consists of a room approximately 16 X 14 X 10 feet, expecially modified to minimize heat and moisture losses. Constant temperature and low relative humidities are maintained by a 31,000 BTU/hr air conditioner with electric heat and reheat capabilities. High relative humidities are maintained by two humidifiers. Both temperature and relative himidity are controlled by an electronic control system with controls set to maintain relative humidity in a range between 30 to 80 $\pm$ 2% and temperature in a range of 65 to 85 $\pm$ 2°F. A continuous record of both temperature and humidity is maintained by a wall mounted recorder.

Samples of alum sludge from the Billerica, Massachusetts water treatment plant were dried in the environmental chamber. Deionized water was simultaneously evaporated for comparison. The containers consisted of rectangular pyrex glass pans with dimensions of 34 X 22 X 4.5 cm. Sludge samples with 2.3 and 6.1 percent solids content were added to a depth of 2.75 cm. Drying conditions during the experimental run were 22 $\pm$ 0.5°C and 40 $\pm$ 2% relative humidity. Air currents in the room were negligible. Loss of weight was measured daily on a triple beam balance to the nearest gram.

FUTURE CONSIDERATIONS

Future work will include a series of experiments designed to determine how sludge drying rates are affected by temperature, relative humidity, solids content, depth of application, and type of sludge. These experiments will be conducted in the environmental chamber previously described.

With this data the various parameters can be correlated to see what effect they have on one another and also the values of B_1 in Equation 2-12 can be obtained. Another important relationship to be further investigated is the relationship of U_{CR} as a function of $I_{S,C}$ and W_{TS}/A as given in Equation 2-20.

The depth of sludge cake will be measured during the drying period with a modified point gauge similar to those used in hydraulic measurements. With sludge thickness as a function of time for various drying conditions, modifications of Equation 9 may permit evaluation of sludge drying rates during the falling rate period. Also some measurement of the surface area of the cracked sludge cake will be attempted, possibly using photographic techniques to record the area of crack.

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III. OPTIMUM SYSTEM DESIGN

by Peter M. Meier, Donald L. Ray, and Kuang-Mei Lo

SIMULATION APPROACH

Simulation is a problem-solving technique for analyzing a definite system which is the object of interest and which is being studied for one purpose or another (1). This technique is broadly defined as a process which "duplicates the essence of a system or activity without actually attaining reality itself" (2).

In studying a system it is usually required that one or more questions be answered. A model which represents the system may be used. This model may be an exact scaled replica or a mathematical equation which describes the system. In any case when a model is used its accuracy must be verified by comparing its behavior with the real system (3).

The system being studied is usually subject to initial and boundary constraints. The initial constraints describes the system at initial conditions, while the boundary conditions represent restrictions on the operation of the system. Often the answers needed can be obtained by observing changes in the model during a sequence of time after the initial time, or by incrementing changes in the initial or boundary conditions and observing changes in the results (3).

The procedure used to obtain desired answers is referred to as the method of solution. Many times there may be more than one method, and in these cases it becomes important to determine which method of solution will be the best. The choice of tools available to implement the method of solution is an important consideration in this decision. Tools used for mathematical solutions include high-speed digital computers, hand operated computers, analog computers, etc. (3).

In summary the study of definite systems by simulation can proceed as follows:

1. Define the system
2. Define the questions to be answered by the study
3. Develop a model of the system
4. Define initial and boundary constraints
5. Choose a method of solution
6. Choose a tool for implementing the solution
7. Obtain a solution.

The technique of simulation was used to study the reduction in moisture from sludge applied to a sand drying bed. From this simulation study it was desired to determine the duration time necessary for the sludge to remain on the beds before removal, and from this the optimum depth at which the sludge should be applied.

The reduction in moisture content of sludge placed on sand drying beds is achieved by two processes. The first process causes moisture to be removed by drying due to atmospheric conditions. The second process removes moisture by gravity drainage through the sand and supporting media. Therefore to simulate these processes two different models have to be used and the results combined to yield the final answer.

The model used to simulate the gravity drainage or dewatering process was developed by Nebiker, et al (4). That study expressed the total time for dewatering (Eq. 13) as:

$$t_{dw} = \frac{\mu S_o R_c}{100\sigma(\sigma+1)H_c^{\sigma}} \left[H_o^{\sigma+1} + \sigma H^{\sigma+1} - (\sigma+1)H_o H^{\sigma}\right] \qquad 3\text{-}1$$

which relates the depth of sludge applied,to time, using the parameters of solids contents, specific resistance, coefficient of compressibility and dynamic viscosity.

The model used to simulate the removal of moisture by atmospheric drying was developed by Nebiker, (5). That study expressed the total time for drying (Eq. 20) as:

$$t_{dry} = \frac{W_{TS}}{100A\ I_{S,C}} [U_o - U_{CR} + U_{CR} \ln(U_{CR}/U_t)] \qquad 3\text{-}2$$

for $U_o \geq U_{CR} \geq U_t$. This equation relates the initial and final moisture contents with time, using the parameters of total solids applied, surface or drying area, drying intensity, and the critical moisture content where drying changes from constant rate to falling rate.

In combining the two models it was considered that the dewatering and drying occurred sequentially. The dewatering process was considered to occur first, reducing the moisture content to a predetermined value, and then the drying process started, reducing the moisture to the desired final value.

The initial constraints or parameters were defined to be the initial solids content, specific resistance, coefficient of compressibility, drying intensity, depth of sand and supporting media, and the quantity of sludge to be produced each day. These parameters would vary from site to site but are readily determined for any particular situation.

The boundary constraints or parameters describing the method of operation were defined as the depth of sludge applied and the final moisture content desired. Parameters such as the surface drying area and the weight of solids applied were determined from the other constraints for various depths of sludge.

Evaluation of these parameters relating to the characteristics of the sludge can be determined by standard laboratory tests, or other methods reported in the literature (6). One of the advantages in the use of simulation techniques is the ease with which these parameters can be varied, thereby determining the sensitivity of the process with different values of a particular parameter.

Programming of the Equations (3-1) and (3-2) and adding the results gives the total time required to reduce moisture content to the desired level. In order to optimize the depth of sludge to be applied, consideration must be given to economic factors. Costs which must be included in the analysis would be, land cost, construction cost of the sand bed, annual maintenance cost, periodic repairing cost, salvageable land value at the end of the economical life span of the beds, and costs of applying and removing sludge with each application. Selection of an appropriate interest rate and an economical life span allows the annual cost, as a function of the area required and the number of applications per year, to be calculated.

By including the economic factors in the program, simulated results are obtained for the optimum depth of sludge. The method utilized was to take incremental changes in the depth of sludge applied and calculate the duration time required, the area required, and the annual cost.

From this data graphs were constructed showing the changes in time of application, and area required with varying depths (Figure 3-1), and also the changes in annual cost with depth (Figure 3-2).

The ways in which these graphs can be used are many. By using Figure 3-2 the minimum cost can be determined and this will give the optimum depth of sludge. Then going to Figure 3-1 the area required and the time of application can be determined.

Another way in which the graphs might be used would be to determine the annual cost if the area available for sand beds were limited. Figure 3-1 would give the depth of sludge required and then going to Figure 3-2 the annual cost could be found. The effects of applying sludge at depths different from the optimum can also be found.

The simulation program should be as general as possible so as to allow for as much variation as needed. The particular situation used to illustrate the

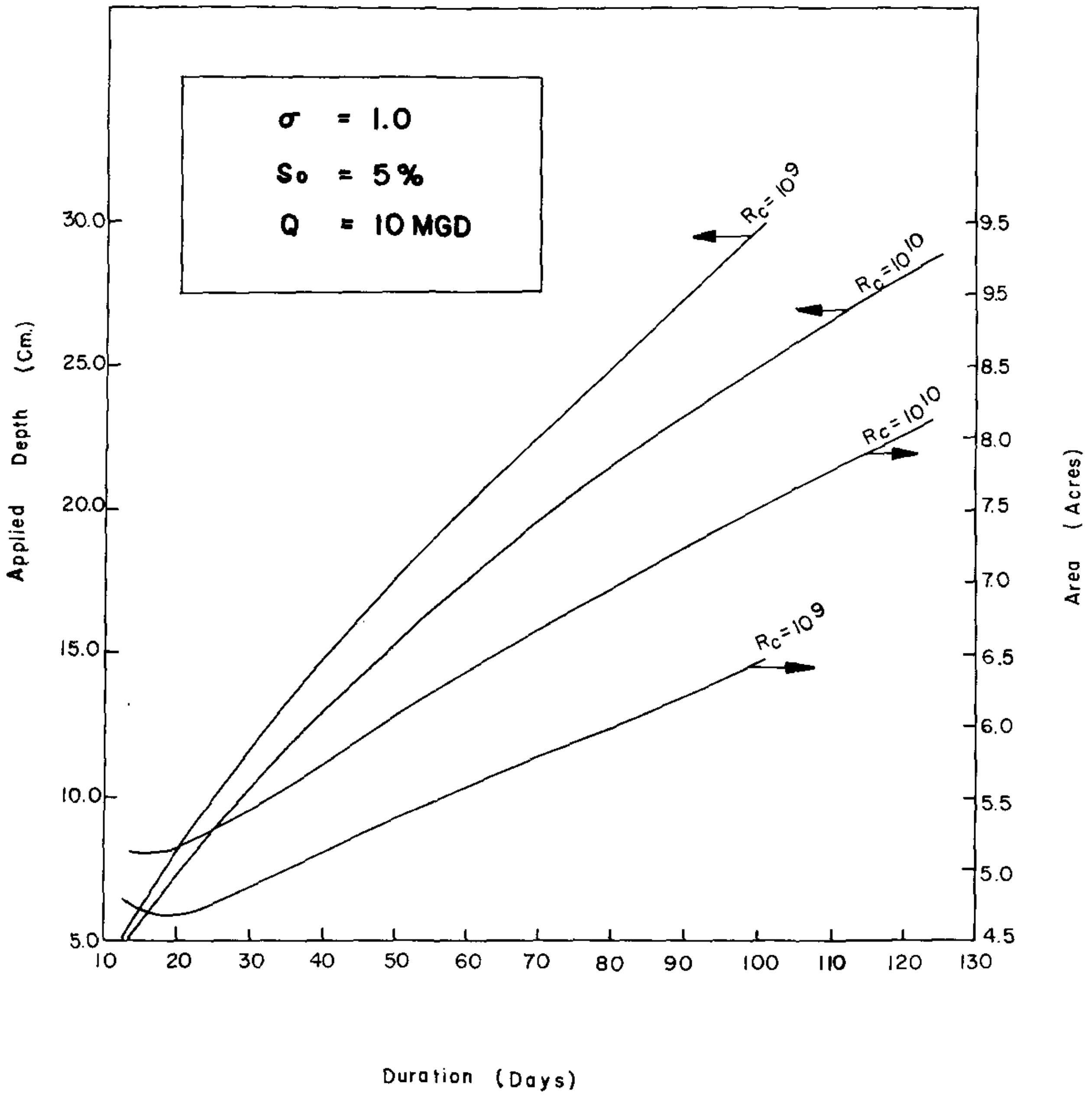

Figure 3-1. Applied depth and area required as a function of the duration time for various values of R_c.

