THERMAL PROPERTIES OF BEEF MANURE

By

ROBERT LLOYD HOUKOM

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North Dakota State University

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Thesis Approved:

Allen F. Butchbaker
Thesis Adviser

Gerald H. Brusewitz

George W. A. Mahoney

D. Durham
Dean of the Graduate College

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CHAPTER I

INTRODUCTION

Background Information

During the last decade, the population of the United States increased from 179.3 million to 200.3 million (8). This same human population demanded more beef per capita than ever before. In the last five years, the per capita beef consumption jumped from 82.1 pounds in 1966 to 113.8 pounds in 1970 (16). According to this USDA survey, beef consumption increased by 3% in 1970.

The number of fed cattle marketed reflects this increased demand for beef. With an average increase of over one million per year, producers in 23 major feeding states marketed 14 million cattle in 1961 and 25 million in 1971 (4, 5). Loehr (15) uses Kansas as an example of growth in the commercial feeding industry, stating that the number of cattle in confinement increased 1000% in ten years. Fed cattle in Oklahoma increased from 163,000 in 1961 to 587,000 in 1971 (5). These increases show the producers' response to the consumer demand.

Since water and feed are brought to confined cattle, a waste problem accompanies the operation. During the finishing period, confined cattle in 22 major feeding states drop an estimated 85 million tons of waste annually (3). The accumulation and eventual removal of this bulky, smelly material is an inherent problem in feeding operations.

In recent years, various methods of volume and weight reduction have been tried on animal manure. Some volume and weight reduction methods require solids separation prior to dehydration. Sobel (19) reports that at least half of the water in chicken manure can be removed by mechanical methods, such as direct pressing. Dairy operations in California have used rotating or vibrating screen separators to separate the solids from liquids in flush systems (7). One researcher suggests lagoons even in a northern climate could handle the liquid portion of animal waste, while the solid portion could be pelleted (17). A California beef cattle production system pumped slurry directly to a dehydrator from a slatted floor collection pit (7).

In addition to volume and weight reduction, dehydrated animal wastes have two other advantages over raw waste: improved handling characteristics and odor reduction. Sobel (19) reports that offensive odor strength decreases as moisture level decreases. He also suggests that grain handling equipment may be used to convey the dried material. Researchers at Michigan State University report that odor given off in the vicinity of the commercial dehydrator they tested was less intense and different than the odor of fresh manure (23).

Incineration of animal wastes offers a solution to the waste problem for producers who have no land for ultimate disposal of manure. However, two drawbacks with this process are the waste of a natural resource with nutrient value and air pollution (20). Since manure with a moisture content greater than 30% cannot be successfully fed into an incinerator, predrying of wastes with higher moisture content would be necessary (3).

Significance of Research

The examples cited in the above paragraphs are evidence that work is being done on dehydration, pelleting, and incineration of animal wastes. Machinery has been used for these purposes without the knowledge of the thermal properties of the material to aid the designers. Just as efficient design of dehydrators, prediction of drying rates, prediction of temperatures, and prediction of temperature distributions are important in the food industry, they are important in any other application of thermal processes. Information regarding temperature prediction and drying rate is sought for feedlot surfaces. Also, such information would be useful for developing the optimum procedures to use in the composting of manure. For accurate equipment design, or the development of optimum processing techniques, it is essential to know how the moisture content influences the values of specific heat, thermal conductivity, and thermal diffusivity of beef manure.

The Objectives

The above discussion points to the need for thermal properties data of animal wastes. Therefore, the following objectives are presented:

1. To determine the thermal conductivity and the specific heat of fresh beef cattle manure as affected by moisture content.
2. To derive the thermal diffusivity of beef manure from experimental values of thermal conductivity, specific heat, and the bulk density.
3. To determine physical and chemical properties, such as viscosity, particle size distribution, specific gravity, volatile

solids, fixed solids, crude protein, and ash, to characterize the manure for engineering application.

CHAPTER II

REVIEW OF LITERATURE

The methods used in this research project for the various tests have been used in other applications, such as for food analysis or soil properties analysis. Since the references used as guidelines for this research project are readily available at most university libraries, a brief review of literature will be given. Basic theory or basic work done elsewhere is reviewed in the discussion below.

Thermal Conductivity Method

Two general methods of determining the thermal conductivity of materials are the steady state method and the transient method. An array of apparatus exists for each general method. Material characteristics and desired accuracy dictate the specific apparatus used.

Steady state methods are useful for dry materials, such as insulation. Reidy (18) suggests that the steady state method be confined to materials of 10% moisture content or less. This method usually employs parallel plates, concentric cylinders, or concentric spheres. The most common is the guarded hot plate apparatus which uses parallel spaced plates at constant temperatures. A guard ring heater insures nearly parallel heat flow from the hot plate to the cold plate. This apparatus requires expensive automated equipment for temperature control and recording. Another disadvantage is that moisture migration occurs in materials over 10% moisture content. Water condenses at the cold plate, thus altering the sample characteristics to such an extent that no confidence could be placed in the thermal properties measured. Compounding the moisture migration problem is the duration of the lengthy tests which run into hours for a single determination.

Challoner and Powell (6) used the parallel plate apparatus for various liquids. To reduce convection currents within the liquids, narrow spacing and low temperature differentials were used. Very precise room temperature control and very accurate instrument readings were needed to obtain meaningful data from those liquids. These tests required controls that are beyond the means of the average researcher.

Transient methods have interested researchers for some time because of the shorter duration of the tests. Of the transient methods, the probe method is one of the simplest and quickest means of evaluating the thermal conductivity of many kinds of material, such as soils, insulation, acids, wheat, and butter. Hooper and Lepper (12) determined thermal conductivities over a fifty-fold range, which testifies to the versatility of the method. A temperature differential of only a few degrees is required. Since most tests run for ten minutes or less, very little moisture migration occurs. Hooper and Lepper (12) reported that moisture content of one of their specimens changed only from 10.0 to 9.8% within $\frac{1}{4}$ of an inch for a 30°F. temperature rise over a six minute test.

The thermal conductivity probe, illustrated in Figure 1, is a simple instrument. In theory, it is a line source of heat of infinite length.

Thermal conductivity in quiescent isotropic medium without heat sources or sinks is expressed by the following equation:

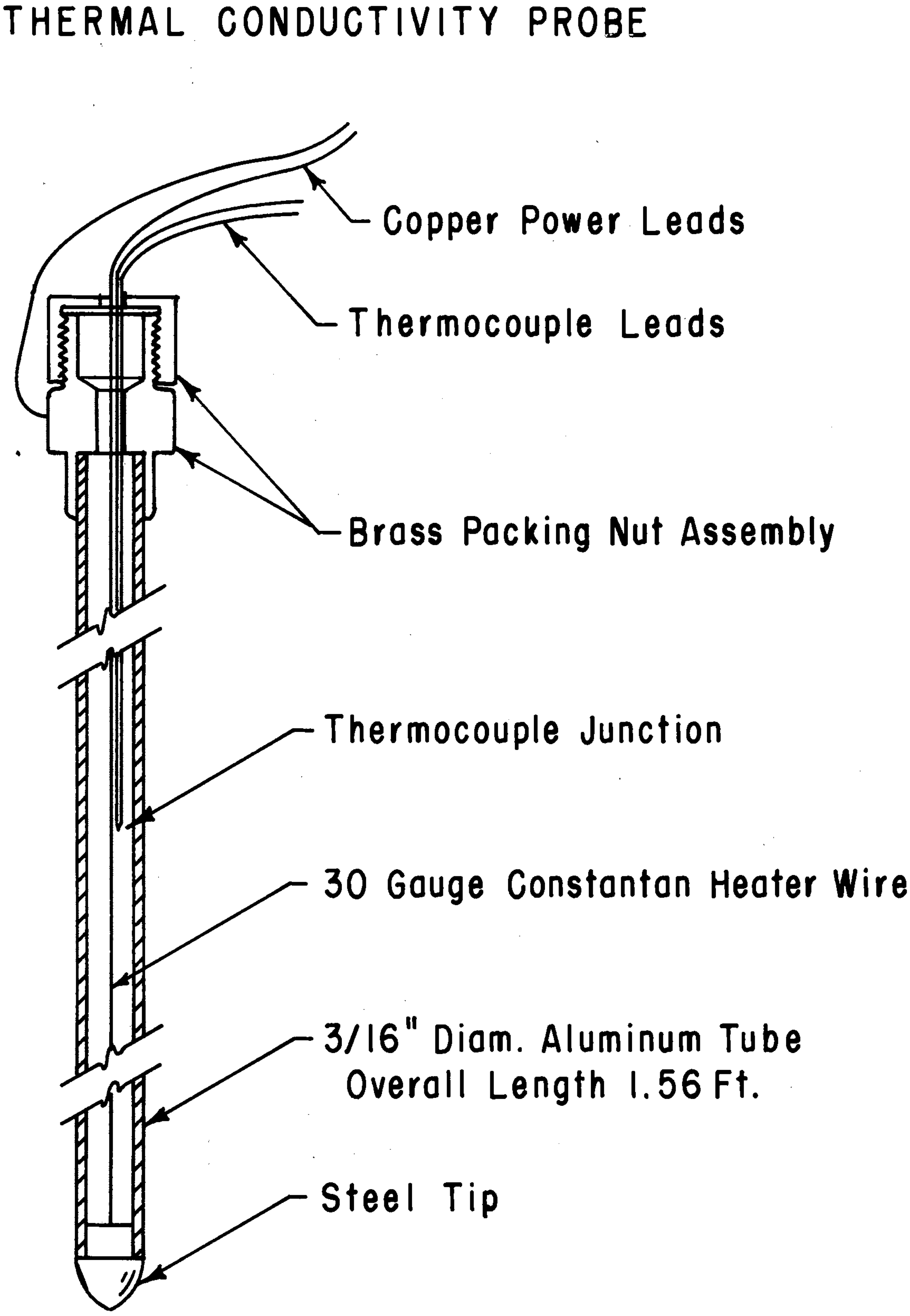


Figure 1. Cross Section of Thermal Conductivity Probe

$$\frac{\partial T}{\partial t} = \frac{K}{c\rho}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{1}$$

where

T = temperature

t = time

K = thermal conductivity

c = specific heat

ρ = bulk density

x, y, and z = coordinate axes

Equation (1) can be written in cylindrical coordinates as

$$\frac{\partial T}{\partial t} = \frac{K}{c\rho}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \varphi^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{2}$$

where (r, φ, z) = cylindrical coordinates. Equation (2) is used to develop the expression for an infinite line source of heat. Tye (25) gives the solution to (2) for an initial boundary condition of constant temperature as

$$T_\infty(r,t) = \frac{-Q}{4\pi K}\left[\mathrm{Ei}\left(\frac{-r^2}{4Dt}\right)\right] \tag{3}$$

where

Q = rate of power

D = diffusivity

and where T (r,t) refers to the initial temperature of the infinite line source and $\mathrm{Ei}\left(\frac{-r^2}{4Dt}\right)$ the exponential integral. For small values of $\left(\frac{-r^2}{4Dt}\right)$, the temperature at a fixed radial distance can be obtained accurately enough from the first two terms of the exponential integral series expansion.

$$\mathrm{Ei}\left(\frac{-r^2}{4Dt}\right) = \ln\left(\frac{4Dt}{r^2}\right) + 0.5772 + \dots \tag{4}$$

Then

$$T_{\infty} = \left(\frac{Q}{4\pi K}\right)\left[\ln\left(\frac{4Dt}{r^2}\right) - 0.5772 + \dots\right] \tag{5}$$

When measuring temperatures at two different times at a fixed radial distance, the expression (5) becomes

$$T_{2,\infty} - T_{1,\infty} = \left(\frac{Q}{4\pi K}\right)\ln\left(\frac{t_2}{t_1}\right) \tag{6}$$

Solving for K, (7) becomes

$$K = \frac{\left(\frac{Q}{4\pi}\right)\ln\left(\frac{t_2}{t_1}\right)}{\left(T_{2,\infty} - T_{1,\infty}\right)} \tag{7}$$

where

T_1 = temperature at first time value
T_2 = temperature at second time value
t_1 = first time value
t_2 = second time value

A plot of the temperature against the natural logarithm of time should result in a straight line with a gradient proportional to the thermal conductivity of the sample.

To reduce end effects, a thermocouple is placed about midway the length of the probe, with a length to diameter ratio greater than 100. At least three inches of a homogeneous test specimen must surround the probe. One other stipulation for the use of the probe specifies that a uniform temperature exist throughout the sample before the test is begun.

According to Hooper and Lepper (12), results are reproducible within 0.5%. They report that absolute accuracy is harder to estimate, but it appeared to be about the same as for the guarded hot plate method.

Van der Held (10) reports a total error of measurement of less than 2%. Vos (28) points out that more measurements have to be made for each thermal conductivity determination using the transient method than with the steady state method. He suggests ± 2% error for steady state methods and a ± 3% error for transient methods.

Specific Heat Method

Specific heat of various materials is commonly measured by the method of mixtures. This method usually employs a Dewar flask, which is similar to the common Thermos bottle. According to one source (13), the low heat loss from a Dewar flask is an advantage over the older types of calorimeters.

Heat balance equations form the basic concept of calorimetry. It is necessary to determine the water equivalent of the flask before specific heat determination can be made. This constant is found by having a known quantity of warm water in the flask, and then adding a known quantity of cold water. Both temperatures are recorded as well as the mixture temperature. The water equivalent can be found by the relationship

$$(m_1 + w)\ (T_1 - T_3) = m_2\ (T_3 - T_2) \tag{8}$$

where

m_1 = initial mass of water

m_2 = second mass of water

T_1 = temperature of initial mass just prior to addition of the second mass

T_2 = temperature of second mass just prior to addition to the first mass

T_3 = temperature of mixture after m_1 and m_2 are well mixed

w = water equivalent

Once the water equivalent has been found, the following equation is used to find an unknown specific heat

$$1.00\ (m_1 + w)\ (T_1 - T_3) = cm_2\ (T_3 - T_2) \qquad (9)$$

The symbol c is the unknown specific heat and m_2 becomes the mass of the unknown.