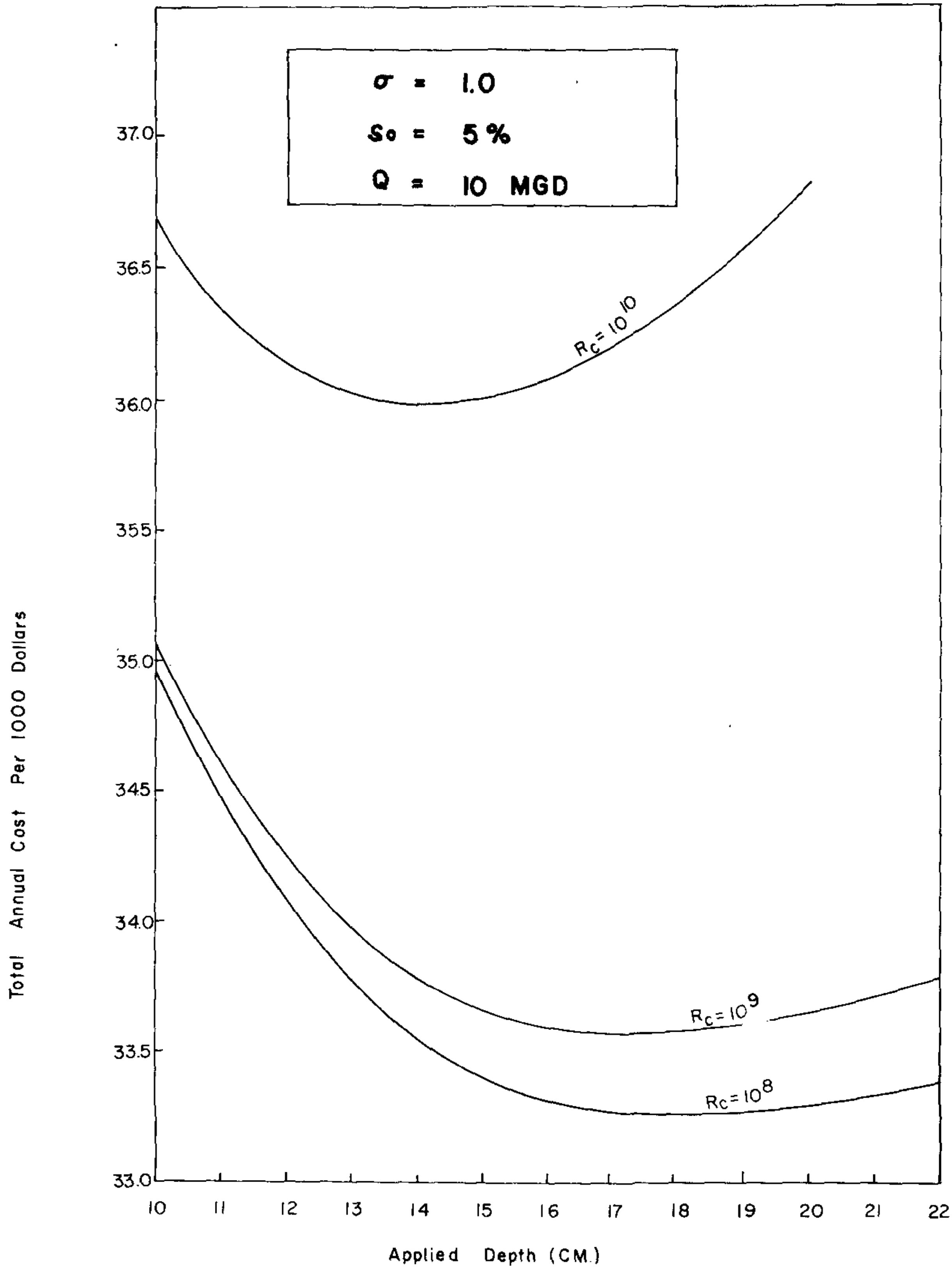

Figure 3-2. Total annual cost as a function of the applied depth for various values of R_c.

use of this technique was a 10 MGD water treatment plant producing 20,000 gallons per day of sludge containing 5% solids. It was assumed that moisture was removed by dewatering until the solids contents reached 25% and then drying due to atmospheric conditions reduced the sludge to a final solids content of 50%. The specific resistance of the sludge was permitted to vary between values of 10^8 & 10^{10} sec^2/gm to show the sensitivity of the model to this parameter. The other parameters used were as follows:

Viscosity of sludge	0.01 gr/cm-sec
Coefficient of compressibility	1.0
Drying intensity	0.02 kg/m^2-hr
Depth of sand bed and supporting media	45.00 cm.

Cost used in the economic analysis were:

Land cost	\$10,000/acre
Construction cost	10,000/acre
Maintenance cost	1,000/acre/yr
Repair of beds	5,000/acre every 10 yrs
Application and removal of sludge	100/acre/application + 5.00/ton of solids
Interest rate	6%
Economic life	30 years
Salvage value	10,000/acre

Two days were allowed between each application to allow for sludge removal. A digital computer was programmed to give the solution for the simulation of this system. The output shown in Table 3-1 indicates that the optimum depth of sludge would be 17 cm for a sludge with a specific resistance of 10^9 sec^2/gm. The time required to reach the final moisture content was 48 days with the surface area of the sludge bed being 5.26 acres. Annual cost per year was \$33,570.00 or \$21.43/ton/yr. of which the operating cost amounted to \$12.56/ton/yr.

TABLE 3-1

DEPTH	T, DAYS	N	ACRES	COST	CTON	COPTON
1.00	4.31	2541	8.06	105258.87	67.1539	53.5666
2.00	6.40	1710	5.99	65632.79	41.8729	31.7800
3.00	8.49	1289	5.30	52444.34	33.4589	24.5297
4.00	10.64	1029	4.98	45909.50	29.2897	20.9003
5.00	12.87	851	4.81	42060.58	26.8341	18.7198
6.00	15.18	721	4.73	39563.50	25.2410	17.2623
7.00	17.59	622	4.70	37852.63	24.1495	16.2232
8.00	20.11	544	4.70	36630.49	23.3698	15.4418
9.00	22.74	481	4.73	35734.50	22.7982	14.8313
10.00	25.47	429	4.77	35060.95	22.3685	14.3358
11.00	28.32	386	4.82	34582.24	22.0631	13.9448
12.00	31.28	350	4.88	34255.12	21.8544	13.6352
13.00	34.35	318	4.94	33948.00	21.6584	13.3265
14.00	37.53	291	5.02	33763.98	21.5410	13.0869
15.00	40.83	268	5.09	33681.19	21.4882	12.9043
16.00	44.24	247	5.17	33582.98	21.4255	12.7057
17.00	47.77	229	5.26	33573.00	21.4192	12.5584
18.00	51.40	213	5.34	33596.65	21.4343	12.4283
19.00	55.16	198	5.43	33580.15	21.4237	12.2691
20.00	59.02	185	5.52	33634.71	21.4585	12.1524
21.00	63.00	173	5.61	33678.88	21.4867	12.0266
22.00	67.09	163	5.71	33839.01	21.5889	11.9727
23.00	71.29	153	5.80	33903.55	21.6301	11.8560
24.00	75.60	144	5.89	33994.96	21.6884	11.7550
25.00	80.02	136	5.99	34127.84	21.7732	11.6793
26.00	84.55	129	6.08	34317.84	21.8944	11.6389
27.00	89.20	122	6.18	34433.26	21.9680	11.5501
28.00	93.95	116	6.28	34625.95	22.0909	11.5099
29.00	98.81	110	6.37	34751.35	22.1709	11.4261
30.00	103.78	105	6.47	34976.63	22.3147	11.4055

STOP
TIME: 0.846 SEC.

ANALYTICAL APPROACH

As an alternative approach, the problem may be expressed in terms of an objective function that includes all relevant cost terms and their associated variables.

If this objective function Z can be expressed in terms of the initial depth of sludge application H_o, differentiation of Z with respect to H_o will yield the optimum depth H_o^* on setting $\frac{dZ}{dH_o} = 0$ and solving for H_o. This global optimum will correspond to cost minimization if $\frac{d^2Z}{dH_o^2} > 0$. Clearly, fixed costs may be neglected since only the optimum depth of application is to be located.

If variable costs comprise a cost associated with the required land area (acquisition, maintenance of sand beds,etc.) and a cost associated with the number of applications per land area (e.g., reworking beds after each drying-dewatering cycle), then the objective function to be minimized is

$$Z = C_1X_1 + C_2X_1X_2 \qquad 3\text{-}3$$

where C_1 = cost per unit land area

C_2 = cost per application per unit land area

X_1 = area of land required

X_2 = number of applications.

If the total annual volume of sludge is V_T, then the volume per application is

$$V_A = \frac{V_T}{X_2} \qquad 3\text{-}4$$

and

$$H_o = \frac{V_T}{X_1X_2} \qquad 3\text{-}5$$

therefore

$$Z = C_1 \frac{V_T}{H_oX_2} + C_2 \frac{V_T}{H_o} \qquad 3\text{-}5$$

but $X_2 = \dfrac{365 \cdot 24}{t_{dw} + t_{dry} + 48}$ where t_{dw} is the dewatering time and t_{dry} the drying time in hours.

So,

$$Z = \frac{C_1 V_T}{365 \cdot 24\ H_o} [t_{dw} + t_{dry} + 48] + \frac{C_2 V_T}{H_o} \qquad 3\text{-}7$$

The dewatering time is given by Equation 3-1 letting

$$\gamma_1 = \frac{\mu R_c S_o}{100\sigma(\sigma+1)H_c^{\sigma}} \qquad 3\text{-}6$$

The height H at the end of the dewatering period is given by λH_o where

$$\lambda = \frac{S_o}{S_{dry}} \cdot \frac{\rho_o}{\rho_{dry}}$$

where S_{dry} = solids content at end of dewatering

ρ_{dry} = density of sludge at end of dewatering

Equation 3-1 becomes

$$t_{dw} = \gamma_1(H_o + \varepsilon)^{\sigma+1} + \gamma_1\sigma(\lambda H_o + \varepsilon)^{\sigma+1} - \gamma_1(\sigma+1)(H_o + \varepsilon)(\lambda H_o + \varepsilon)^{\sigma} \qquad 3\text{-}8$$

where ε = depth of sand and supporting media

This equation is then substituted for t_{dw} in Equation 3-7.

The drying time, given by Equation 3-2 can be transformed as follows with the critical moisture content given by Equation 13 of Nebiker's study (5):

$$\frac{W_{TS}}{A} = \frac{S_T}{X_1 X_2} = \frac{S_T}{V_T} \cdot H_o \qquad 3\text{-}4$$

$$U_{CR} = 500(I_{S,C} \cdot \frac{S_T}{V_T})^{0.5} \cdot H_o^{0.5}$$

therefore

$$t_{dry} = \beta_2 H_o[U_o - \beta_1 H_o^{0.5} + \beta_1 H_o^{0.5} \ln(\frac{\beta_1 H_o^{0.5}}{U_t})] \qquad 3\text{-}9$$

where

$$\beta_2 = \frac{S_T}{V_T\ 100\ I_{S,C}} \quad \text{and} \quad \beta_1 = 500(I_{S,C} \cdot \frac{S_T}{V_T})^{0.5}$$

Note that $\frac{S_T}{V_T} = \frac{S_o\ o}{100}$, and thus β_2 and β_1 are independent of the total annual quantities of sludge. Given β_1, β_2, U_o, U_t, the drying time can thus be expressed in terms of H_o, and Equation 3-9 can be substituted for t_{dry} in the objective function [3-7], which can now be written as:

$$Z = \frac{C_1\ V_T}{365 \cdot 24\ H_o}[\beta_2\ U_o\ H_o - \beta_2\ \beta_1\ H_o^{1.5} + \beta_2\ \beta_1\ \ln(\frac{\beta_1 H^{0.5}}{U_t}) + 48$$

$$+ \gamma_1(H_o+\varepsilon)^{\sigma+1} + \gamma_1\sigma(\lambda H_o+\varepsilon)^{\sigma+1} - \gamma_1(\sigma+1)(H_o+\varepsilon)(\lambda H_o+\varepsilon)^{\sigma}] + \frac{C_2\ V_T}{H_o} \qquad 3\text{-}10$$

If $\sigma = 1.0$, then differentiation yields

$$\frac{dZ}{dt} = \frac{C_1\ V_T}{365 \cdot 24}[\frac{\beta_1\ \beta_2}{2}\ H_o^{-0.5}\ \ln(\frac{\beta_1\ H_o^{0.5}}{U_t}) - \frac{48}{H_o^2}$$

$$-\gamma_1(1 - \frac{\varepsilon^2}{H_o^2}) + \gamma_1(\lambda^2 - \frac{\varepsilon^2}{H_o^2}) - 2\gamma(\lambda - \frac{\varepsilon^2}{H_o^2})] - \frac{C_2\ V_T}{H_o^2} \qquad 3\text{-}11$$

setting $\frac{dZ}{dH_o} = 0$ and dividing by $\frac{C_1\ V_T}{365 \cdot 24\ H_o^{*2}}$ we obtain

$$\frac{\beta_1\ \beta_2}{2}\ \ln(\frac{\beta_1\ H_o^{*0.5}}{U_t})\ H_o^{*1.5} + H_o^{*2}\ \gamma_1(1-\lambda)^2 - 48 - \frac{C_2}{C_1}\ 8740 = 0 \qquad 3\text{-}12$$

Note that this expression is independent of V_T and ε, thus the total annual volume does not affect the location of the optimum H_o^*.