If the mixture temperature is above or below the room temperature, a correction term must be added for heat transfer to or from the environment. Such a method has been used at the Oklahoma State University Agricultural Engineering Laboratory by Wright (29) for specific heat determination of peanuts.

Using t_m for time in minutes and R for the change in temperature in degrees per minute, the above equation becomes

$$1.00\ (m_1 + w)\ (T_1 - T_3 - t_m R) = cm_2\ (T_3 - T_2 + t_m R) \qquad (10)$$

for a mixture temperature above room temperature.

Viscosity Method

Kumar (14) developed a coaxial cylinder viscometer for use on animal slurries. Dilution recommendations for pumping purposes were made as a result of his research.

However, the purpose of determining the viscosity in this research project was to adequately describe the physical properties of the beef manure tested for thermal properties. Therefore, it was important to use a readily available instrument for viscosity determination. A Stormer viscometer with a paddle rotor was the instrument selected. A company bulletin (25) lists a wide variety of materials including canned corn, tomato pulp, and tomato paste, that can be tested by a Stormer viscometer. One source (27) suggests that the Stormer viscometer is one of the better instruments to use for non-homogeneous materials, and that the inventive rheologist will be devising methods to adapt the instrument to the needs of particular test materials. This instrument was selected for determining an approximate viscosity of the 85% wet basis moisture level slurry, following an ASTM method (24).

Particle Size Distribution

Since sieve numbers 4, 8, 16, 30, 50, 100, and 140 were used by Kumar (14) in wet sieving of dairy slurry, the same numbers were selected for this project as a means of comparison. Rations for dairy and beef animals are quite different in most cases, so a difference should exist in particle distribution and in the percent passing. Wet sieving done in this project followed the guidelines for the Yoder sieve apparatus which were found in an agronomy textbook (2).

Slump Test

As a test for measuring the fluidity of manure, Hart (9) used the slump test which is found in ASTM (22) standards. He tested manure with less than 30% total solids and found that the manures were in no sense free-flowing liquids. This test was applied in this project to the 25%, 45%, and 65% moisture content levels.

CHAPTER III

THE EQUIPMENT

A brief summary of the instruments used and the equipment constructed is given in the following discussions. No new design of equipment has been employed in this research project, although this is thought to be the first time the thermal conductivity probe and the specific heat equipment have been applied to beef manure. Short discussions of the Stormer viscometer and the Yoder sieve machine note only the equipment option or modification used for testing.

Thermal Conductivity Equipment

A thermal conductivity probe similar to that designed by Hooper and Lepper (12) was constructed in the Agricultural Engineering Laboratory. As shown by Figure 1, the probe consisted of an aluminum tube 3/16 inch outside diameter and 1.56 feet long. At one end a bullet-shaped steel tip was soldered in place and at the other end a brass packing nut was soldered on. Then, a 30 gauge insulated constantan wire was fed through the tube into a hole in the tip. The constantan wire was soldered in the steel tip. To keep the wire from touching the inside wall of the aluminum tube, the wire was held taut as the packing nut secured it and a 36 gauge copper constantan thermocouple. This thermocouple tip was placed about half way down the length of the probe tube to minimize the influence of end effects. Constantan wire was used for the heater element since its resistivity changes so little with a wide variation of temperature.

Voltage drops across the probe element were read by a Type 502A Dual Beam Tektronix oscilloscope. The oscilloscope had previously been calibrated to within ± 2% accuracy.

The oscilloscope's lower beam displayed the voltage drop across a one ohm, one-percent tolerance resistor of 30 watt capacity. Since a one ohm resistor was employed, amperage could be read directly from the oscilloscope screen. The greatest amount of power dissipated in the resistor was only a fraction of its power rating to assure as little change as possible in the resistivity of the material.

Power was supplied by a 12 volt automotive type storage battery. Figure 2 shows the circuit which included two parallel rheostats in series with the precision resistor and the thermal conductivity probe. One rheostat functioned as a coarse adjustment while the other was used as a fine adjustment for power regulation.

For temperature measurement, a Westronics Model M11D 24 point strip chart potentiometric recorder was used. A pen attachment was mounted on the printing head assembly for constant temperature sensing. This was accomplished by having the print control knob in the "indicate" position. The scale on this instrument ran from 32° F. to 120° F.

An eight-inch diameter, three-foot long Plexiglas cylinder was used to hold the sample. Figure 3 shows the probe within the Plexiglas cylinder, as well as the remainder of the thermal conductivity equipment.

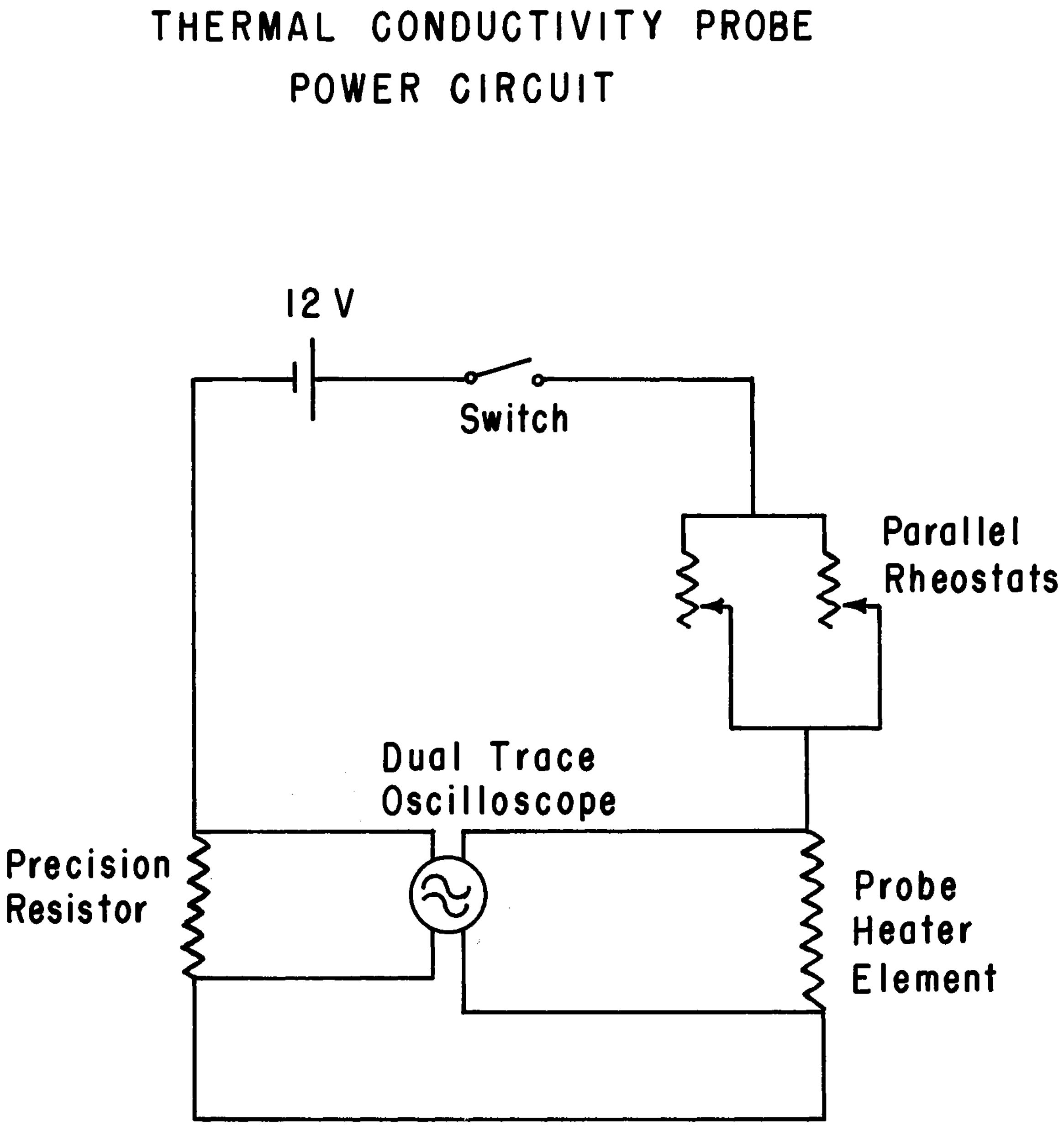
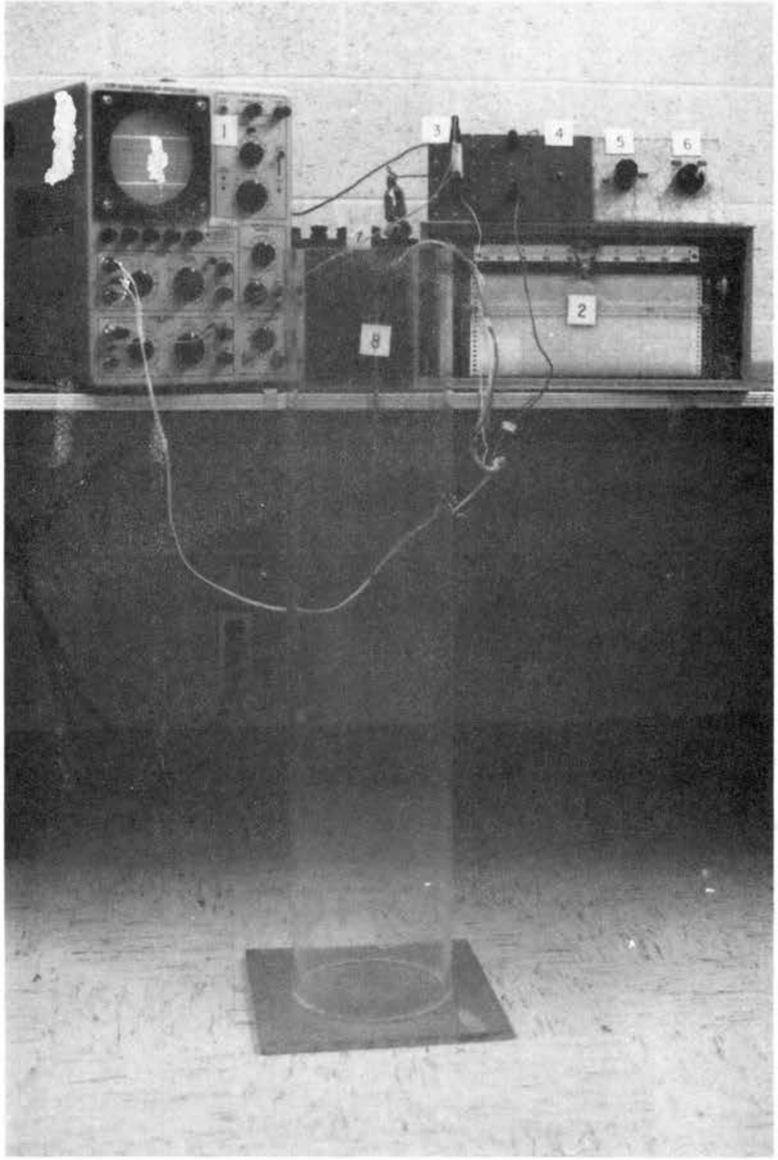


Figure 2. Schematic Diagram of Thermal Conductivity Probe Power Circuit



1. Oscilloscope
2. Potentiometric Recorder
3. Precision Resistor
4. Switch
5. Rheostat
6. Rheostat
7. Battery
8. Cylinder and Probe

Figure 3. Thermal Conductivity Equipment

Specific Heat Equipment

A quart-size Dewar flask, the basic piece of equipment for the specific heat experiments, is illustrated in Figure 4. The Dewar flask was mounted in an oscillating container that was powered by a gear reduction electric motor with a variable speed. Temperature of the flask's contents was measured by a 36 gauge copper-constantan thermocouple mounted on an aluminum rod. The aluminum rod in turn was fastened to a rubber covered cork stopper. The temperature readings were recorded by a Model M11D Westronic 24 point strip chart potentiometric recorder.