This expression may be solved for H_o^* by trial and error given the required values of constant terms. Alternatively, a bisection routine may be employed to locate the roots of this expression on the computer over given ranges of initial conditions. Figure 3-3 shows the optimum depth H_o^* as a function of R_c and C_1/C_2 for given S_o = 5% and U_t = 100.

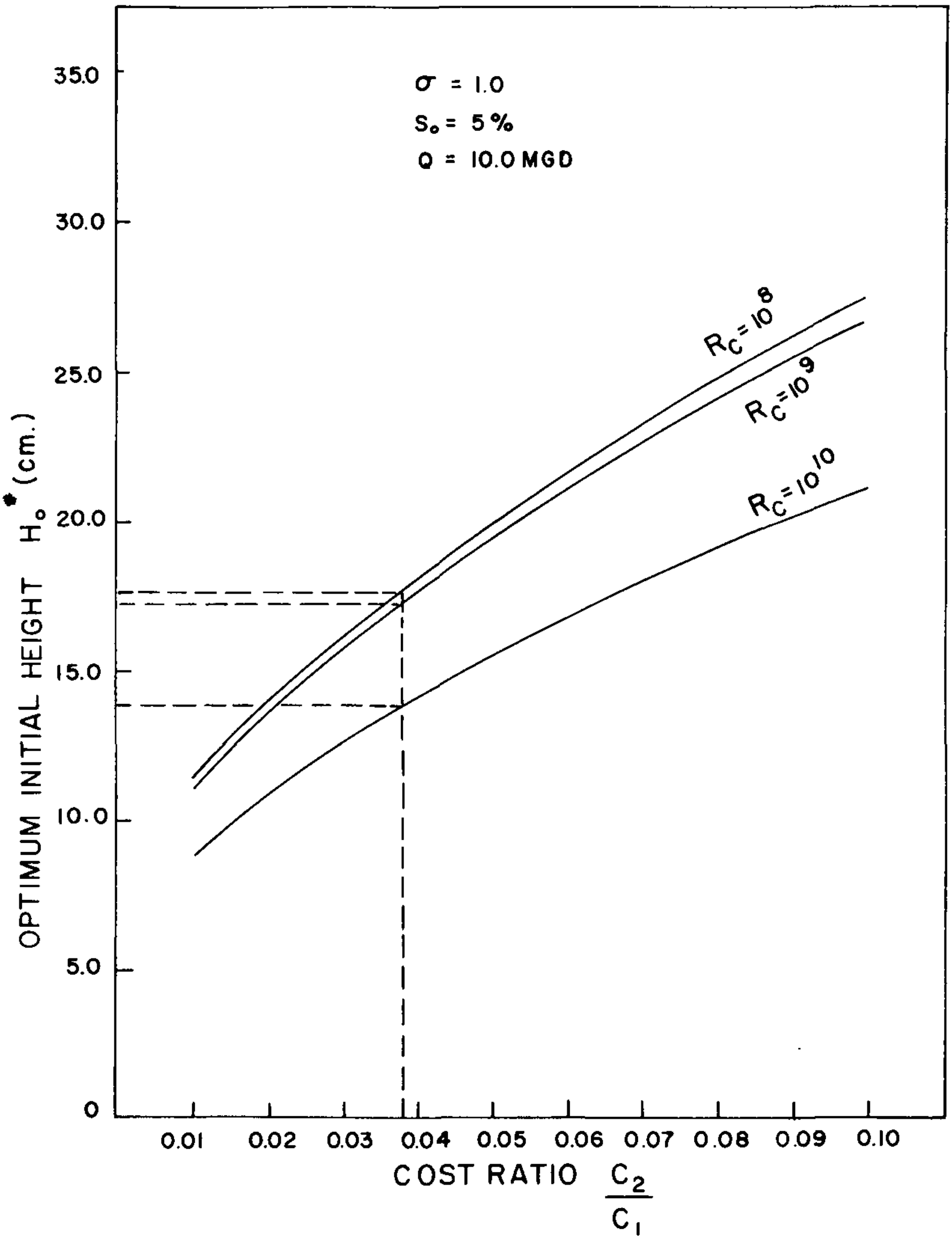

Figure 3-3. Optimum initial height H_0^* as a function of C_1/C_2 (ratio of cost per unit land area to cost per application per unit land area), for various values of R_c.

For $C_1/C_2 = \frac{1}{26.40}$ and $R_c = 10^9\ sec^2/gm$, $H_o^* = 17.3$ cm, which corresponds well with the value obtained by direct simulation.

Promising lines of further exploration of simulation models currently under development include a simultaneous rather than sequential-dewatering-drying cycle, incorporation of stochastic variables to simulate the effect of varying climatic and meteorological conditions (precipitation, temperature, freezing) and multivariate statistical models expressing the optimal depth as simple polynomial functions of initial conditions. Modified objective functions to include fixed costs per application and cost of storage capacity are also under study.

It is anticipated also that inclusion of this simulated model for sludge dewatering and drying could be incorporated into a study such as Smith's (7), providing an alternative to the vacuum filter. Effort to accomplish this will be undertaken.

Explanation of Symbols

A = surface area of drying sludge = X_1, sq. m

ρ_o = density of sludge kg/m^3

H = final depth of sludge at the final solids content, m

H_o^* = optimum initial depth, m

H_o = initial depth of sludge application, m

$I_{S,C}$ = drying intensity [kg]/[m^2][h]

S_o = initial solids content, in %

S_T = total weight of sludge solids per year, kg

V_A = volume per application, m^3

V_T = total volume of sludge per year, m^3

U_{CR} = critical moisture content, in %

U_o = moisture content at beginning of drying, in %

U_t = moisture content at end of drying, in %

X_2 = number of spplications per year

t_{dry} = drying time, hours

t_{dw} = dewatering time, hours

ε = depth of sand, cm

μ = viscosity of sludge $[\frac{kg}{m\text{-}hr}]$

R_c = specific resistance of sludge $\frac{[hr]^2}{kg}$

H_c = reference head for R_c determination

σ = coefficient of compressibility

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IV. CONDITIONING OF SLUDGE BY FREEZING

by Thomas R. Roule

INTRODUCTION

Several conditioning methods have been attempted to increase the dewatering rate of waste sludges. One such method is freezing and thawing of the sludge. Experiments have been conducted by others to evaluate the effects of freezing on sludges (1). The results have been striking. They have shown that the rate of freezing as well as the time the sludge is frozen has an effect on the dewatering characteristics of the sludge. Natural freezing appears to be an important factor in land disposal by dewatering methods (2), and hence justifies further research in order to develope drainage relationships. The purpose of this paper is to present results at this interim stage of development.

Two physical parameters of sludge, namely, specific resistance and coefficient of compressibility, would normally be used to evaluate the effects of freezing and thawing upon the dewatering characteristics of sludge. A decrease in the value of the specific resistance brought about by freezing and thawing would indicate the dewaterability of the sludge had been improved. Similarly, lower values of the coefficient of compressibility obtained after freezing and thawing would indicate that the sludge solids matrix had become more rigid. The combined effect upon dewaterability of changes in the specific resistance and the coefficient of compressibility would be evaluated by use of the methods outlined in reference (3).

However, if freezing and thawing brought about a rapid, ready separation of the sludge solids from the surrounding liquid, the normal specific resistance and coefficient of compressibility tests would not be applicable. For inherent in the normal vacuum filtration testing and data evaluation procedure is the assumption that the sludge solids are not separated from their liquid environment by sedimentation but are separated by filtration. The concept of sludge cake resistance is an applicable parameter which may be used to evaluate the filtration properties of a sludge cake, even one which separates readily by sedimentation from its liquid environment.

THEORETICAL DEVELOPMENT

The applicable relationship for use in evaluating the sludge cake resistance is equation 2-20b of reference (3):

$$\frac{dV}{dt} = \frac{\rho\ g\ A\ h_f}{\mu(LR' + L_F\ R'_F)} \qquad 4\text{-}1$$

with t = time

μ = dynamic viscosity of filtrate

ρ = mass density of filtrate

A = cross sectional area

h_f = head loss

V = volume of filtrate

R' = resistance of sludge cake

R'_F = resistance of filter

L = depth of sludge cake

L_F = depth of filter.

The sludge cake does not increase in thickness during an experiment; this justifies treating L as a constant and integrating Equation 4-1 to obtain

$$t = \frac{\mu V (LR' + L_F R'_F)}{\rho g A h_f} \qquad 4\text{-}2$$

which is applicable for h_f remaining constant during a test. A constant head permeameter fulfills the assumptions used in obtaining Equation 4-2.

EXPERIMENTAL PROCEDURE

Sludge samples were prepared by taking a one-liter container of sludge and dividing it into five 200-ml portions. This would minimize the freezing time of each portion. After the 200-ml portions were frozen in a -10° C freezer and thawed, they were recombined into the one-liter container to maintain uniformity in testing. Samples for testing were then drawn from the one-liter container. If the samples had been incompletely frozen, specific resistance and coefficient of compressibility tests were run. If the sludge had frozen completely, cake resistance tests were run in a constant head permeameter as shown in Figure 4-1.

The procedure used for determining the specific resistance and the coefficient of compressibility was the same as outlined in reference (3). The procedure used to evaluate the sludge cake resistance in the constant head permeameter consisted of recording the volume of outflow from the permeameter at regular intervals (30 seconds) so that the average volume per time could be calculated. Then by recording the temperature, the length of the cake, and the head loss, the sludge cake resistance could be calculated by Equation 4-2. A FORTRAN program for use on a remote console teletype communicating with a time-sharing CDC 3600 Computer was utilized for calculating the sludge cake resistance.

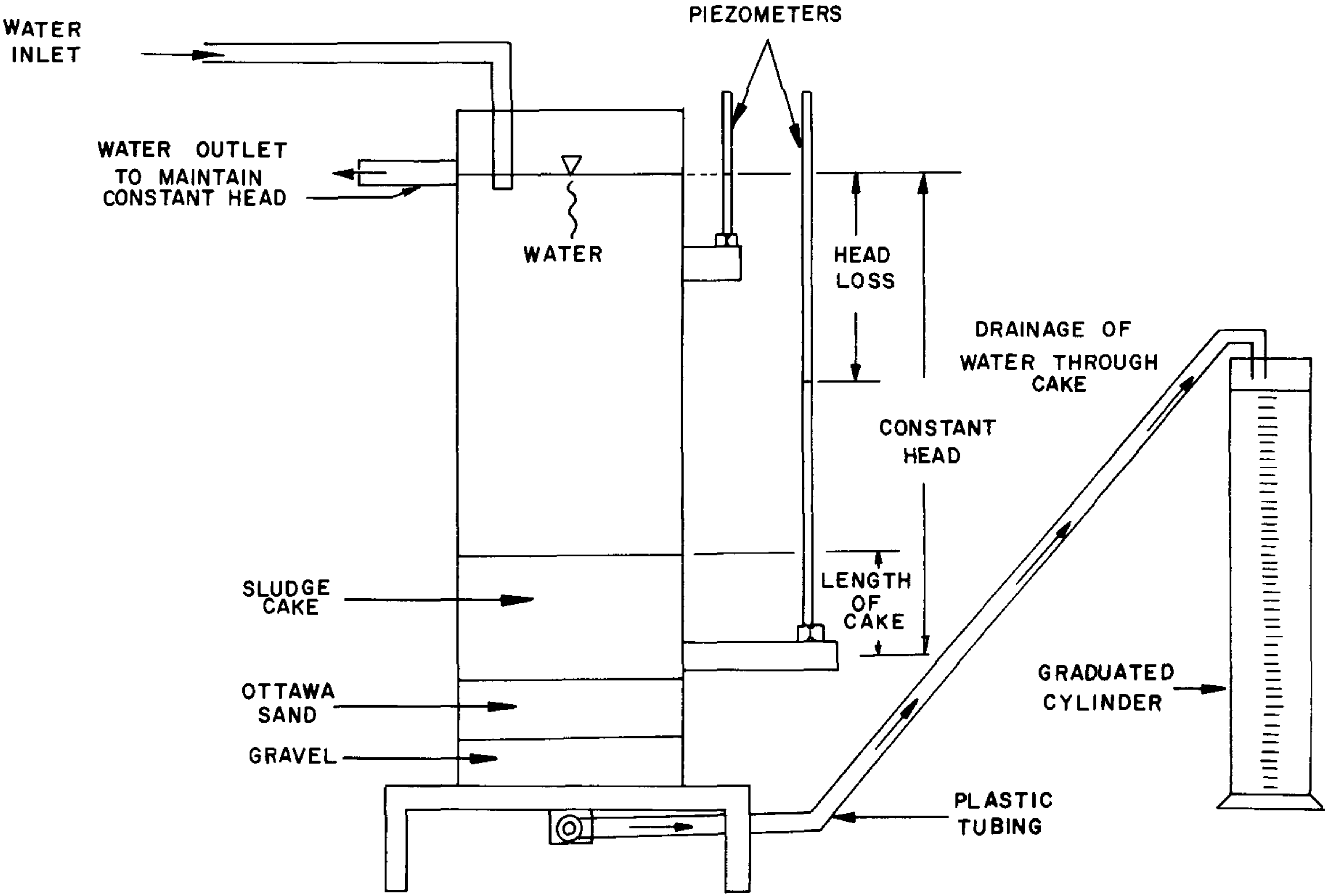

Figure 4-1. Constant head permeameter.