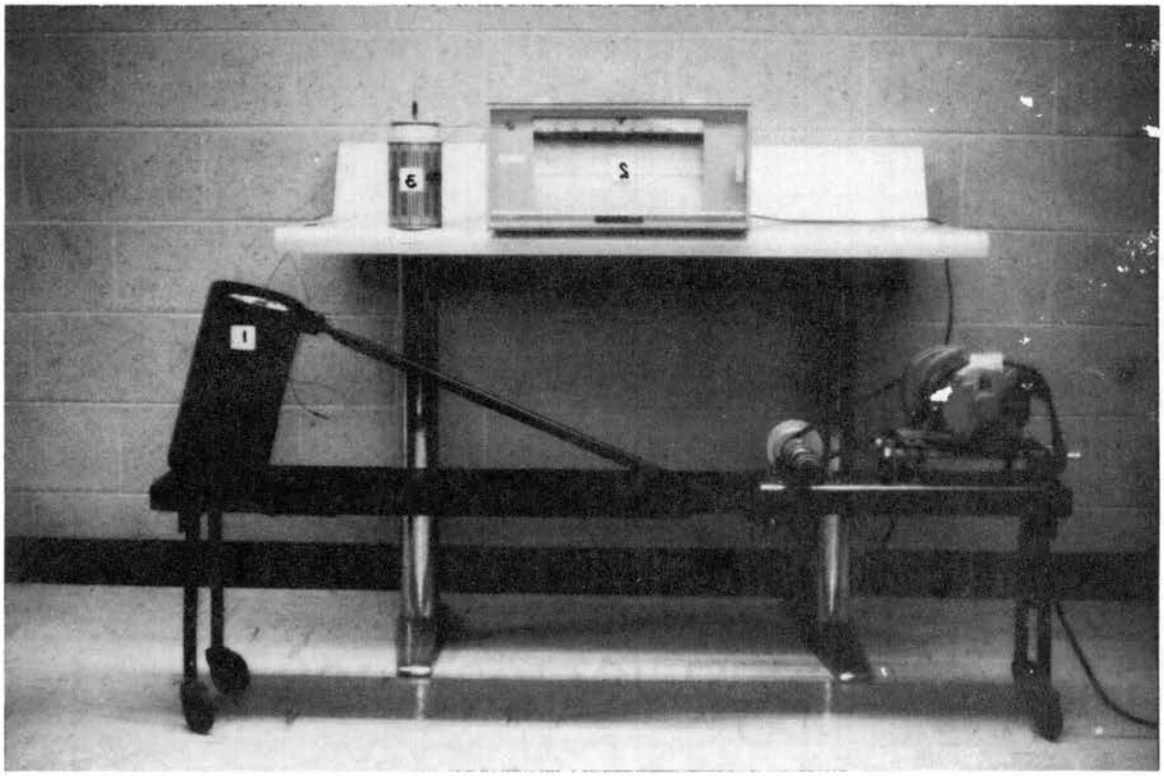
Temperature readings of the wettest samples were taken when the samples were contained in a pint volume Thermos bottle. One 36 gauge thermocouple was mounted on a wood dowel held in place by a force fit through holes bored in the plastic, insulated lid.

Viscometer

A Stormer viscometer with a paddle type rotor was used for viscosity tests. Samples were contained in a 3-3/8 inch can. Temperatures were taken by a Centigrade thermometer. The Stormer viscometer, pictured in Figure 5, is a constant shearing stress instrument. A revolution counter on the machine indicated the revolutions the paddle rotor turned while a stop watch was employed to record the time lapse for 100 revolutions.

Yoder Sieve Machine

Wet sieving was done by a modified Yoder machine as shown by Figure 6. This modified version has a frame to accept the standard



1. Dewar flask 2. Potentiometric Recorder 3. Thermos

Figure 4. Specific Heat Equipment

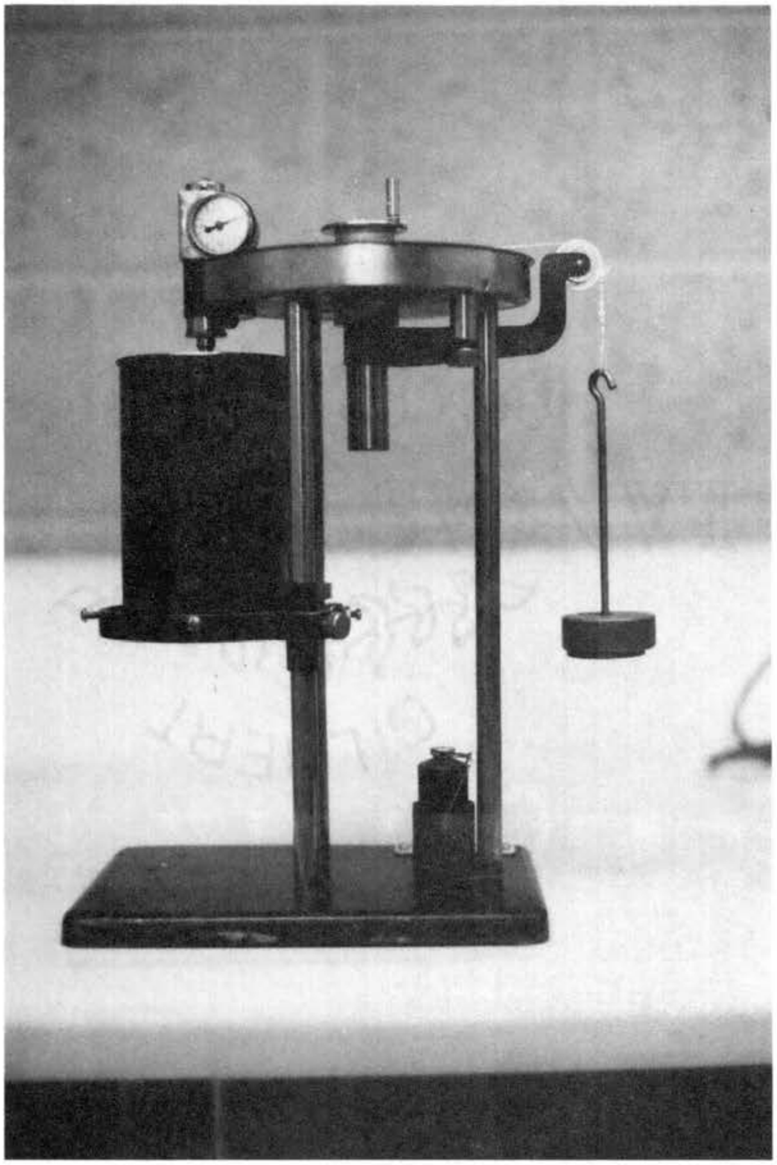


Figure 5. Stormer Viscometer

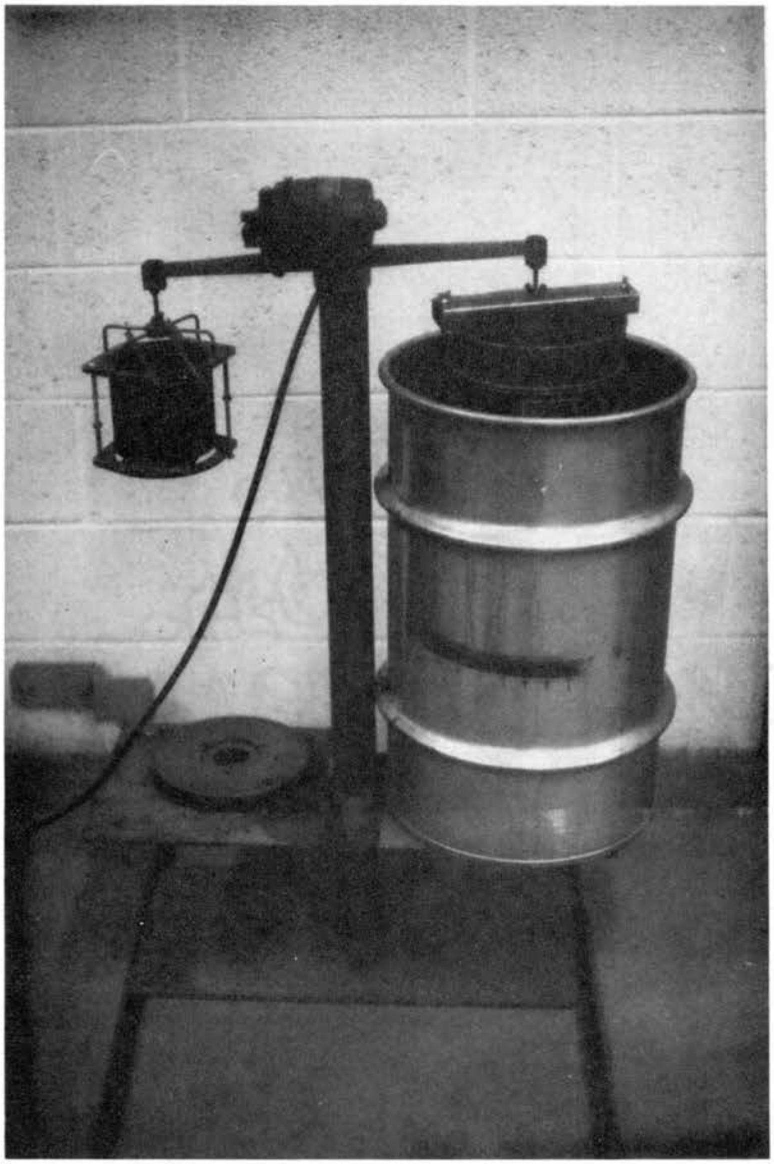


Figure 6. Yoder Sieve Machine

eight inch diameter Tyler sieve. A larger can replaced the original water can and a counterweight took the place of a second set of sieves. Having the weight and sieve in close balance enabled the small electric motor to function smoothly.

CHAPTER IV

EXPERIMENTAL PROCEDURE

The primary concern of this research project was finding the relationship of the thermal properties to the moisture content. Detailed procedures are given for the thermal properties tests, as there exists no standards for such tests. For the physical and chemical properties, average values were sought. Standard methods exist for the other tests, so only brief outlines are given for them.

Statistical Design

A one-way classification was the design used for statistical analysis. The design consisted of four moisture levels, three replications at each moisture level, and three runs of each replication. The number of replications was limited because it required approximately 175 pounds of 85% moisture content slurry to produce enough material at 25% moisture for the thermal conductivity samples and the specific heat subsamples.

Sample Preparation

Thermal conductivity tests and specific heat tests were conducted at 25%, 45%, 65%, and 85% moisture levels by wet basis. Feces and urine collections were taken separately and stored in 15 gallon stainless steel drums, which were kept in a walk-in refrigerator maintained at 43° F. ± 1° at the Agricultural Engineering Laboratory. Moisture tests were then run on the feces and urine specimens. On the basis of the moisture tests, feces and urine were blended in proportions to create an 85% moisture slurry by wet basis. Subsamples for the particle size tests and for the viscometer tests were drawn off as the slurry was stirred. Batches of the remaining slurry were dried down to less than 25% moisture. Reconstituting the dried manure produced the 25% moisture level samples, and adding more water to the samples produced the 45%, 65%, and 85% moisture levels.

Drying the slurry was accomplished by a radiant heat dryer, shown in Figure 7, that was fabricated at the Agricultural Engineering Laboratory. It consisted of an angle-iron frame supporting a sheet metal pan about two and one-half feet above six 250 watt heat lamps. The sides of the framework were covered by plywood sheets to reduce the effects of air currents and to protect the lamps. Flat black paint applied to the underside of the pan increased heat absorption.

Slurry was poured into the pan until it was two to three inches deep. About four days were required to dry a batch of slurry down to less than 25% moisture content, wet basis. The length of drying time varied with changing weather conditions, since the dryer was located in a pole barn with open sides. A crust formed on top of the slurry within a few hours. Stirring the slurry occasionally helped break up the crust into small chunks. During the first day and into the second day, the warmed slurry bubbled and appeared spongy.

The dried manure was scraped from the pan into stainless steel drums, which were stored in the walk-in refrigerator at 43° F. ± 1° until enough dried manure was collected for three large samples. The

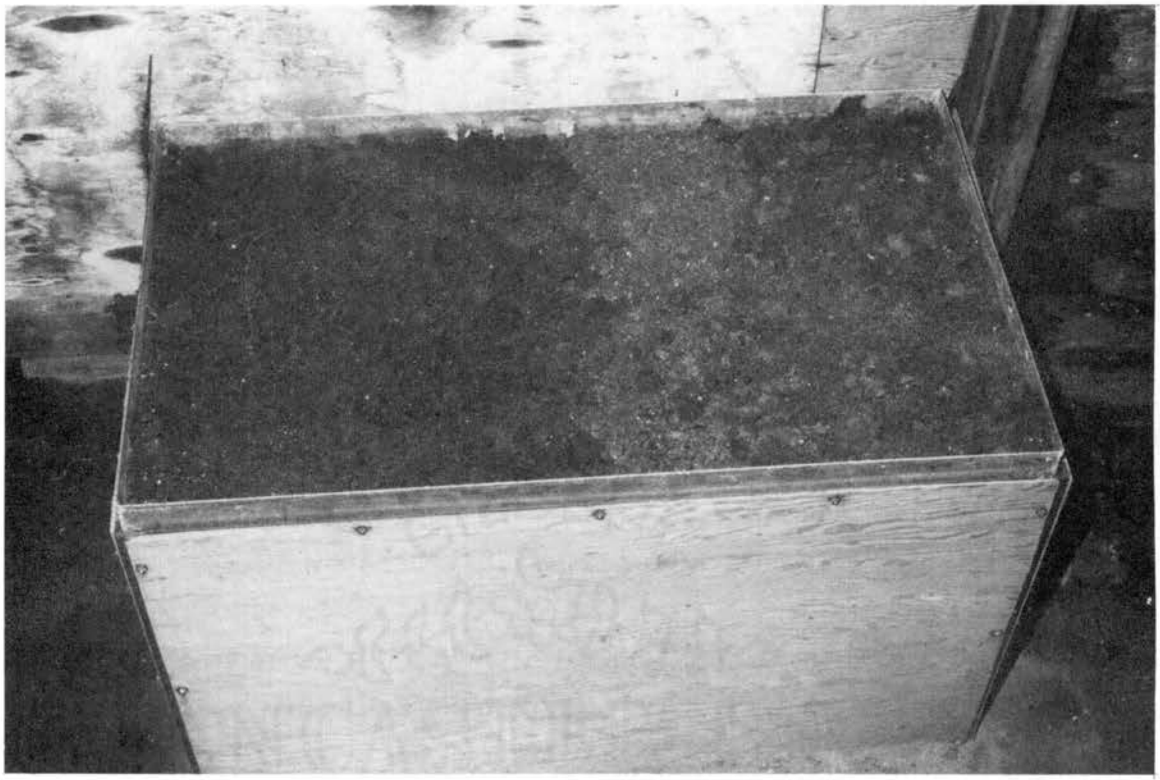


Figure 7. Radiant Heat Dryer

dried manure chunks were crushed until all of the material passed through a size 3 1/2 Tyler sieve.

The moisture content was determined by standard procedures, using a forced convection oven at 103° C. for 24 hours. A cement mixer was used to blend water and the sample to obtain a particular moisture level. Blending continued for ten minutes following the addition of water. Each sample remained at room temperature (25° C. $\pm$ 1°) for two days, allowing the water to diffuse throughout the sample.

Thermal Conductivity Tests

Thermal conductivity tests were performed as follows:

(1) Samples were mixed for three minutes in a cement mixer.

(2) The Plexiglas tube was filled to a specified depth, and was weighed to obtain density.

(3) The probe was pushed into the sample. The probe and the surrounding material were allowed ten minutes to reach equilibrium temperature.

(4) The electrical power to the probe's constantan heating element and the potentiometric recorder chart drive were turned on after the ten minute wait.

(5) The fine adjustment rheostat was used to compensate for minor changes in the voltage drop across the probe's heating element.

(6) Voltage drops across the probe and the precision resistor were recorded.

(7) After twelve minutes the probe's electrical power was turned off, and the contents of the tube were dumped.

Specific Heat Tests

Calibration

The calibration of the Dewar flask was done as follows:

(1) About 220 grams of warm water were poured into the Dewar flask, the stopper was put in place, and the agitation was started.

(2) The potentiometric recorder printer and chart motors were started.

(3) About 220 grams of cold water were poured into the Thermos bottle, and the bottle was weighed.

(4) The thermocouple cap was screwed on, and the Thermos was agitated manually until a straight line of recorded points occurred.

(5) Contents of the Thermos were dumped into the Dewar flask, and the Dewar stopper and thermocouple were replaced. Again, the Thermos was weighed.

(6) Temperature of the mixture was recorded.

(7) The water equivalent of the flask was then calculated.

Sulfur lumps were used for a calibration check which used the same procedure with only minor alterations. There were differences in the methods of measuring temperature and mass. Before the check runs were made, sulfur lumps were oven dried and sealed in cans. The cans were then weighed and refrigerated the day before the tests were run. The Thermos bottle was allowed to cool for a day, also. During a check run, the sulfur lumps were dumped into the Thermos, the temperature of the lumps was taken, and the lumps were covered by placing a lid on the Thermos. This all took place within the walk-in refrigerator that was held at 43° F. $\pm 1^{\circ}$. Then, the Thermos and its contents were rapidly placed in the oscillating Dewar flask. The oscillating flask was stopped briefly as the sulfur lumps were quickly dumped into the warm water. The oscillating motion was started again, and the Thermos was returned to the refrigerator. The empty sulfur can was weighed to determine the weight of the sulfur.

These minor differences in procedure were as important to test as was running a calibration check. In actual testing of manure, the 85% moisture level specific heat tests followed the water calibration procedure. However, the tests at 25%, 45%, and 65% moisture levels had to follow the sulfur calibration check procedure because the manure at these moisture levels was no longer fluid. It is difficult to remove temperature gradients of cold solids or semisolids in a warm container. Keeping both the Thermos and the sulfur lumps in the refrigerator removed as much temperature gradient as possible.

The water equivalent of the Dewar flask, based on water calibration is 24.56 BTU's per degree F. Check tests with sulfur agreed within ± 5%.

Testing manure subsamples followed the same procedures. Each subsample for specific heat testing was about 150 ml. in volume. To determine the mixture temperature, each test was run until the temperature became constant. Since the mixture temperature was close to room temperature, no heat flow was expected.

Viscosity Tests

Since viscosity is a physical property very sensitive to temperature variation, the room temperature was regulated as closely as possible. The tests were run on 85% moisture slurry at 25° C. $\pm$ 0.2°.

A little difficulty with the test subsamples was noted. If a subsample was taken from the refrigerator to warm up at room temperature for a few hours, the specimen tended to bubble gas. Apparently, the subsamples in storage had turned anaerobic. To counteract this problem, the subsamples were warmed in a water bath. Then, the subsamples were dumped into the pint volume viscometer can and stirred until the temperature was within the tolerance limits.

Another viscometer test difficulty concerned the viscometer paddle. A long hair from the cattle occasionally wrapped around the paddle and caused it to turn heavier than normal. These isolated hairs were easily removed.

Calibration was accomplished by using four sucrose solutions. Solutions of 63%, 70%, 73%, and 75% sucrose were made. The procedure is outlined by the following steps:

(1) One of the sucrose solutions was poured into the viscometer can. The temperature was maintained at 25° C.

(2) Enough mass was used on the cord to turn the submerged paddle 100 revolutions in 35 seconds.

(3) Mass was added to the cord until 100 revolutions were accomplished in 25 seconds.

(4) Time versus mass was plotted as shown in Figure 8.

(5) The mass was estimated for 100 revolutions in 30 seconds. (200 rpm.)

(6) The viscosity of a sucrose solution at 25° C. was found by referring to tables based upon measurements made at the National Bureau of Standards (11).

(7) Viscosity versus mass was plotted for 200 rpm., as shown in Figure 9.

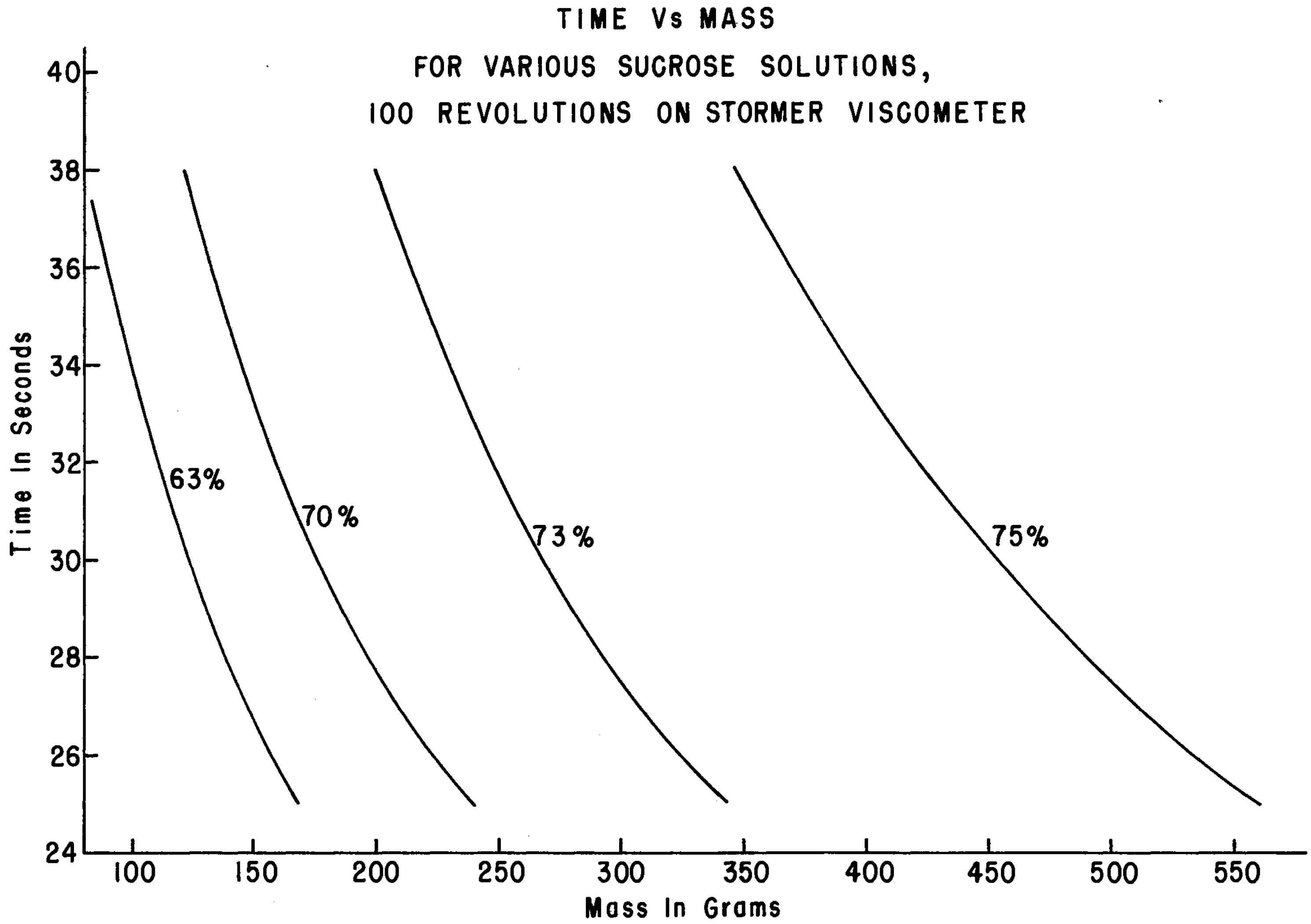


Figure 8. Viscometer Calibration Curves for Four Sucrose Solutions

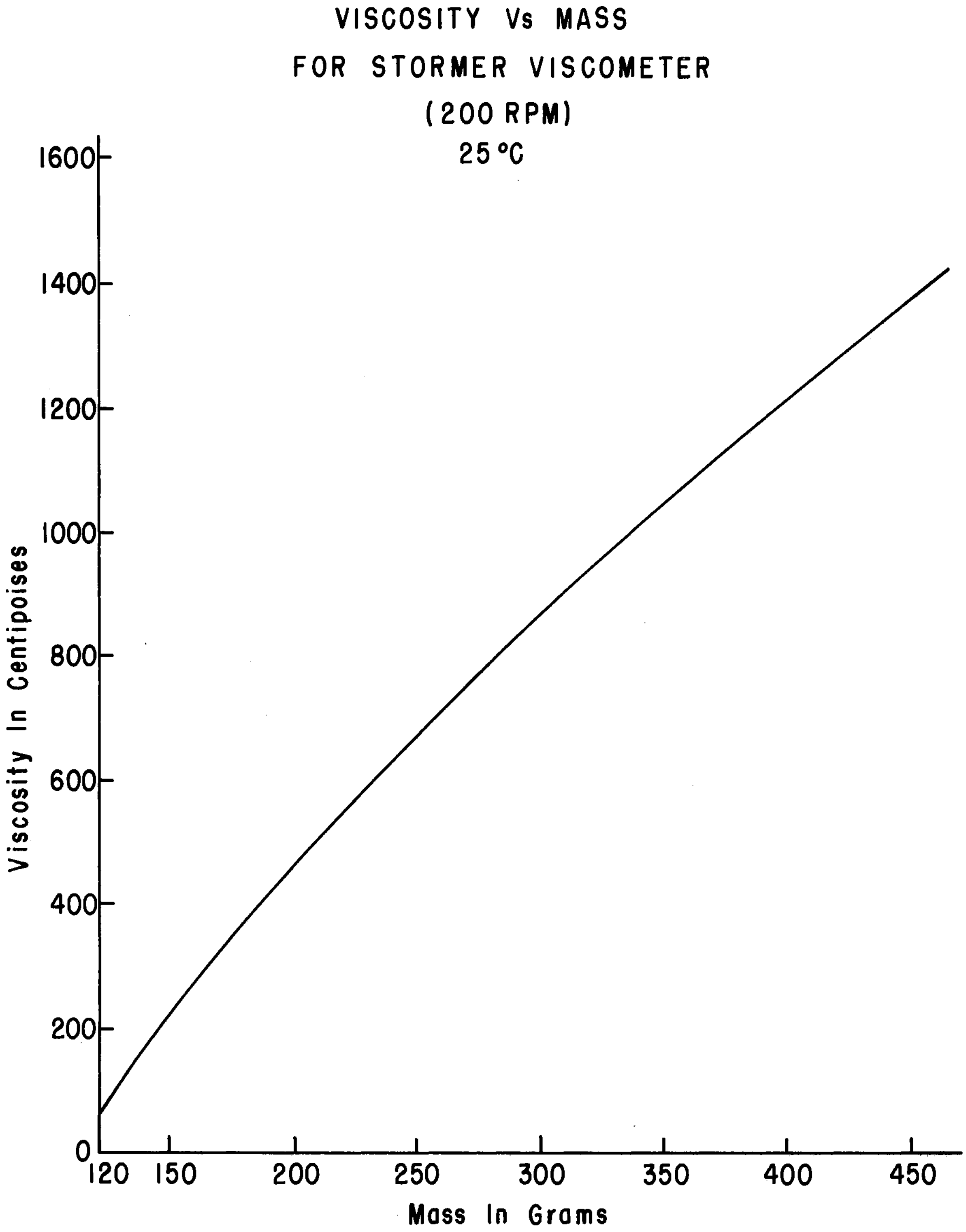


Figure 9. Viscometer Calibration Curve
of Viscosity Versus Mass

To find the viscosity of an unknown, steps one through five were followed in the outline above. Then, the chart made in step seven can be employed in finding the unknown viscosity. Details of specifications can be found in ASTM publications (24).

Slump Tests

Slump tests were used to measure the fluidity of the manure at moisture levels below 85%. The standard ASTM (22) method for concrete was applied. Hart (9) used this method for the same purpose a few years ago.

In spite of wetting the cone as the standard method directs, the cone had to be jarred slightly before it would release its contents. But the results were fairly consistent, as the results given in the next chapter show.

Particle Size Distribution Tests

The method used for wet sieving of soils (2) was helpful in establishing a procedure for wet sieving the 85% slurry. Each subsample was about 170 grams. For each test, enough fresh water was run into the Yoder can to just cover the screen of the top sieve in its highest position. Then, the slurry subsample was poured onto the top sieve. After ten minutes of sieving, the water was siphoned from the can. The sieves were allowed to drip for two hours before they were placed in the oven for 24 hours. Then, the sieves were weighed by a balance to the nearest tenth of a gram before they were cleaned with an air nozzle for the next test.