In addition to the above tests on sludge drawn from the sedimentation basins of water treatment plants, tests were carried out on the effects of freezing and thawing on the dewatering properties of concentrated sludge cakes. The concentrated sludge cakes were obtained from gravity dewatering columns after gravity drainage had essentially ceased. The solids content of the sludge cake was recorded prior to freezing, then the sludge cake was frozen, then thawed. Water which separated from the sludge solids was permitted to drain freely, then the solids content of the remaining sludge cake was noted. The sludge cake after freezing, thawing and draining is shown in Figure 4-2.

EXPERIMENTAL RESULTS

Table 4-1 shows results of specific resistance tests run for unfrozen sludge and the same sludge after being in the freezer for durations of between one and three hours.

Time in Freezer (hrs.)	Final Temperature (°C)	Specific Resistance @ 11 cm Hg (sec^2/gm)	Coefficient of Compressibility
Unfrozen	+20	$.235 \times 10^9$	.89
1	+1	$.24 \times 10^9$	.87
3	-1	$.19 \times 10^9$	.88

TABLE 4-1

The coefficient of compressibility was unchanged while only a slight decrease in the specific resistance was noted. The sludge in the freezer for three hours had been only slightly frozen around the edges. After five or more hours in the freezer, the sludge was frozen throughout.

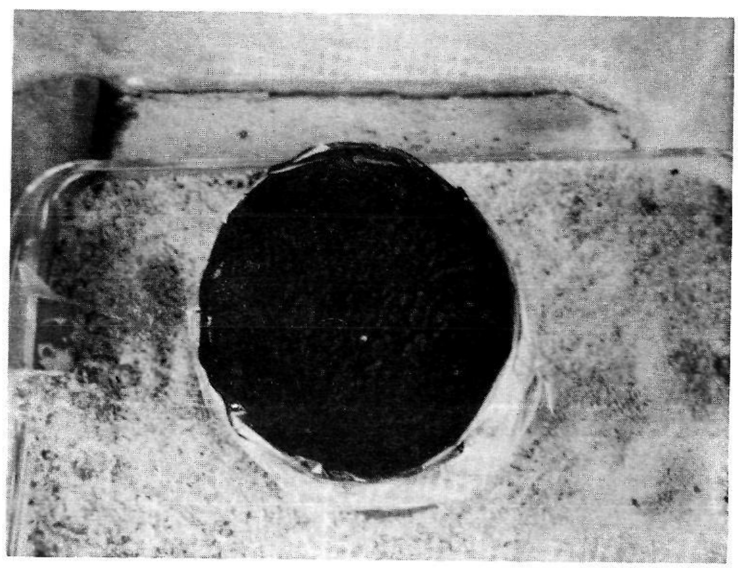

Figure 4-2 Sludge cake after freezing, thawing, and drainage.

When the frozen sludge was thawed, the solids separated readily from the liquid. If allowed to remain quiescent, the solids sedimented rapidly to the bottom of the container leaving behind a clear supernatant. When remixed by agitation and again allowed to become quiescent, they again separated readily although the supernatant was cloudy.

If the agitated sample was placed in a Buchner funnel for specific resistance testing, the water would drain off quickly before an equilibrium pressure differential had been achieved and spurious results would have been calculated. Instead of attempting to run a specific resistance test, the sludge cake resistance was determined by use of the constant head permeameter. Results obtained from the permeameter tests are shown in Table 4-2. The cake resistance for the control was obtained by adjusting the experimental value determined at 30 cm Hg to a pressure differential of 10 cm of water, corresponding to the permeameter tests.

Time in Freezer (hrs.)	Cake Resistance (cm^{-2})
0 Unfrozen	10.70×10^8
5	$.46 \times 10^8$
6	$.17 \times 10^8$

TABLE 4-2

The samples which had been in the freezer five hours were nearly completely frozen while those which had been in the freezer for six hours appeared completely frozen.

Results of test on the concentrated sludge cakes obtained from gravity dewatering beds have shown a breakdown of the cake structure to a watery nature with crystalline solids settling out of the sludge upon thawing (4). Experiments run on sludge cakes dewatered on sand beds have resulted in a thirty per cent decrease in weight from an initial 14% solids content to 20% after thawing. This is consistent with earlier results by Babbitt on wastewater sludges (2).

SIGNIFICANCE OF RESULTS

The results show that freezing is necessary to effect a change in the specific resistance and the coefficient of compressibility. Partial freezing produced a proportionate decrease in the specific resistance and in the sludge cake resistance.

The ready separation of the thawed solids from the liquid environment violates some of the assumptions which are used in developing the specific resistance equation. Therefore, a direct comparison of the specific resistance before freezing and after freezing is not applicable. Instead, the sludge cake resistance becomes the standard of comparison. Results shown in Table 4-2 indicate the magnitude of the decrease in cake resistance which freezing and thawing can effect. The cake resistance R' is the reciprocal of the intrinsic permeability (3). The cake resistances before freezing and after five and six hours in the freezer correspond to intrinsic permeabilities of 0.96 darcy, 2.21 darcy and 5.91 darcy, respectively. In ground water practice the first value is characteristic of poor aquifers while the latter two values are characteristic of good sand aquifers (5).

Microscopic comparisons verify the results obtained by Dean (4) that the solids become crystalline in structure after freezing.

The results show the importance of freezing and thawing as a method of conditioning. Test run on previously dewatered cakes show that freezing may be applicable to this type of sludge if freezing sludge before dewatering is prohibitively expensive. Natural freezing and thawing of sludge on dewatering beds appears very important and justifies more research in this area. There is also a need to relate cake resistance quantitatively to specific resistance. In addition, the relation of freezing and thawing to the drying properties of the sludge cake is worthy of elucidation.

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V. FILTER PRESS FILTRATION

by Thomas J. Beliveau

INTRODUCTION

Pressure filters are used in many processes for liquid-solids separation. The search for effective methods to dewater water treatment waste sludges must therefore include investigation of pressure filters. The purpose of this investigation was to determine the feasibility of using laboratory techniques to predict the performance of large-scale pressure equipment used in the dewatering of water treatment plant sludges.

Filtration is the process of separating the solid particles from a mixture of solid particles and a fluid by means of a permeable medium which allows the passage of the fluid and retains the solid in the form of a thickened cake. Advantages of the filter press (plate-and-frame filter) are its mechanical simplicity, efficient operation, and low investment cost. Inherent disadvantages include cyclic operation due to the necessity of periodic removal of filtered solids from the filter medium and the difficulty of filtering extremely small suspended particles without the addition of filter aid.

This report is designed to provide a brief description of work aimed at determining specific cake resistance and coefficient of cake compressibility for the pressure (30-70 psi) filter press filtration of alum sludge from Billerica, Massachusetts.

Included are brief descriptions of equipment and operating procedures. Results of several test runs at various filtering pressures are summarized.

THEORETICAL BACKGROUND

The theory of compressible cake filtration used as a basis for the calculations of this report is developed fully by Adrian, Lutin, and Nebiker in Source Control of Water Treatment Waste Solids (1). Here it is shown that compressible cake resistance may be computed according to

$$R = \frac{2\ b\ A^2\ \Delta P}{\mu\ C} \qquad 5\text{-}1$$

where R = specific resistance (sec^2/gm)

b = slope of t/V versus V (sec/ml^2)

A = filtering area (cm^2)

ΔP = test pressure ($dynes/cm^2$)

μ = dynamic viscosity (poise)

C = weight of solids per unit volume of filtrate (gm/cm^2-sec^2)

V = volume of filtrate collected (cm^3)

t = time from collection of first filtrate (sec)

The weight of solids per unit volume of filtrate is given by

$$C = \frac{\rho\ g}{\frac{100}{S_o} - \frac{100}{S_f}} \qquad 5\text{-}2$$

where ρ = density of filtrate, assumed water (gm/cm^3)

g = gravitational constant (980.2 cm/sec^2)

S_o = initial sludge solids content (%)

S_f = solids content of filter cake (%)

The coefficient of cake compressibility is related to the filtering pressure by

$$R = R_c\left(\frac{H}{H_c}\right)^{\sigma} \qquad 5\text{-}3$$

where R_c = cake specific resistance at $H = H_c$ (sec^2/gm)

σ = coefficient of cake compressibility (dimensionless)

MATERIALS AND EQUIPMENT

The water treatment sludge used for tests summarized in this report was obtained from the Billerica, Massachusetts, water treatment plant in November, 1968. The solids portion of the sludge contained activated carbon with a particle size of 1 - 5 microns. The average composition was 2-3 weight percent solids. The sludge was stored at room temperature (approximately 80F).

A schematic diagram of the apparatus used for the tests covered in this report is given in Figure 5-1. More detailed descriptions of major pieces of equipment follow.

The plate-and-frame filter press was fabricated by T. Shriver & Co., Inc., Harrison, N. J., of cast iron. The press contained four plates and two 1 1/2-inch frames providing a total filtering area of 3.06 square feet. It is shown in Figure 5-2 together with peripheral equipment.

The filter cloths used were manufactured by the T. Shriver Co. and were of cotton duck. Count warp and fill was specified at 36 X 30 while cloth weight was approximately 15.5 oz. per yard.

The feed tank contained approximately 15 cubic feet when full and was equipped with an electric motor with a 3-inch impellor for agitation of the contents. The inlet to the 3-horsepower Worthington Corporation centrifugal pump ran from the bottom of the feed tank. A recycle line was provided from the pump outlet to the top of the feed tank.