CHAPTER V

PRESENTATION, ANALYSIS, AND DISCUSSION OF DATA

The primary concern of this research was the thermal properties of beef manure, so thermal conductivity tests and specific heat tests will be presented first. Bulk density is used for calculation of thermal diffusivity, so bulk density results will follow thermal conductivity and specific heat results in order to go into a discussion on thermal diffusivity.

Some difficulties were encountered during the tests due to the wide range of the physical state of the beef manure found at the four moisture levels selected. At the 25% moisture level the manure was easily handled and had a tendency to flow like grain, if it were not compacted. Then at 45% moisture level the manure had a sticky consistency, but it was still granular and it could still flow some, though not nearly so easily as it could when it was drier. The 65% moisture manure samples appeared to be much like the feces of the animals before the feces were mixed with urine and dried. The samples were very difficult to transfer, especially for the specific heat tests. If the subsamples for specific heat tests were placed in the cold flask carefully, the subsample could be transferred to the Dewar flask with a minimum of residual material left in the Thermos. At 85% moisture the manure samples were very easily handled. These samples were quite fluid, though particles remained dispersed throughout the liquid medium fairly well. The samples appeared much like the 85% moisture samples before drying. The most noted differences were the lack of bubbles and less odor in the reconstituted manure as compared to the samples before drying.

The results of the other tests follow the presentation of the thermal values. Viscosity was given only for the 85% moisture manure before drying. Manure at the other levels was too sticky or too dry to use the viscometer, so the slump test was used to measure the consistency of the test samples. Particle size distribution tests were run on the 85% moisture level before drying in order to describe the manure dropped by the animals. At 25% moisture, particle size distribution tests were run to indicate how much the dry lumps were broken down. These results are given under the next section. A few other physical and chemical test results are found in the last section of this chapter.

Thermal Conductivity Results

The power to the thermal conductivity probe heater wire was adjusted to result in a temperature rise of about 40 to 45° F. in ten minutes. Only 2.70 watts were required at the 25% moisture level to obtain a temperature response in that range. About 3.04 watts were required at the 45% level and 5.72 watts were required at 65% and 85% levels. This variation of power requirement indicated that the thermal conductivity varied considerably from the lowest to the highest moisture levels.

In addition to the variation of power, the slopes of the temperature vs. $\log_e$ (time) lines became less as moisture content increased. Since the thermal conductivity value is proportional to the power dissipated in the probe's heater wire and inversely proportional to the slope of the temperature vs. $\log_e$ (time) lines, thermal conductivity changed more than either one. This is seen in the relationship of the terms in Equation 7

$$K = \frac{Q}{4\pi\beta} \tag{7}$$

where $\beta = \dfrac{T_2 - T_1}{\ln(t_2) - \ln(t_1)}$

and β is the slope of the line.

The temperature response was recorded by a strip chart potentiometric recorder. A resulting curve is shown in Figure 10. Reading the data was accomplished by placing a grid over the chart paper. On the grid were 25 lines corresponding to equally spaced $\log_e$ (time) intervals.

These values were then placed on computer cards along with the power data. Figure 11 shows the results for a particular run at the 25% moisture level. Hooper and Lepper (12) suggested that a 5 second correction could be applied to the time in order to allow for the warm-up period with their probe and material. The solid line in Figure 11 represents the actual data and the broken line on the same figure represents the corrected line.

Van der Held (10) and Hooper and Lepper (12) recommended plotting the derivative of time with respect to the derivative of temperature $\left(\frac{dt}{dT}\right)$ versus time to determine the correction factor. This was found to be a little difficult to accomplish accurately. Instead, correction factors for each moisture level were found by trial and error. An analysis of variance (AOV) was used in conjunction with a regression procedure. Both were subprograms of the "Statistical Analysis System"

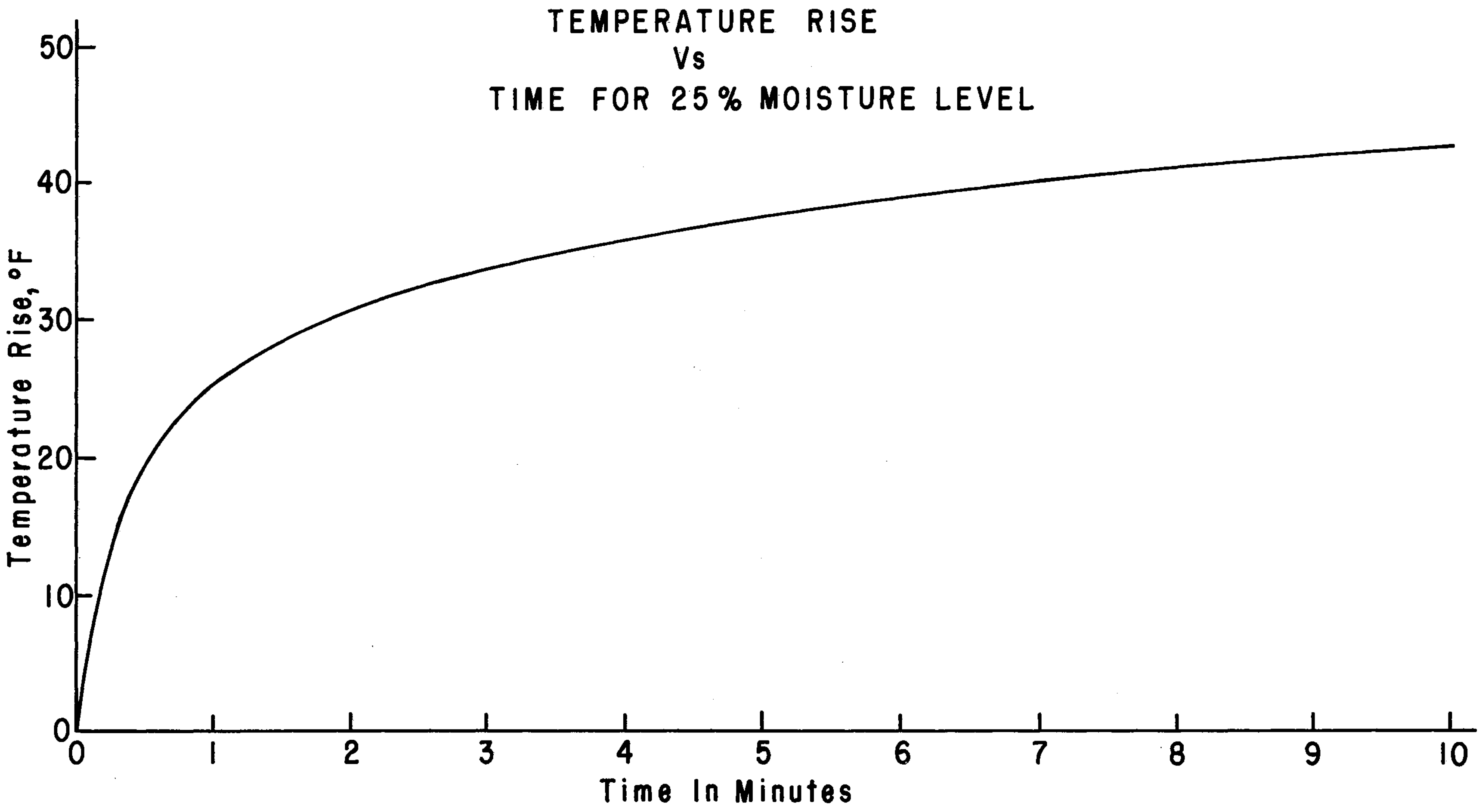


Figure 10. Typical Potentiometric Recording of Temperature Versus Time

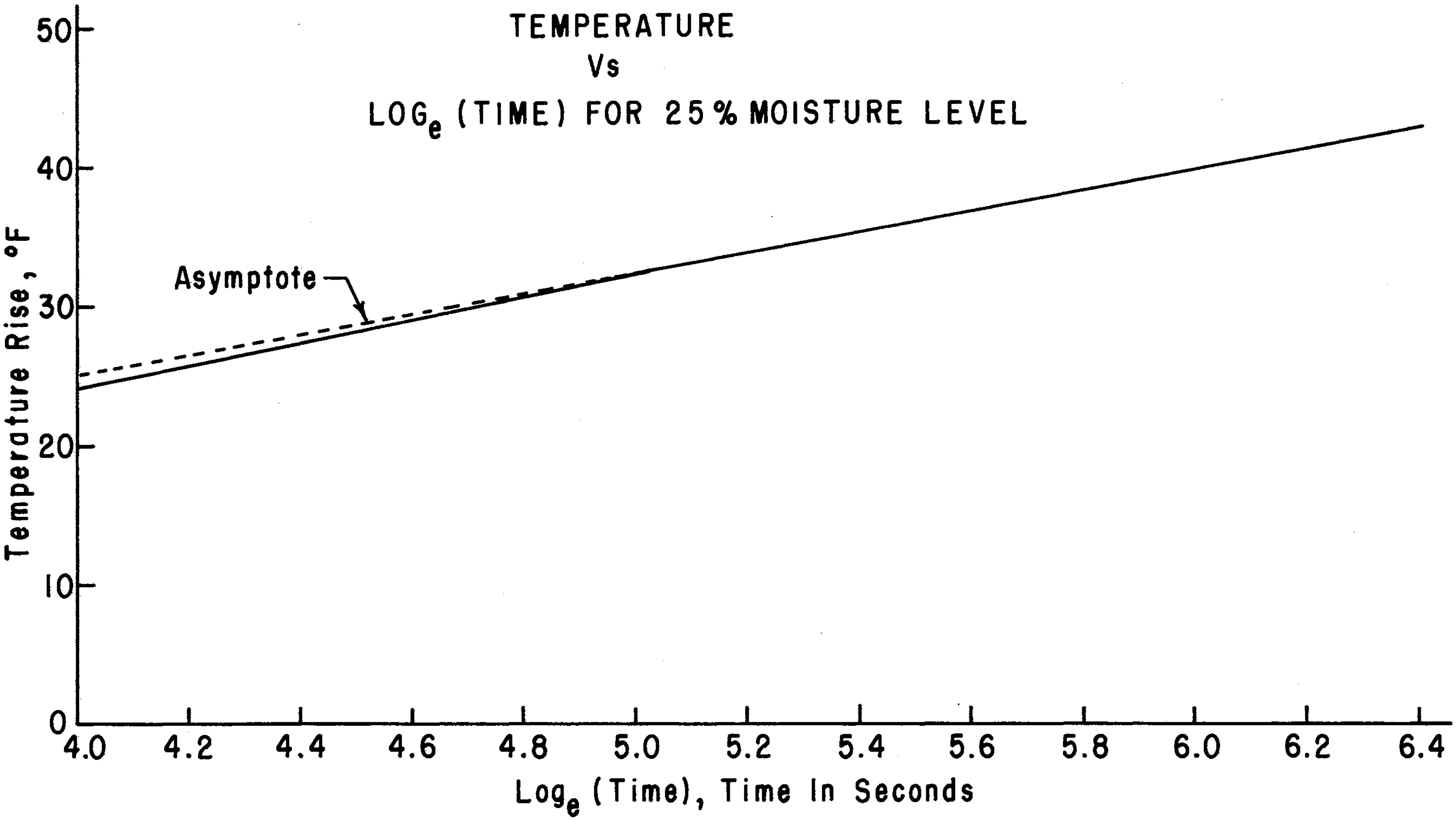


Figure 11. Typical Results of Temperature Versus the Logarithm of Time

(SAS) program by Barr and Goodnight (1) of North Carolina State University. The program is stored on the IBM 360 Model 65 computer at the Oklahoma State University computer center. The AOV in this particular case was used to isolate the variation of the lack of fit of the regression lines to the original data. When this was a minimum, it was assumed that the time correction factor that was arbitrarily selected was the most suitable to use at that one moisture level.

For the 25% moisture level, 5 seconds was sufficient for a time correction factor. At 45% moisture level, 18 seconds corrected the original data the best. No correction was required for the 65% and 85% moisture levels.

The means of the nine thermal conductivity tests at each moisture level were calculated, as plotted in Figure 12. Based on the mean square of the three samples (two degrees of freedom), the confidence intervals were calculated for each of the four moisture levels. The confidence intervals were for a 95% probability. The confidence interval became much wider at the 85% moisture level; this is probably due to convection currents arising in the slurry. This is supported by the fact that some of the test runs resulted in calculated thermal conductivities beyond that of water. Although there are substances that have thermal conductivities greater than water, it is unexpected in a substance that has 85% water by wet weight. Also supporting the convection theory is the fact that after six minutes some of the test runs resulted in no further temperature rise. Because of this lack of response, the last 5 values of all nine tests were disregarded while calculating the thermal conductivity value for the 85% level.