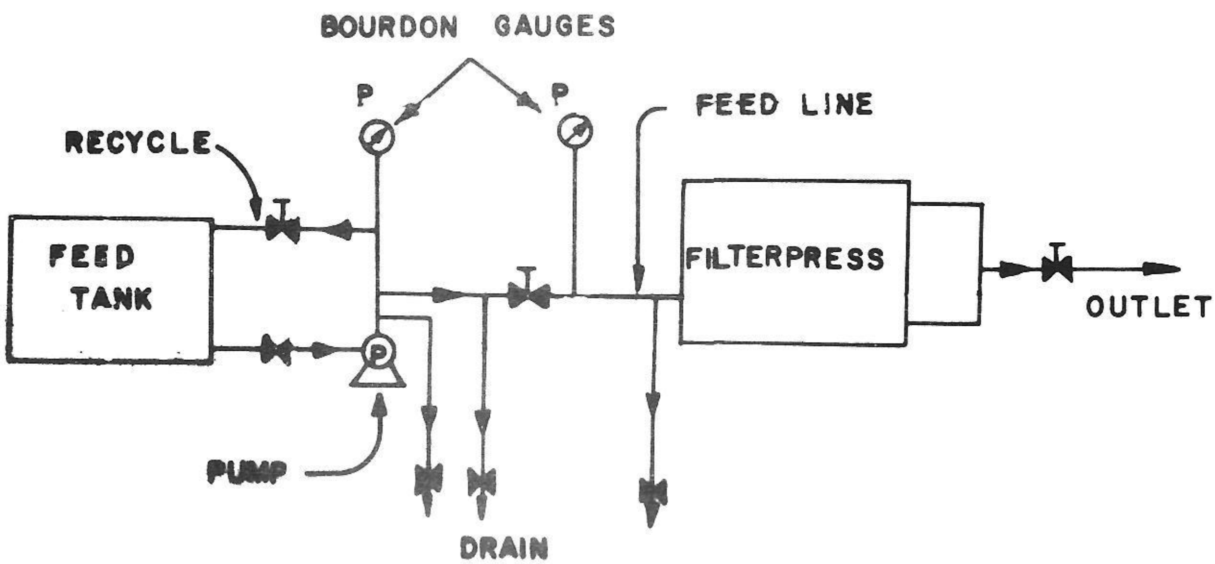

Figure 5-1. Schematic of filter press apparatus.

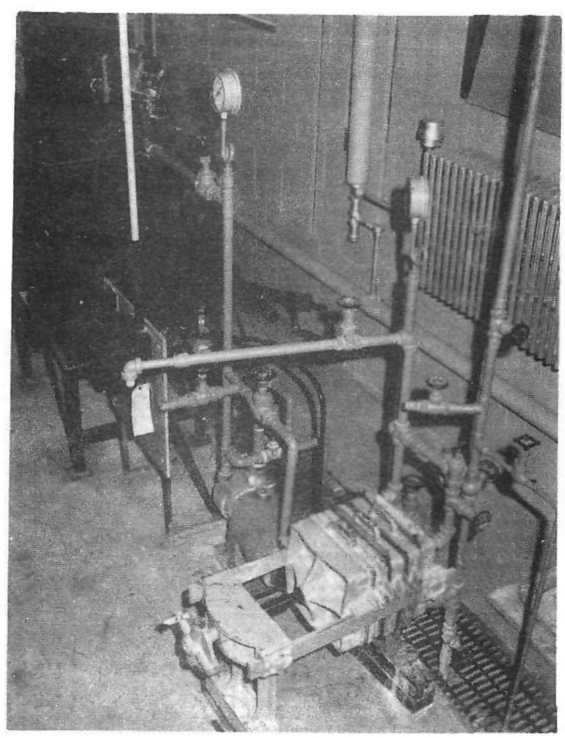

Figure 5-2. Plate-and-frame filter press apparatus.

Sludge filtrate was fed directly from the filter press to a 5-gallon pail resting on a double-arm balance (0 - 75# ± 0.5 oz.).

OPERATIONAL PROCEDURE

Samples to be used for the determination of the solids content of the sludge were taken directly from the feed tank within 30 minutes prior to an experimental run. To insure proper mixing, the agitator was started 5 minutes before sampling. At the same time, total recycle was maintained through the pump to the feed tank to aid mixing and to minimize sedimentation in the feed tank, system piping, and pump head. Solids analyses were performed in accordance with Standard Methods for the Examination of Water and Wastewater, 12th Edition. 1965.

Each cloth was cleaned in soap and water before each test and soaked in cold water before installation in the press. The edges of the filter press plates and frames were coated with vacuum grease to eliminate pressure leaks.

The feed tank agitator and full recycle was employed 5 minutes before the start of a run to provide a constant composition feed stock throughout the duration of the test. The inlet valve to the press was then opened to allow the filter press frames to fill with sludge. The recycle line was kept full-open at this time until a steady 10 psi head was developed across the filter press. When a reasonably stable system had been obtained, the recycle valve was rapidly closed until the desired operating pressure was observed at the Bourdon gauges. Timing and filtrate weighing was then immediately begun.

The run was terminated by opening the recycle valve to reduce the filtering pressure. Unfiltered sludge was then drained from filter press frames and three samples of cake from all four filtering surfaces were collected, weighed, and dried as previously described.

EXPERIMENTAL RESULTS

TABLE 5-1 Resistance and Operational Data

ΔP	T	S_o	S_f	R
(PSI)	(°C)	(WGT %)		(SEC^2/GM)
30	27.8	2.49	6.82	$9.35(10^8)$
30	26.1	2.46	10.81	$3.45(10^9)$
30	26.7	2.45	11.81	$4.63(10^9)$
50	27.2	2.53	12.86	$5.96(10^9)$
50	26.7	2.46	13.91	$6.66(10^9)$
70	28.3	2.48	12.96	$8.15(10^9)$

Calculation of the compressibility coefficient was made from the average value of the specific resistance for each of the pressures noted in Table 5-1. Figure 5-3 is a plot of the specific resistance versus filtering pressure on log-log paper from which the coefficient of compressibility was computed to be 1.16.

DISCUSSION OF RESULTS

Rapid sludge sedimentation has been shown to be a difficult problem in obtaining accurate sludge solids samples from the feed tank. With this fact in mind, the largest practical sample was taken and weight measurements were made to be accurate to at least a milligram per 100 milliliter sample. Reasonable care thus limited deviations of any one sample from the average of three samples to less than 5% in most cases.

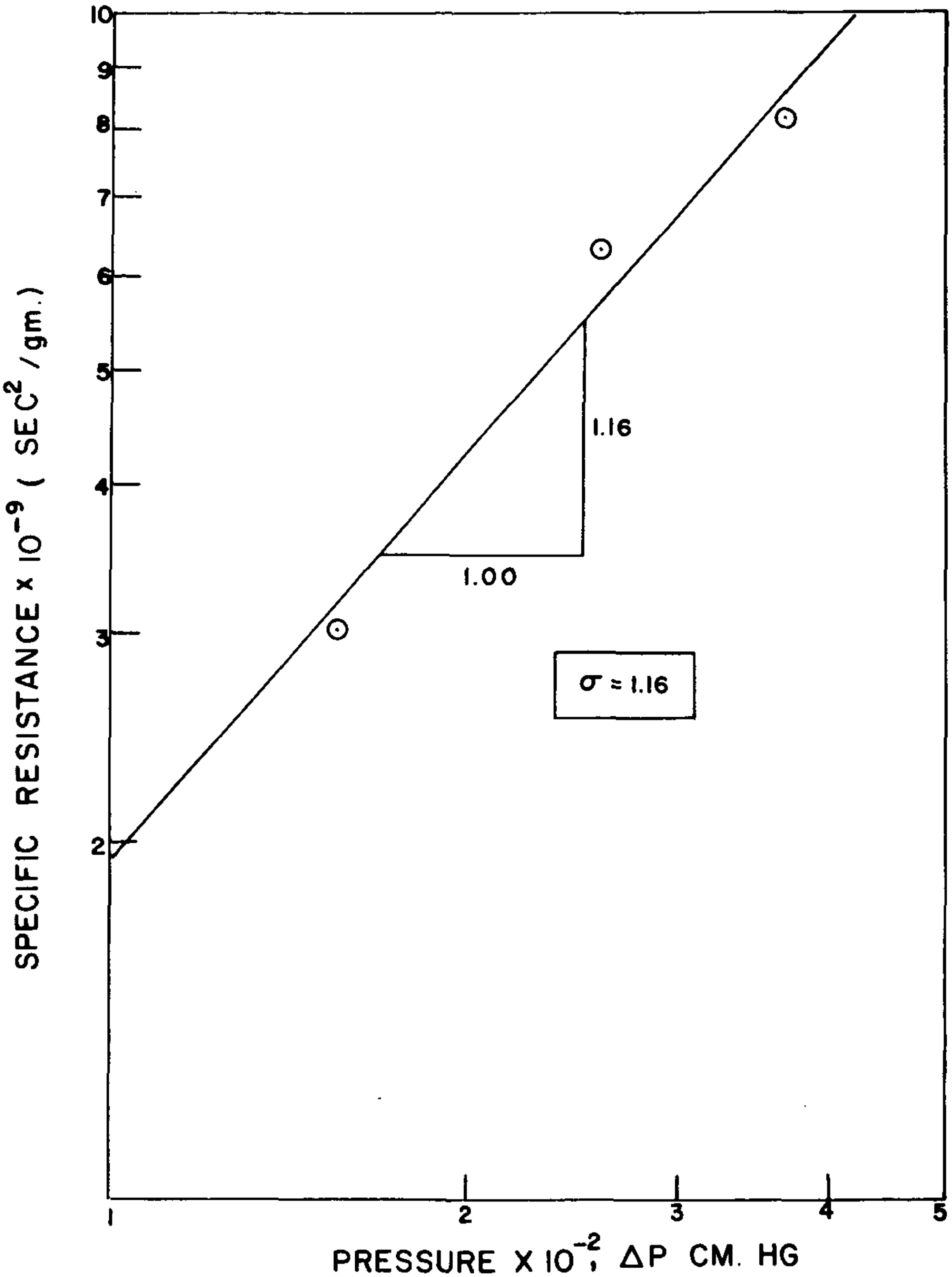

Figure 5-3. Specific resistance, R, versus pressure, ΔP.

Difficulty was experienced in cake sampling, where the nature of the compressible filter cake complicated exact definition between the actual cake and the bulk of the unfiltered sludge. Care must be taken to standardize the sampling procedure so that valid comparisons may be made among various tests. Some success has been realized in this area, for the deviation of any one sample from the average of three samples is again within an acceptable 5% experimental spread.

Other sources of error have been isolated although their relative significance has not been determined. The first of these is related to the amount and intensity of agitation provided by the mixing impellors of the agitator shaft and the centrifugal pump. It is strongly suspected that high shear forces exerted by these two impellors serve to deflocculate the sludge being tested as it is circulated through the system. Thus, from one test to the next it is probable that the sludge cake specific resistance could increase merely because of particle deflocculation. This postulate is supported by data reported in Table 5-1 where it is seen that the specific resistance increases from one test to the next even without an increase in filtering pressure.

A second variable which may be a source of experimental error concerns the reuse of filter cloths for all six tests summarized in this report. An inherent assumption in the derivation of Equation (5-1) for specific resistance is that the resistance of the filter medium be much less than that of the sludge cake. Slow clogging of the interstices of the filter cloths over the period of several tests might greatly affect the measurements of cake resistance. Such an effect could also explain the generally increasing specific resistances already noted in Table 5-1 and should be considered in subsequent filter press design work.

There is need for additional work in using the specific resistance and coefficient of compressibility obtained by standard procedures to predict the performance of a filter press. Such tests may have to be carried out in a pressure cell instead of by vacuum filtration in order to avoid extrapolating test results from tests conducted at atmospheric pressure, or less, to predict the performance of pressure filters operating at several atmospheres of pressure.

Also, additional data is needed about the role of the several types of filter cloth which are available. Can pressure cell tests predict the performance of a filter cloth for various types of sludge? Can factors such as the expected life of a filter cloth be estimated from pressure cell or vacuum filtration tests?

Filter aids show great promise in increasing the yield of a filter press. Is it necessary to run pilot tests on scaled down pressure filters in order to determine the optimum dosage of precoat and body feed, or can a rapid simplified test such as vacuum filtration or pressure cell filtration predict the results?

The laboratory tests performed on the filter press described herein have helped to answer some questions while raising several more. Additional research will provide the answers to many of these important questions. An important start has been made and the tests described herein have pointed out some of the potential applications of the filter press to dewatering water treatment sludge.

SAMPLE CALCULATIONS - Analysis No. 5

(1) Specific Resistance

$b = 3.0(10^{-5})\ sec^2/gm$ - from regression analysis of plot of t/V versus V (see Theory section)

$A^2 = 8.08(10^6)\ cm^4$

$\Delta P = 3.44(10^6)\ dynes/cm^2$

$T = 26.7\ C$

$\mu = 8.60(10^{-3})$ poise (from viscosity tables)

$S_o = 2.46\%$ $\quad S_f = 13.91\%$

$\rho = 0.9966\ gm/cm^3$ (from density tables for water)

$$C = \frac{0.9966\ (980.2)}{\frac{100}{2.46} - \frac{100}{13.91}} = 29.9 \qquad 5\text{-}2$$

$$R = \frac{2.0(3.0)(10^{-5})(8.08)(10^6)(3.44)(10^6)}{(8.6)(10^{-3})(29.9)} \qquad 5\text{-}1$$

$$= 6.66(10^9)\ sec^2/gm$$

(2) Coefficient of Cake Compressibility

See Figure 5-3 in the text for a graphical computation (the actual computation was made using a computerized curve fitting technique).