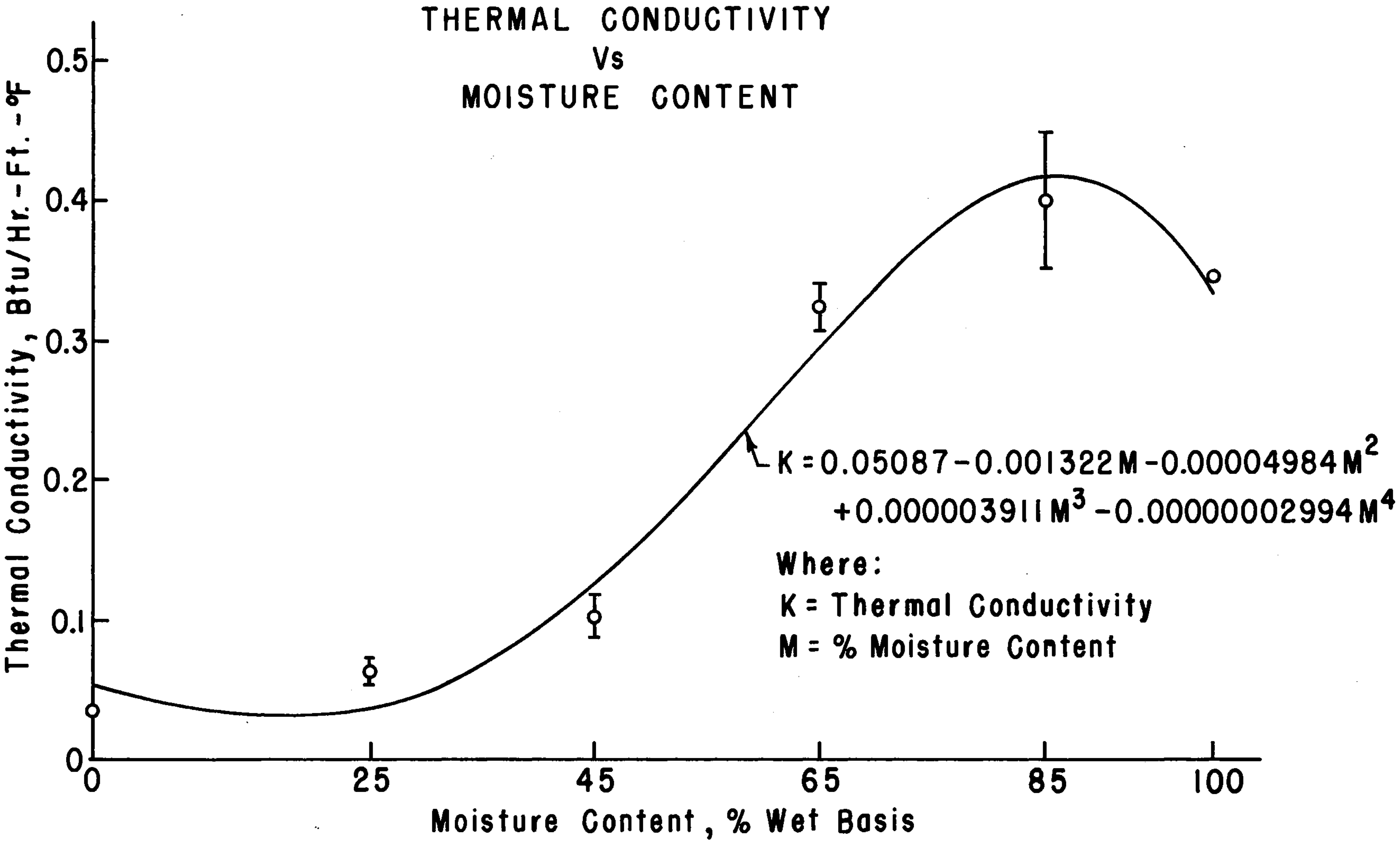


Figure 12. Thermal Conductivity Means, Confidence Intervals (Based Upon Replication Mean Square at Each Moisture Level), and Regression Equation (Based Upon Means)

Finding a suitable regression line for the thermal conductivity values was impossible when based upon the four means; therefore, the thermal conductivity values at 100% and 0% moisture content were added. The value for water was used as the 100% thermal conductivity value, and the 0% thermal conductivity value was obtained by running a test on manure that had been dried to 0%. A public program called "Polfit", available at the University Computer Center through the conversational programming system (CPS), was the regression program used to find the polynomial to fit the six thermal conductivity values. The best equation found is expressed as

$$K = 0.05087 - 0.001322M - 0.00004984M^2 + 0.000003911M^3 - 0.0000002994M^4$$

where

K = thermal conductivity, BTU/Hr. - Ft. - °F.

M = % moisture content

This equation fitted the values with an index of determination of 0.98.

The values of the thermal conductivity means for the 25%, 45%, 65%, and 85% moisture levels are 0.0618, 0.103, 0.325, and 0.397 (BTU/Hr. - Ft. - °F.), respectively. The greatest change in thermal conductivity lies between the 45% and 65% moisture levels, as illustrated in Figure 12. This most likely is due to the change in physical state. Results of the particle size distribution tests for the 25% moisture level are presented in Table I. The particle sizes were fairly well distributed at the 25% moisture level, permitting the smaller particles to nest between the larger ones. However, some of the smaller particles tended to adhere to one another at 45% moisture level. This was observed through the walls of the Plexiglas cylinder. More air spaces existed at the 45% level, causing the thermal conductivity to be lower than

TABLE I

PARTICLE SIZE DISTRIBUTION FOR 25% MOISTURE LEVEL

Sieve Number	Aperature in Inches	Percent on or Between Sieves	Total Percentage on Sieve	Total Percentage Passing Sieve
4	0.1870	3.8	3.8	96.2
8	0.0937	35.4	39.2	60.8
16	0.0469	27.8	67.0	33.0
30	0.0234	18.3	85.3	14.7
50	0.0117	9.5	94.8	5.2
100	0.0059	3.4	98.2	1.8
140	0.0041	1.0	99.2	0.8
Pan		0.8	100.0	0.0
Total		100.0		

expected. At the 65% level, a complete absence of air pockets on the walls of the Plexiglas cylinder was observed. This would tend to increase the thermal conductivity compared to a substance having air pockets.

The repeatability was good in all tests except at the 85% level, where some convection problems were noticed. Absolute accuracy is somewhat difficult to establish. Hooper and Lepper (12) suggest that the thermal conductivity probe is a standard apparatus that needs no calibration against another standard or material. The confidence interval for the 85% moisture level, as illustrated in Figure 12, includes the thermal conductivity of water which is 0.344 BTU/Hr. - Ft. - °F. This fact suggests that the instrument is fairly accurate.

One of the major stipulations of the thermal conductivity probe test method is the requirement of no temperature gradients in the test material at the beginning of the test. This requirement was met by mixing the test sample for ten minutes in a covered cement mixer. Both the test sample and the mixer were kept in a stable temperature room for the duration of the tests. All the tests were run at 25° C. ± 1°. Temperature control over a broader range would be required to determine the effect of temperature on the thermal conductivity.

Specific Heat Results

Once the water equivalent of the Dewar flask was known, the testing procedure became one of transferring the subsamples, mixing the subsamples with a given quantity of water in the Dewar flask, and recording the temperatures before and after mixing. Separate values for each specific heat test were calculated with a desk top calculator that included memory registers. Then each specific heat test was placed on a computer card for an analysis of variance (AOV). Again, the "Statistical Analysis System" (SAS) program by Barr and Goodnight (1) of North Carolina State University was used to analyze the data.

The results indicated that there was little variation between runs within each replication. The replication mean square was a little larger than the run mean square, but the large moisture mean square indicated a significant difference of values for specific heat at different moisture levels. As illustrated by Figure 13, the specific heat means were 0.417, 0.626, 0.789, and 0.922 (BTU/lb. - ^{o}F.) for 25%, 45%, 65%, and 85% moisture levels, respectively. The confidence intervals given at each level were calculated by using the replication mean square and the 95% value of the two-tailed t test. With the four means and the specific heat value for water at 100% moisture level, a regression program calculated the equation

$$c = 0.1128 + 0.01335M - 0.00004486M^2$$

where

c = specific heat, BTU/lb. - ^{o}F.

M = % moisture content

The index of determination was 0.98 for the equation. The program used was "Polfit", a regression program available for the public through the conversational programming system (CPS) on the IBM 360 Model 65 at the OSU computer center.

Equation 10 was used to calculate the specific heat values for each run at the 65% and 85% moisture levels. The mixture temperature of the system at these moisture levels was at about room temperature. The mixture temperatures of the tests at the other two levels were higher

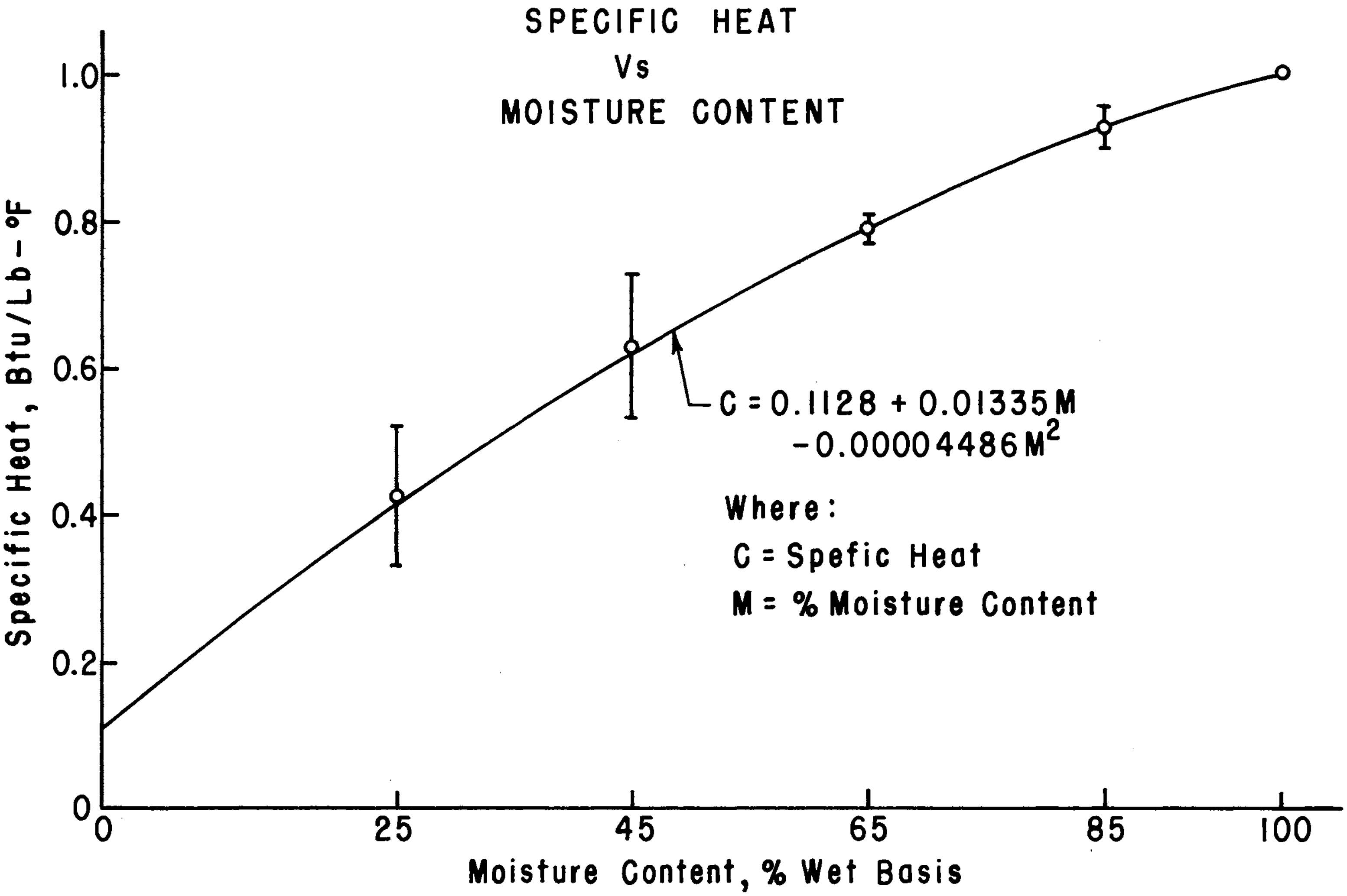


Figure 13. Specific Heat Means, Confidence Intervals (Based Upon Relication Mean Square at Each Moisture Level), and Regression Equation (Based Upon Means)

than the room temperature so Equation 11 was used to correct the mixture temperature for heat loss. A straight line was drawn through the mixture temperature as recorded on the strip chart. The point where the mixture temperature separated from the straight line drawn was taken as the equilibrium value and the time was noted. The product of the time and the slope of the straight line was used to calculate the new mixture temperature at the time of the initiation of the mixing action. A typical curve that has a mixture temperature above room temperature is illustrated in Figure 14 along with the correction method.

Bulk Density Results

The means of the bulk density tests were 26.3, 32.6, 67.2, and 65.7 (lb./Ft.^{3}) for 25%, 45%, 65%, and 85% moisture levels, respectively, as shown in Figure 15. The regression equation determined was

$$\rho = 20.41 - 0.3648M + 0.01972M^2 + 0.00001036M^3 - 0.000001304M^4$$

where

ρ = density, lb./Ft.^{3}

M = % moisture content

The index of determination was 0.99 for this equation. The regression equation was calculated by using the values of the four means, the value of an additional test at 0% moisture level, and the density of water at 100% moisture level. The confidence intervals were calculated by using the 95% two-tail t test and the replication mean square.

At 65% and 85% moisture levels, the bulk density values were greater than that of water. This is expected because the average particle density is 1.48 gr./cc. The values for the other moisture levels appear to be dependent on moisture content. However, the bulk density

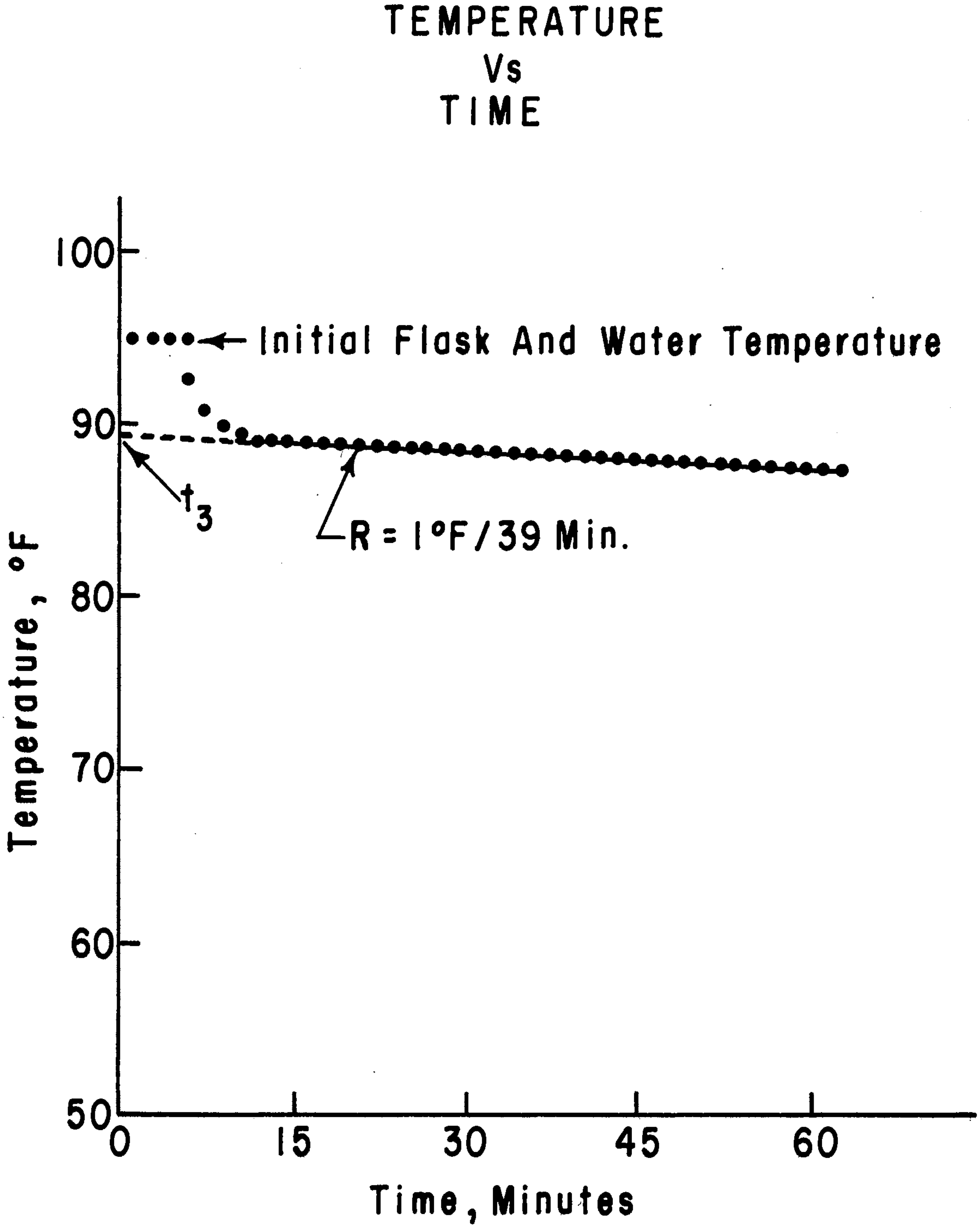


Figure 14. Correction Method for Specific Heat Tests

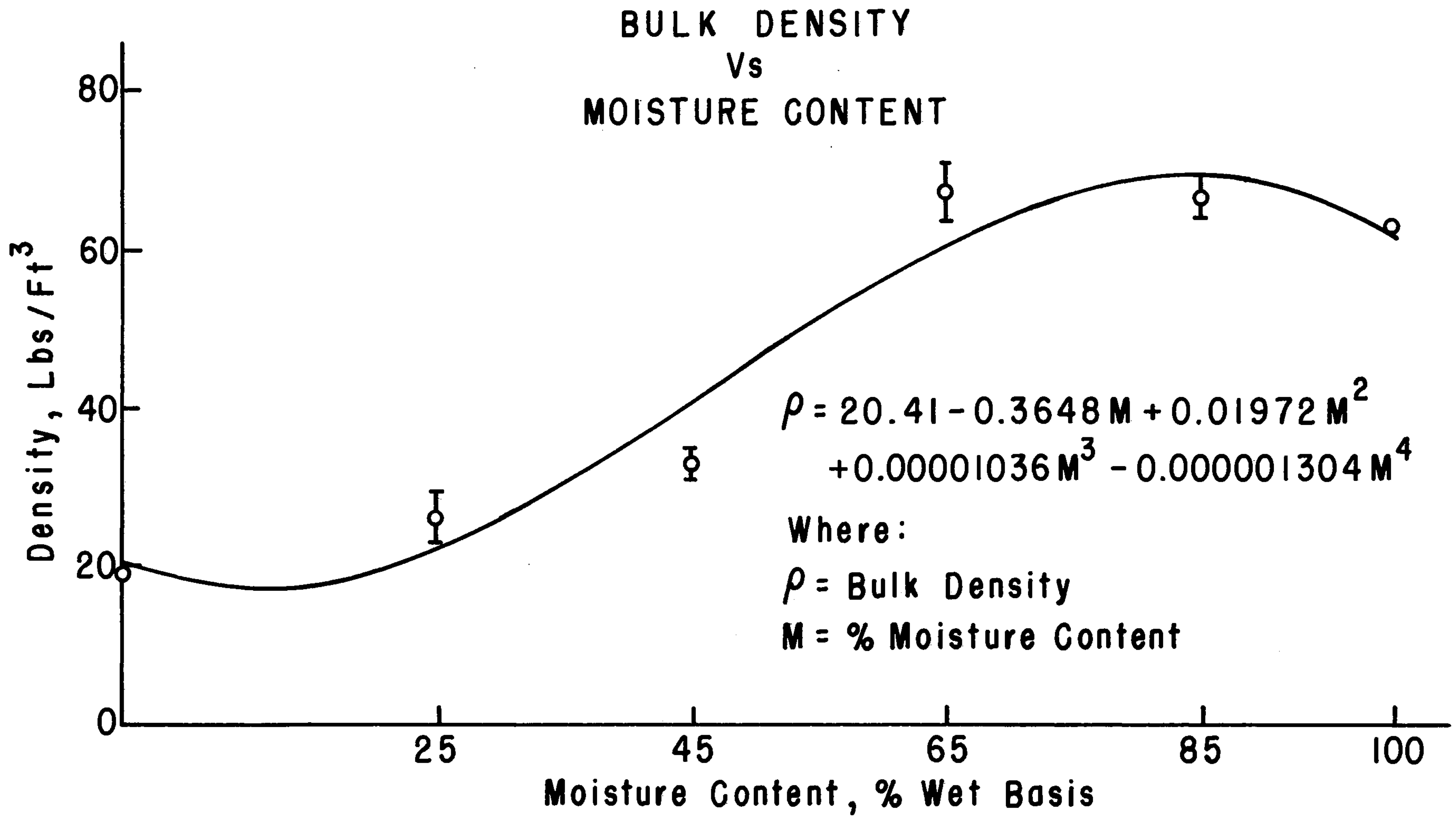


Figure 15. Bulk Density Means, Confidence Intervals (Based Upon Replication Mean Square at Each Moisture Level), and Regression Equation (Based Upon Means)

probably is more of a function of void space, since the bulk density at 0% moisture content should be the same as the density calculated from the average particle density.

Estimation of Thermal Diffusivity

Thermal diffusivity is a function of thermal conductivity, specific heat and the bulk density, as seen in the following equation:

$$\partial = \frac{K}{\rho c} \tag{12}$$

Thermal diffusivity was calculated for each run, and the means of the calculated values were 0.00565, 0.00505, 0.00614, and 0.00656 (Ft.^{2}/Hr.) for 25%, 45%, 65%, and 85% moisture levels, respectively, as shown in Figure 16. In addition, the thermal diffusivity value of water was used with the other four values to derive a regression equation. The equation found was

$$\alpha = 0.005321 + 0.000007195M$$

where

α = thermal diffusivity, Ft.^{2}/Hr.

M = % moisture content

The equation fitted the given values with an index of determination of 0.14. The confidence intervals, as shown in Figure 16, were based upon the extremes of each component. Because of the low index of determination of the regression equation, and the wide confidence intervals on the means, it is difficult to show that thermal diffusivity increases or decreases over the range of values.

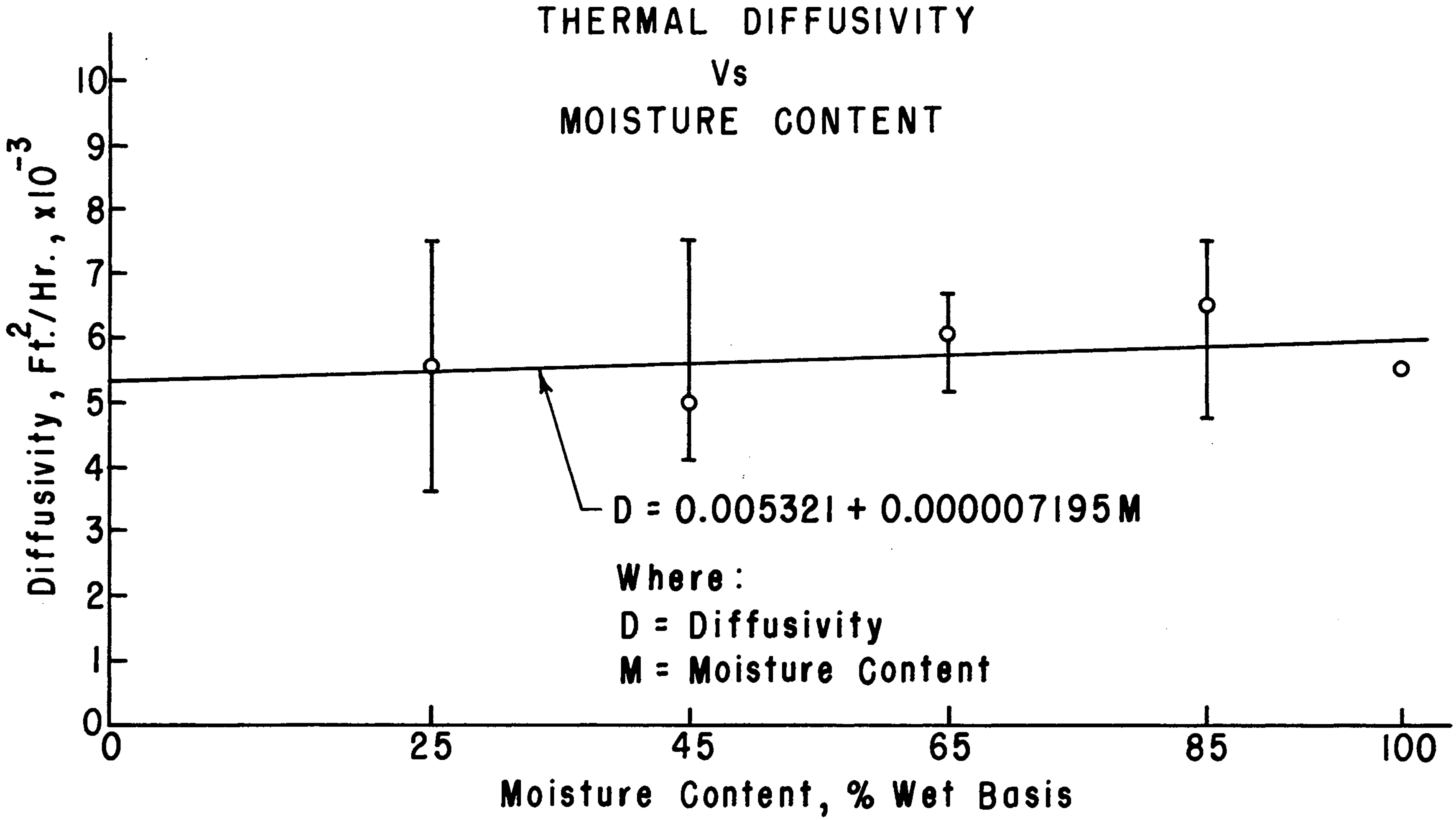


Figure 16. Thermal Diffusivity Means, Confidence Intervals (Based Upon Thermal Conductivity, Specific Heat, and Bulk Density Confidence Intervals), and Regression Equation (Based Upon Means)

Viscosity

A typical time versus mass curve for 85% moisture manure slurry is shown in Figure 17. The mass value for 30 seconds was read from each of eight test curves. The average mass used for the 100 revolutions per 30 seconds (200 rpm.) was 323 grams. Then a value of 960 centipoises was read from the viscosity versus mass curve in Figure 11. This value compares favorably with Kumar's (14) value of 848 centipoises at 25° C. for dairy manure with 11% total solids.

One problem encountered during the viscosity tests was that animal hair, if present, tended to wrap around the paddle rotor. The wrapped hair increased the required mass for 200 rpm. Stirring was required between timings within each test to keep the heavier particles, such as corn kernals, up around the paddle rotor. The paddle in motion stirred the sample enough to counter settling.