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VI. An Appendix of Definitions for Disposal of Wastewater Treatment Sludge*

D. D. Adrian and J. H. Nebiker

The following selective list of definitions is applicable to the manual on sludge dewatering; it is not proposed as a comprehensive glossary.

1. activated sludge - a biological growth produced by the activated sludge process. Waste activated or excess sludge is the component to be disposed. Return sludge is recirculated within the biological treatment process.

2. alkalinity - the capacity for neutralizing acid. Bicarbonate alkalinity is due to the presence of bicarbonate in the absence of hydroxide or carbonate alkalinity.
   Methyl orange or methyl purple alkalinity measures total alkalinity. Phenolphthalein alkalinity generally results from the presence of hydroxide or normal carbonate.

3. alum - aluminum sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$); used as a coagulant.

4. anion - a negatively charged ion.

5. B.O.D. or biochemical oxygen demand - the amount of oxygen required for the biological oxidation of degradable organic content in a liquid, in a specified time and at a specified temperature. Usually expressed in mg/l as 5-day 20°C BOD.

6. biological sludge - also known as secondary sludge. Includes all activated sludges, and trickling filter humus.

*Prepared for the ASCE-WPCF Manual of Practice on Sludge Disposal

7. British thermal unit (BTU) - a unit of heat equal to the amount necessary to raise one pound of water one degree Fahrenheit.

8. Buechner or Buchner funnel - a laboratory device for filtering, used with filter papers, cloths or other media, frequently used to determine specific resistance of sludge.

9. cake compressibility factor (s) - also known as the coefficient of compressibility. An empirically derived factor relating specific resistance of sludge cake to filtering pressure (dimensionless).

10. cake solids - percent dry solids in wet cake discharged from filter; as commonly reported this includes weight of sludge conditioning chemicals which may amount to 5 to 15 percent of the dry sludge solids.

11. cation - a positively charged ion.

12. centrate - the effluent, or liquid portion of a sludge, removed by or discharged from a centrifuge.

13. centrifuge - a dewatering device utilizing centrifugal force for concentration of suspended matter. A centrifuge may either thicken or dewater sludge.

14. chemically precipitated sludge - sludges resulting from the addition of coagulants and flocculants to wastewaters. Many sludges from advanced waste treatment and wastewater renovation are of this type.

15. clarification - removal of turbidity or other suspended solids from the suspending liquid.

16. coagulant - a chemical added to wastewater or sludge to promote agglomeration and flocculation of suspended solids in order to induce faster settling or more efficient filtration. Typical coagulants are polyelectrolytes, alum, and ferric chloride.

17. concentrate - to increase the proportion of solids in a sludge or wastewater.

18. colloid - a nonsettleable suspended solid.

19. conditioning - a pretreatment of sludge to facilitate water removal.

20. copperas - a chemical, ferrous sulfate ($FeSO_4 \cdot 7H_2O$), used as a coagulant. Chlorinated copperas ($FeSO_4 \cdot Cl$) is prepared by the application of chlorine to ferrous sulfate.

21. dehydrating - removal of moisture by drying, usually at elevated temperatures. Hydrate water is molecularly bound in a solid. The adjective anhydrous refers to a dehydrated material, such as anhydrous lime.

22. dewatering - any process of water removal or concentration of a sludge slurry, as by filtration, centrifugation, or drying. (In this manual a dewatering method is considered any process which will concentrate the sludge solids to at least 15% by weight.)

23. dewatering bed - a wastewater treatment unit usually containing a bed of sand upon which sludge is placed to dewater by gravity drainage and evaporation. Usually synonymously the same as a drying bed or a sludge bed.

24. digested sludge - sludge biologically stabilized by either aerobic or anaerobic digestion.

25. dosage or dose rate - dry weight of coagulant added to sludge per unit weight of dry sludge solids. Frequently expressed as a percentage of dry sludge solids.

26. drum submergence - also known as filter submergence. Fraction of the total drum filter area of vacuum filter which is submerged. Also defined as the ratio of filter cake form time to total cycle time.

27. drying bed - a wastewater treatment unit usually containing a bed of sand upon which sludge is placed to dry by evaporation and drainage. Usually synonymously the same unit as a sludge bed or dewatering bed.

28. effective size - the sieve size which will pass 10 percent by weight of a soil or sand. Designated as d_{10}.

29. elutriation - a washing of sludge, usually with sewage effluent, reducing the sludge alkalinity and fine particles, and thus decreasing the amount of required coagulant in further treatment steps, or in sludge dewatering.

30. feed solids - dry weight of suspended solids in the influent to a sludge treatment or a sludge dewatering device.

31. ferric chloride - a chemical ($FeCl_3$) often used for sludge conditioning.

32. filter aid - materials added to sludge to increase the rate of dewatering.

33. filter blinding - clogging of filter media by sludge particles, coagulants, or other materials.

34. filter leaf - a laboratory device for testing potential performance of a vacuum filter on a sludge.

35. filtrate - the effluent or liquid portion of a sludge removed by or discharged from a filter.

36. filtration rate (W/A) - a rate of solids removal by vacuum filtration expressed as weight of dry cake solids per unit area ($lbs/ft^2/hr$).*

37. floccule - a small loosely aggregated mass of material precipitated from or suspended in a liquid.

38. form filtration rate (W/Ae) - rate of suspended solids removed by vacuum filtration expressed as weight of dry cake solids per unit area and per unit formation time ($lbs/ft^2/hr$).*

39. form time - time period during one drum revolution of vacuum filter in which vacuum is applied for moisture removal and cake formation.

40. Imhoff tank sludge - a digested primary sludge produced by an Imhoff tank.

41. ions - dissociated charged atom or group of atoms in a solution.

42. liquor - also known as sludge liquor or natant. The liquid portion of sludge; or water removed during concentration process such as filtrates, centrates, and supernatants or subnatants; from sludge digestion tanks or sludge concentration tanks.

43. load factor - fractional amount of time that a machine is in operation, or the ratio of output to capacity.

44. mesh number - a measure of the number of wire grids in a mesh per inch. These are standardized as the U.S. Series and the Tyler Series.

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* As commonly reported these include the weight of chemicals used for sludge conditioning, which may amount to 5 to 15 percent of the dry sludge solids.

45. mixed sludge - a mixture of raw or digested primary and secondary sludges. In some activated sludge plants the sludges are mixed by returning waste sludge to the primary sedimentation tanks, or to sludge thickeners.

46. moisture content - also called water content. Weight of water in the sludge per unit total weight of sludge. Expressed as percent.

47. nonionic - referring to an uncharged or electrically neutral particle.

48. oxidation - process which increases the proportion of oxygen, acid forming element, or radical in a compound.

49. pH - the base-10 logarithm of the reciprocal of the concentration of hydrogen ion in solution. The pH range is generally considered to be from 0 to 14, the lower numbers representing acidic conditions; the higher numbers represent alkaline conditions. A pH of 7 represents a neutral solution.

50. pickling liquor - acid solution used to clean metal surfaces.

51. polyelectrolytes - long-chained, high molecular weight, synthetic, water soluble, organic coagulants, also referred to as polymers.

52. polymers - long-chained, high molecular weight, synthetic, water soluble organic coagulants, also referred to as polyelectrolytes.

53. polyvalent - referring to atoms or atomic radicals with more than one free electrical charge.

54. pretreatment - as applied to sludge concentration or dewatering, pretreatment means conditioning or treatment previous to concentration or dewatering in order to make the sludge more amenable to the desired process.

55. raw sludge - highly putrescent solids removed by wastewater treatment processes. It is generally any undigested wastewater sludge, although it is frequently used in describing undigested wastewater sludge removed in primary sedimentation.

56. reducing agent - a material which can change a molecule from a higher to a lower oxidation state. Electrons are added to the molecule as it is being reduced.

57. secondary sludge - biological sludge such as activated sludge or trickling filter humus.

58. sludge - the accumulated semi-liquid suspension of settled solids deposited from wastewaters, raw or treated, in tanks or basins.

59. sludge cake - dewatered sludge resulting from filtration or centrifugation. Cake is generally plastic in nature ranging from a spadable to a forkable stiff consistency.

60. solids content - also called percent total solids. Weight of total solids in sludge per unit total weight of sludge. Expressed in per cent. Water content plus solids content equals 100%.

61. solids recovery - fraction of solids retained in sludge concentration process. Amount of recovery plus amount recycled per unit of time equals the solids inflow to the concentrator.

62. solids recycle - solids returned with sludge liquor to beginning of treatment process.

63. solute - substance in solution.

64. specific gravity - the ratio of the weight of a substance to the weight of an equal volume of water.

65. specific resistance - a sludge filterability index (generally expressed as sec^2/gm).

66. suspended solids - solids that either float on the surface of, or are in suspension in wastewaters, or other liquids; and which are largely removed by laboratory filtering.

67. syneresis - destruction of a gel structure by heat-treatment.

68. thickened sludge - a sludge concentrated to a higher solids content by gentle mixing, gravimetric settling, centrifugation, or air flotation.

69. total cycle time - time required for one complete revolution of a filter drum.

70. total residue - also known as total solids. Residue remaining after drying at 103°C to a constant weight.

71. trickling filter humus - sludge removed in clarifiers following biological stabilization in trickling filter units.

72. underflow concentration - the solids content of the sludge thickened and removed from the bottom of a clarifier or sludge thickener.

73. uniformity coefficient - the ratio of the sixty percent sand size to the ten percent sand size, i.e., d_{60}/d_{10}. These respective sizes refer to the sieve size which will pass the corresponding weight percentages to the total of a soil or sand.

74. vacuum filter - a sludge dewatering device utilizing a vacuum applied across a filter medium and sludge cake for liquor removal.

75. van der Waals force - the force of mass attraction between floccules.

76. viscosity - a flow characteristic, (poise).

77. volatile content - determined from total residue as the ratio of weight lost after heating to 600°C to the weight of total residue prior to heating to 600°C. Generally assumed to indicate approximate organic content. Expressed in percent.

78. water content - also called moisture content. Weight of water in sludge per unit total weight of sludge. Expressed in percent. Water content plus solids content equals 100%.

79. wet air oxidation - a heat and pressure treatment designed to synerize and oxidize sludge particles.

80. zeta potential - an electrical charge at the boundary between particles and the suspending medium that is related to repelling forces between floccules. Measured by the zetameter.

VII. A Bibliography on Disposal of Water Treatment Wastes

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VIII. PERSONNEL

RESUME

NAME	Donald Dean Adrian
TITLE	Associate Professor of Civil Engineering
BIRTHPLACE AND DATE	Winner, South Dakota July 29, 1935
EDUCATION	Notre Dame University B.A. 1957
	Notre Dame University B.S. 1958
	University of California at Berkeley M.S. 1959
	Stanford University Ph. D. 1964

RESEARCH AND/OR PROFESSIONAL EXPERIENCE

Registered professional engineer in Tennessee.

1967-present: Associate Professor, University of Massachusetts. Principal Investigator on FWPCA research project WP-01239, "Source Control of Water Treatment Waste Solids." Principal Investigator on OWRR research project WR-B011-MASS, "A Methodology for Planning Optimal Regional Waste Management Systems."

1964-1967: Assistant Professor, Vanderbilt University. Co-principal investigator on FWPCA research project WP-01053, "Dewatering and Drying of Sewage Sludge on Porous Media."

1964 Summer: Engineer, Water Resources Engineering, Inc., Lafayette, California.

1959-1960: Assistant Sanitary Engineer, California State Health Department, Berkeley.

RESUME

NAME	John H. Nebiker
TITLE	Assistant Professor of Civil Engineering
BIRTHPLACE AND DATE	Eastport, Maine, May 26, 1936
EDUCATION	Massachusetts Institute of Technology B.S.C.E. 1958 Swiss Federal Institute of Technology Dr. techn. sc. 1965
RESEARCH AND/OR PROFESSIONAL EXPERIENCE	Full-time and part-time consulting with Malcolm Pirnie Engrs., New York; Turner Engng. Co., Nashville; Leeds Hill & Jewett, Los Angeles; New England Survey Service, Inc., Boston; AWWA Research Foundation, New York; Curran Assoc. Inc., Northampton, Mass.; and De Deuw Cather & Brill, New York. Taught at Vanderbilt University. Registered in Massachusetts.

RESUME

NAME	John F. Ramsay
TITLE	Research Associate
BIRTHPLACE AND DATE	West Stewartstown, N. H., October 14, 1939
EDUCATION	Norwich University B.S.C.E 1961
	San Jose State College M.S.C.E 1968

RESEARCH AND/OR PROFESSIONAL EXPERIENCE

Registered professional engineer in California and Pennsylvania.

October 1968-present: Research Associate, University of Massachusetts. Member of team investigating "Source Control of Water Treatment Solids," WP-01239. Responsible for performance of laboratory experiments, collect and analyze data, and assist principal investigators in the overall prosecution of the work, including dissemination of information.

January 1968-October 1968: Assistant Sanitary Engineer, Capitol Engineering Corporation, Dillsburg, Pa. Designed sewer and water distribution systems. Prepared proposals for promotional work.

January 1967-January 1968: Graduate student, San Jose State College, San Jose, Calif. 20 Semester units in major field of Sanitary Engineering over 12 units in minor areas of Biochemistry and Numerical methods. Special Problems research on carbon chloroform-alcohol extracts of organic refractories from Public Water Supplies.

June 1964-January 1967: Assistant Civil Engineer, California Department of Water Resources.

RESUME

NAME	Edward E. Clark
TITLE	Research Assistant
BIRTHPLACE AND DATE	Cincinnati, Ohio February 18, 1940
EDUCATION	Tennessee Technological University B.S. 1962
	Vanderbilt University M.S. 1966

RESEARCH AND/OR PROFESSIONAL EXPERIENCE

Registered professional engineer in Tennessee

1968-present: Ph. D. candidate in Environmental Engineering program, University of Massachusetts.

1967-1968: Associate, Ryckman Edgerley, Burbank and Associates, Inc., St. Louis, Mo.

1964-1967: Engineer, Turner Engineering Co., Nashville, Tennessee.

1962-1964: Engineer, Burkhalter Hickerson and Associates, Nashville, Tennessee.

RESUME

NAME	Kuang-Mei Lo
TITLE	Research Assistant of Civil Engineering
BIRTHPLACE AND DATE	China June 13, 1938
EDUCATION	National Taiwan University B.S. 1960
	University of Massachusetts M.S. 1968
RESEARCH AND/OR PROFESSIONAL EXPERIENCE	1968-present: Ph. D. candidate in the Environmental Engineering Program, University of Massachusetts.
	1964-1968: Part-time research assistant in Agricultural Engineering, University of Massachusetts.
	1961 - 1964: Full-time research assistant in Agricultural Engineering, National Taiwan University, Taiwan, China.

RESUME

NAME	Donald Lee Ray
TITLE	N. S. F. fellow and Research Assistant
BIRTHPLACE AND DATE	Nashville, Tennessee October 12, 1938
EDUCATION	Tennessee Technological University B.S. 1962 University of Massachusetts
RESEARCH AND/OR PROFESSIONAL EXPERIENCE	Registered professional engineer in Tennessee 1968-present: Ph. D. candidate in Environmental Engineering Program, University of Massachusetts. 1965-1967: Engineer, Turner Engineering Co., Inc., Nashville, Tennessee. 1963-1965: Engineer, Antjony Papuchis Engineers, Nashville, Tennessee 1962-1963: Engineer, Tennessee Highway Department, Nashville, Tennessee

RESUME

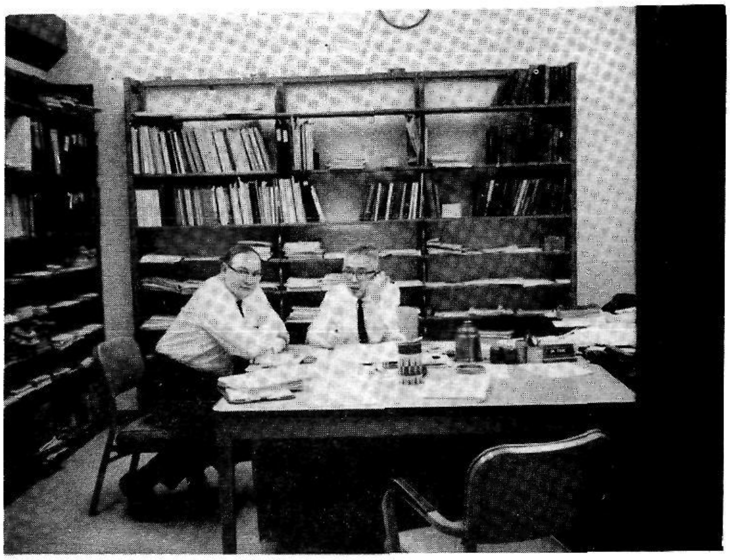
NAME	Peter Meier
TITLE	University Fellow
BIRTHPLACE AND DATE	Beaconsfield, Great Britain, May 15, 1942
EDUCATION	Swiss Federal Institute of Technology Dipl. es Sci. Nat. 1966 University of Massachusetts M.S. 1968
RESEARCH AND/OR PROFESSIONAL EXPERIENCE	1968-present: Fellow of the University of Massachusetts. 1968 Summer: Research Associate, Mass. Water Resources Research Center. 1967: Teaching Assistant, Vanderbilt University, Nashville, Tennessee. 1965-1966: Research Assistant, Swiss Federal Inst. Technology, Zurich.

RESUME

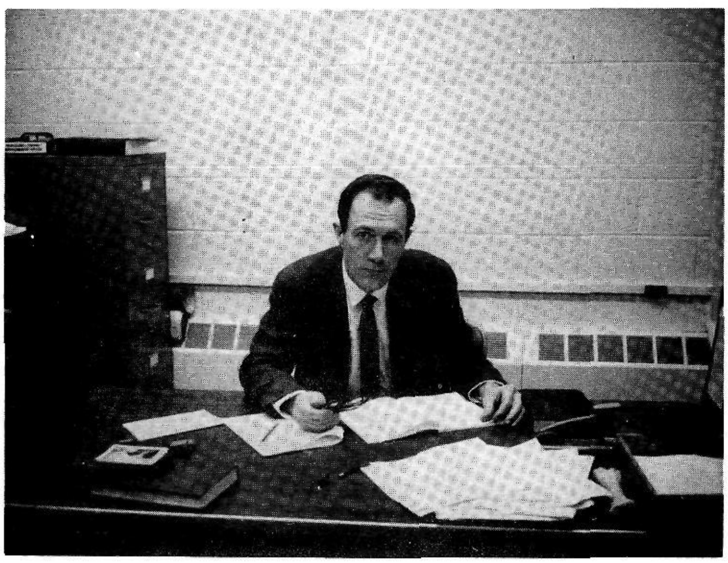
NAME	Thomas J. Beliveau
TITLE	Undergraduate Research Assistant
BIRTHPLACE AND DATE	Manchester, N. H., September 8, 1947
EDUCATION	University of Massachusetts B.S.C.E. 1969
ORGANIZATIONS AND SOCIETIES	Tau Beta Pi, Phi Kappa Phi, American Institute of Chemical Engineers
RESEARCH AND/OR PROFESSIONAL EXPERIENCE	October 1968-present: Laboratory Technician, University of Massachusetts. Responsible for performance of waste water sludge filtration studies in support of a team investigating "Source Control of Water Treatment Solids," WP-01239. Summer 1968: Pilot Plant Technician, General Electric Company, Pittsfield, Mass. Responsible for design and performance of yield and efficiency measurements to be used in the scale-up design of a new polymer process. Summer 1967: Laboratory Technician, General Electric Company, Pittsfield, Mass. Responsible for the performance of bench-scale tests in the field of catalysis development.

RESUME

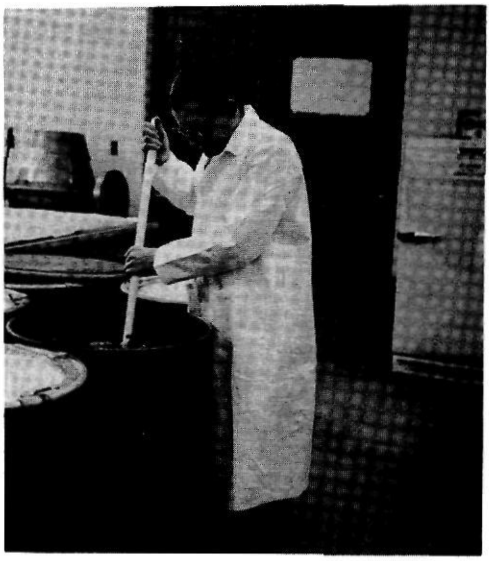
NAME	Thomas R. Roule
TITLE	Undergraduate Research Assistant
BIRTHPLACE AND DATE	Holyoke, Mass. April 4, 1944
EDUCATION	University of Massachusetts, B.S.E.E. 1969
RESEARCH AND/OR PROFESSIONAL EXPERIENCE	1968-present: Part-time job investigating the effects of conditioning of water treatment water sludge by freezing. 1968: Friendly Ice Cream Corp. - part-time summer job. 1968: Part-time job as a lab assistant and electrical technician for FWPCA grant WP-01239.



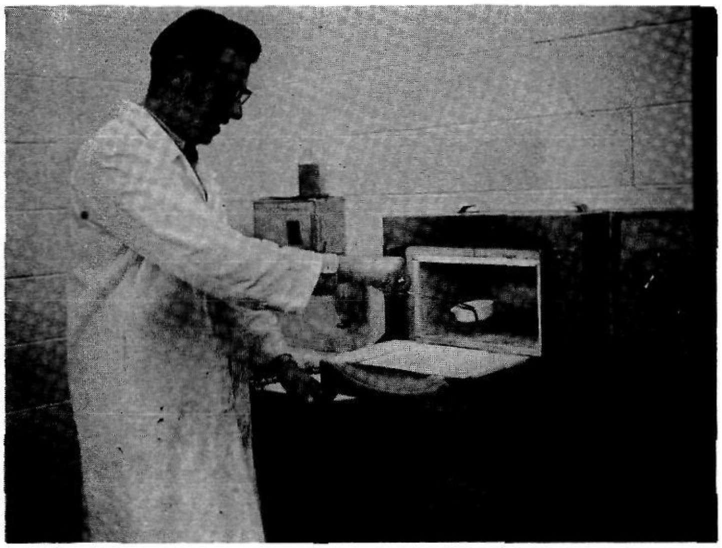
Dr. Donald D. Adrian (L.), Principal Investigator, and
Dr. Tsuan T. Feng, Director of Environmental Engineering,
reviewing research program.



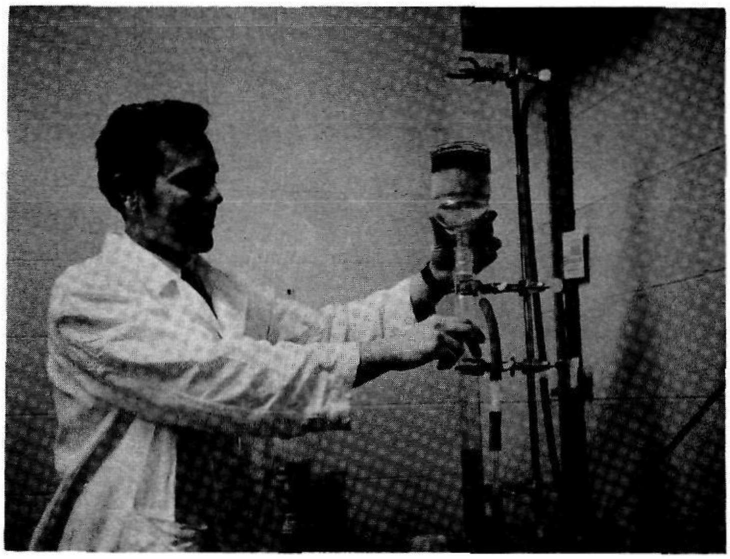
Dr. John H. Nebiker, Principal Investigator studying
results of recent research.



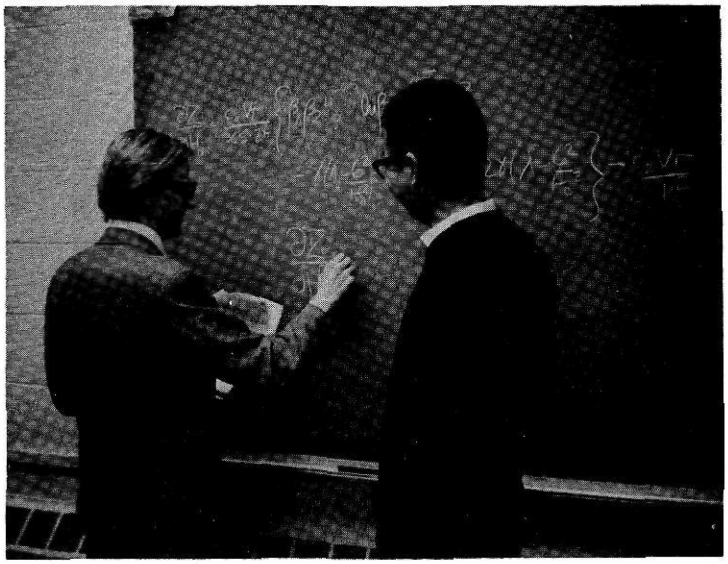
John Ramsay, Research Associate, sampling sludge prior to application to sand beds.



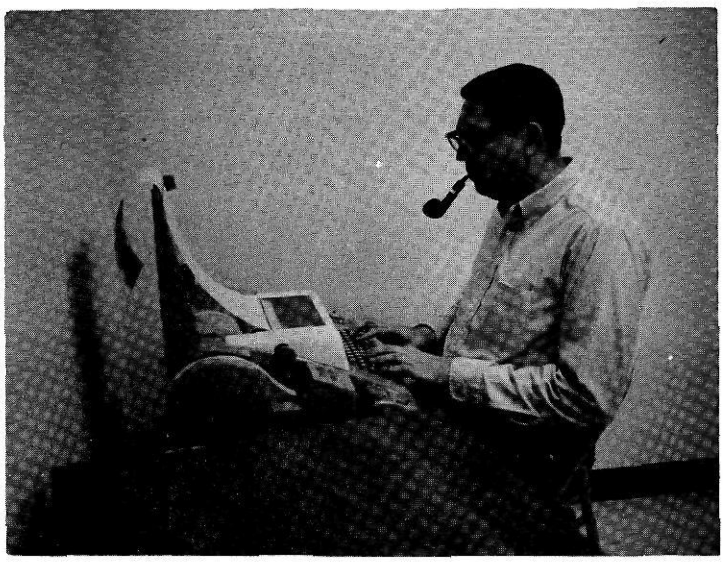
Edward Clark, Ph.D. candidate and graduate research assistant, performing solids analysis in connection with sludge drying experiments.



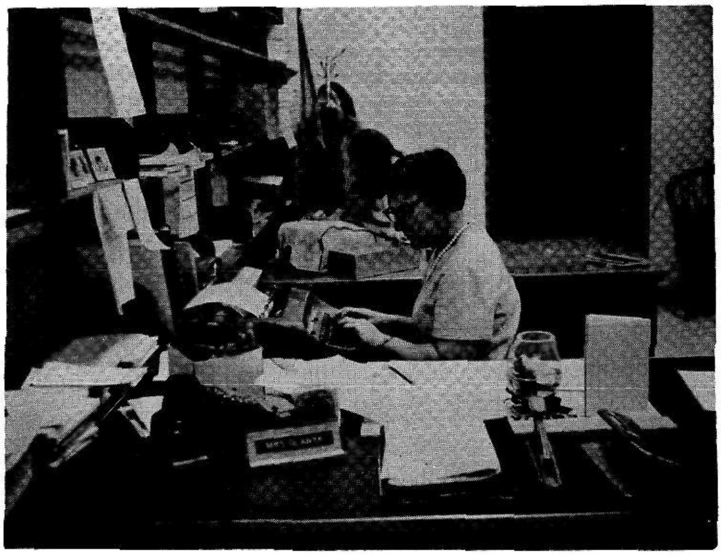
Philip A. Lutin, Research Associate, testing equipment developed at the University of Massachusetts for specific resistance testing.



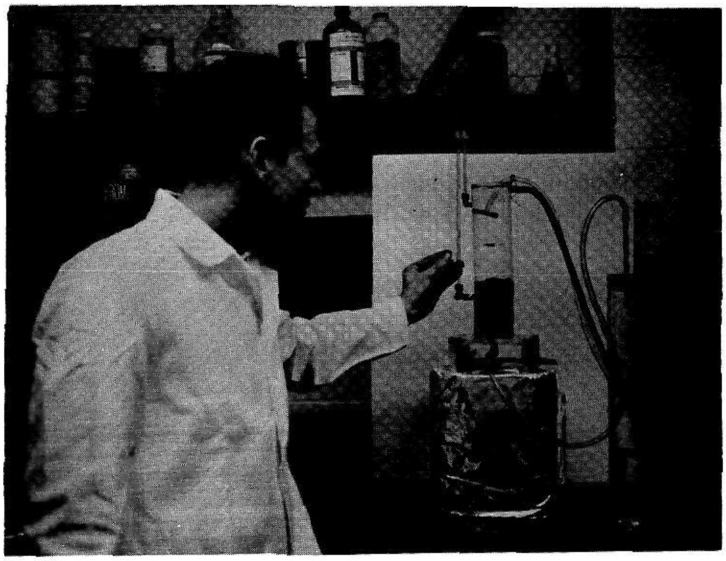
Peter Meier (L.) and Kuang-Mei Lo, Ph. D. candidates and graduate research assistants, pondering equation for use in simulation study.



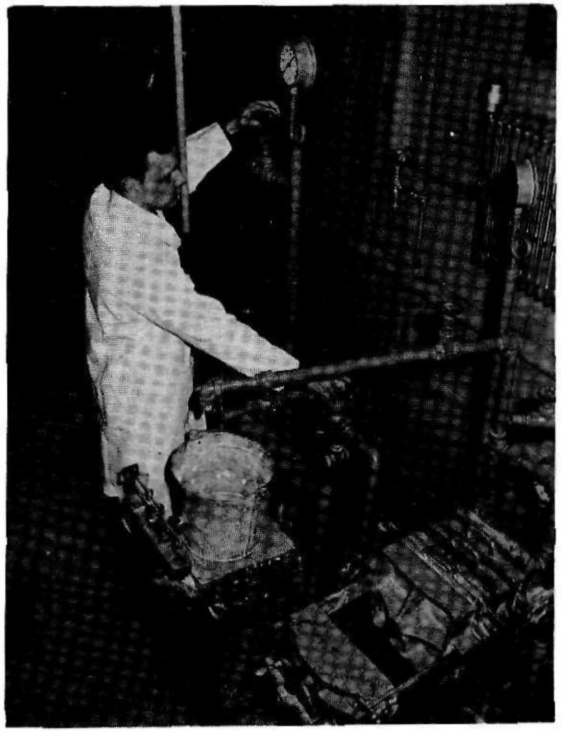
Donald L. Ray, Ph. D. candidate and graduate research assistant, applying computer techniques to solve equations in simulation study.



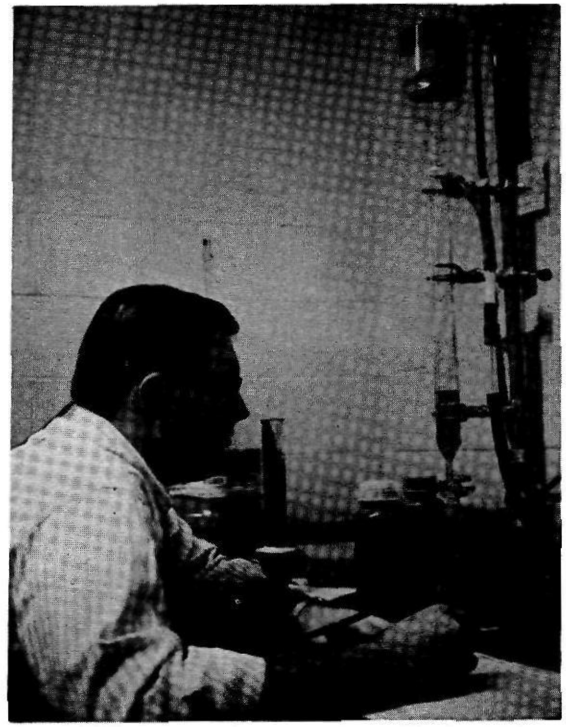
Marjorie Olanyk, Secretary, typing manuscript for report.



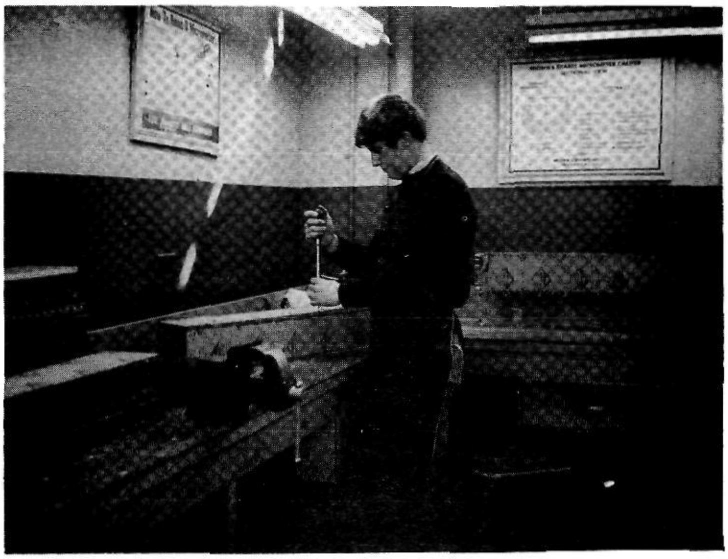
Tom Roule, Undergraduate Research Assistant, operating permeameter during studies of freezing-thawing effects on sludge dewaterability.



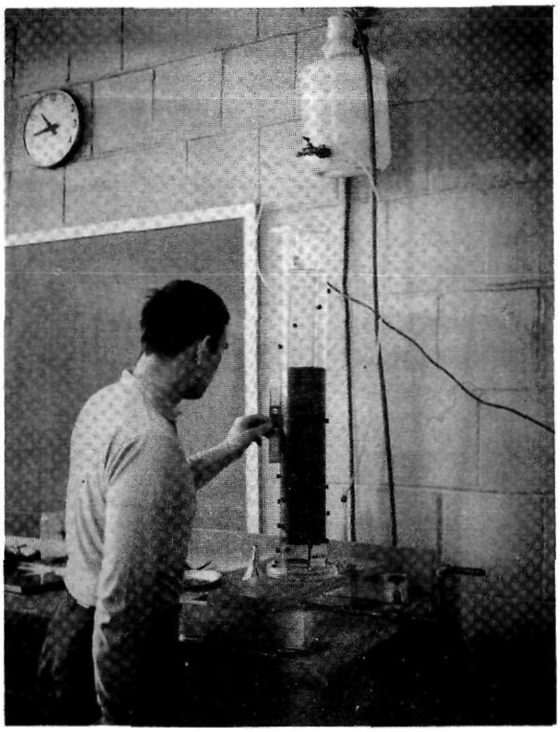
Tom Beliveau, Undergraduate Research Assistant, using filter press for sludge dewatering.



Richard Misiaszek, Graduate Research Assistant, performing filterability tests.



Peter Rogers, Undergraduate Research Assistant, assembling new columns to be used in dewatering experiments where solids measurements will be made by gamma ray attenuation.



Stephen Claughton, Graduate Research Assistant, plumbing column used in investigation of the influence of additions of fly ash to sludge.