Slump Tests

The slump test was performed at the 25%, 45%, and 65% moisture levels. Table II shows the result of the tests for these three moisture levels. Shearing caused the subsidence recorded at the 25% level. Because of less packing, the top of the cone tended to crumble first, and this action increased the effect of the sliding on the sides. At the 45% level, the manure exhibited the least subsidence with one test that had no detectable subsidence. Again, the subsidence was caused by the crumbling action of the top part. A true slumping action was noted at the 65% level, however. This was by far the most uniform slump test results. All levels exhibited a stickiness that prevented the material from dropping out of the cone, in spite of the fact that the inside of

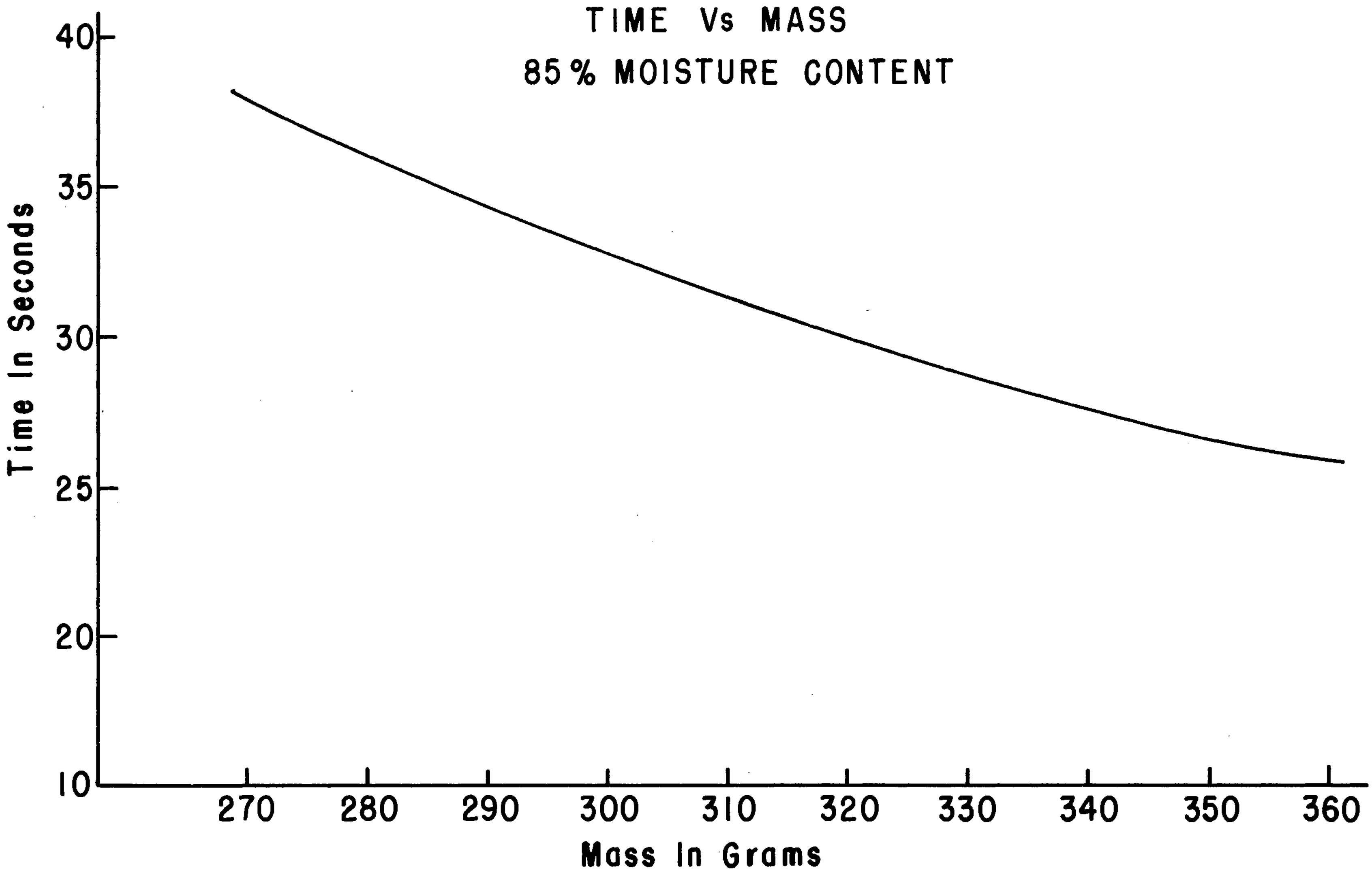


Figure 17. Typical Time Versus Mass Curve for Viscosity Tests

TABLE II

SLUMP TESTS FOR 25%, 45%, AND 65% MOISTURE LEVELS

Moisture Level	Sample Number	Slump in Inches
25	1	1.50
	2	1.25
	3	1.00
45	1	1.25
	2	1.00
	3	0.00
65	1	3.25
	2	3.50
	3	3.50

the cone was wetted before the test and the cone was lifted gently, as it was suggested. A sharp rap against the floor was needed to jar the material loose. This may have increased the subsidence over what would have been noted if the rap wasn't needed.

Hart (9) plotted the slump versus the total solids in dairy manure. A slump of 3 1/2 inches corresponds with 17% total solids on his graph. This shows the effect of the higher roughage ration fed to the dairy cows, compared to the corn ration fed to the steers in this project.

Particle Size Distribution

The results tabulated in Table III are different in comparison to Kumar's (14) results on dairy manure, as shown in Table IV. A much greater percentage of the steer manure, from steers fed a low roughage ration, was finer than the 140 screen. Also, on screens 16, 30, and 50 nearly the same amount was retained on each sieve in both cases. The steer manure had fewer particles on the two coarser screens, fewer particles on the finer screens, about the same amount on the three middle screens, and a much greater amount passing all screens.

Other Properties

1. Moisture content = 85%.
2. Total solids content = 15%.
3. Volatile solids on the basis of total solids content = 97.21%.
4. Fixed solids on the basis of total solids content = 2.79%.
5. Bulk density at 85% moisture content = 1.05 gr./cc.
6. Average particle density = 1.48 gr./cc.
7. Crude protein = 4.21%.
8. Ash = 2.79%.

TABLE III

PARTICLE SIZE DISTRIBUTION OF BEEF MANURE

Sieve Number	Aperature in Inches	Percent on or Between Sieves	Total Percentage on Sieve	Total Percentage Passing Sieve
4	0.1870	3.2	3.2	96.8
8	0.0937	7.1	10.3	89.7
16	0.0469	11.9	22.2	77.8
30	0.0234	9.7	31.9	68.1
50	0.0117	7.9	39.8	60.2
100	0.0059	3.6	43.4	56.6
140	0.0041	1.3	44.7	55.3
Finer than 140		55.3	100.0	
Total		100.0		

TABLE IV

PARTICLE SIZE DISTRIBUTION OF DAIRY MANURE AS REPORTED BY KUMAR (14)

Sieve Number	Aperature in Inches	Percent on or Between Sieves	Total Percentage on Sieve	Total Percentage Passing Sieve
4	0.1870	6.808	6.808	93.192
8	0.0937	16.798	23.606	76.394
16	0.0469	12.862	36.468	63.532
30	0.0234	9.118	45.586	54.414
50	0.0117	10.010	55.596	44.404
100	0.0059	6.138	61.734	38.266
140	0.0041	4.138	65.872	34.116
Finer than 140		34.116	99.988	
Total		99.988		

Thermal Properties and Bulk Density Before Drying

Some specific heat and thermal conductivity tests were run at 85% moisture content before the slurry was dried. Bulk density was determined by the same method as in the previous tests. The mean of the thermal conductivity was less in this case than the mean for the reconstituted manure, but it was still within the 95% confidence interval. This means that it did not vary significantly at the 95% probability level. The same was true for the specific heat.

For density, however, the opposite was true. The mean bulk density in this case was lower than that of the reconstituted manure. Bubbles of gas formed in the manure slurry while it was held in the Plexiglas cylinder, which would cause the bulk density to be less.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

Feces and urine were collected from three steers at the Oklahoma State University Animal Science Nutrition Laboratory. They were fed an 84% ground corn ration with the remaining 16% consisting of cottonseed hulls, dehydrated alfalfa, and a premixed pellet. Based upon oven-drying method tests, the urine and feces were mixed to produce an 85% moisture content slurry. Samples were refrigerated while awaiting test runs.

Thermal conductivities, specific heats, and bulk densities were determined at 25%, 45%, 65%, and 85% wet basis moisture levels. From these properties, an estimate of thermal diffusivity was obtained. Tests were later run on density and thermal conductivity at 0% moisture content to help establish regression curves.

A thermal conductivity probe was constructed at the Agricultural Engineering Laboratory, and the necessary electrical and electronic equipment were used with the probe to take the power and temperature readings required for determining the thermal conductivity. The temperature of all thermal conductivity test samples was held constant at 25° C. Thermal conductivities were 0.0618, 0.103, 0.325, and 0.397 (BTU/Hr. - Ft. - $^{\circ}$F.) for the 25%, 45%, 65%, and 85% wet basis moisture levels, respectively.

Specific heat tests were run by using the method of mixtures. This equipment was adapted from earlier use as a specific heat tester for peanut research. The same electronic potentiometric strip chart recorder was used to sense temperatures in the specific heat tests as was used in the thermal conductivity tests. Subsamples for the specific heat tests were held at a constant temperature, although the final mixture temperature at various moisture levels varied 10° F. Specific heats were 0.417, 0.626, 0.789, and 0.922 (BTU/lb. - °F) for the 25%, 45%, 65%, and 85% moisture levels, respectively.

Bulk densities ranged from 26.3 lb./Ft.^{3} to 67.2 lb./Ft.^{3} for the four moisture levels. These values were determined by weighing and measuring the dimensions of the Plexiglas cylinder in which thermal conductivity test samples were contained.

Other tests were run to establish other physical properties of the manure but not at all moisture levels. Viscosity tests and particle size distribution tests were run at 85% moisture level in order to more fully describe the manure from the steers. A particle size distribution test was employed at the 25% level, also, to show the particle range of the crushed, dried manure. Slump tests were run on the three lower moisture levels to show the consistency of the material. Average particle density was determined by following an ASTM (21) method. Finally, crude protein and the ash were determined by the Animal Science Department.

Conclusions

As a result of the work done in this research project, the following conclusions are presented:

1. Thermal conductivity of beef waste is a function of the moisture content. There may be other factors involved in the variation of thermal conductivity, but moisture content is statistically significant.

2. Specific heat of beef manure is very dependent upon moisture content, and it shows a more linear relationship with moisture content than does thermal conductivity.

3. Thermal diffusivity does not appear to be directly related to moisture content. The confidence intervals are so wide for the thermal diffusivity means that no trend is clearly seen.

4. Particle size of beef manure averages smaller than that of dairy manure. Particle density is about the same in either case.

5. Bulk density of manure appears to reach a maximum around 65% moisture content.

6. A large change in bulk density and thermal conductivity existed between 45% and 65% moisture contents.

Suggestions for Further Work

1. A study of how thermal properties vary with bulk density is needed.

2. It would be desirable to know how the thermal properties vary with temperature.

3. Thermal properties research involving different rations for beef animals and for other animals would be valuable.

4. More work should be done on thermal properties between 45% and 65% moisture levels.

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APPENDIX A

THERMAL CONDUCTIVITY DATA

TABLE V

ORIGINAL THERMAL CONDUCTIVITY DATA

Moisture	Probe Voltage	Amps	Time (Min.)	Replicate 1			Replicate 2			Replicate 3		
				Runs ($T_2 - T_1$, in °F.) 1	2	3	Runs ($T_2 - T_1$, in °F.) 1	2	3	Runs ($T_2 - T_1$, in °F.) 1	2	3
25%	1.8	1.5	0.91	25.1	24.3	23.4	24.8	24.2	24.6	24.7	24.4	24.5
			1.00	25.8	25.0	24.3	25.7	24.9	25.4	25.5	25.2	25.3
			1.11	26.6	25.9	25.2	26.5	25.8	26.3	26.3	26.1	26.2
			1.23	27.5	26.7	25.9	27.4	26.6	27.2	27.1	26.9	27.1
			1.36	28.2	27.5	26.7	28.2	27.4	27.9	27.8	27.7	28.0
			1.50	29.0	28.2	27.5	29.1	28.3	28.8	28.6	28.6	28.9
			1.66	29.8	29.1	28.4	29.9	29.2	29.7	29.3	29.5	29.8
			1.83	30.5	29.9	29.2	30.8	30.1	30.5	30.0	30.4	30.6
			2.02	31.2	30.7	30.0	31.6	30.8	31.4	30.9	31.1	31.4
			2.23	32.0	31.5	30.8	32.3	31.7	32.1	31.8	31.8	32.3
			2.47	32.8	32.1	31.6	33.3	32.5	32.8	32.7	32.5	33.2
			2.74	33.8	32.9	32.4	34.2	33.4	33.6	33.6	33.2	34.0
			3.02	34.7	33.6	33.2	35.1	34.2	34.4	34.3	34.1	34.9
			3.33	35.3	34.2	34.0	35.9	35.2	35.3	35.1	35.0	35.8
			3.68	36.1	35.1	34.6	36.8	36.0	36.2	35.8	35.8	36.6
			4.08	37.1	36.0	35.5	37.7	36.7	37.1	36.7	36.5	37.4
			4.52	37.9	36.8	36.2	38.4	37.5	37.7	37.5	37.2	38.2
			4.98	38.6	37.5	37.0	39.2	38.2	38.5	38.3	38.0	39.0
			5.50	39.2	38.2	37.7	40.0	39.0	39.4	39.0	38.6	39.7
			6.08	39.9	39.2	38.4	40.8	39.6	40.1	39.7	39.2	40.5

TABLE V (Continued)

Mois-ture	Probe	Amps	Time (Min.)	Replicate 1, Runs 1 ($T_2 - T_1$, in °F.)	Replicate 1, Runs 2	Replicate 1, Runs 3	Replicate 2, Runs 1 ($T_2 - T_1$, in °F.)	Replicate 2, Runs 2	Replicate 2, Runs 3	Replicate 3, Runs 1 ($T_2 - T_1$, in °F.)	Replicate 3, Runs 2	Replicate 3, Runs 3
			6.72	40.7	39.9	39.2	41.5	40.3	40.7	40.5	39.8	41.2
			7.44	41.4	40.6	40.0	42.1	40.9	41.5	41.3	40.5	42.1
			8.21	42.2	41.3	40.6	42.9	41.6	42.1	41.8	41.1	42.9
			9.08	42.9	42.0	41.2	43.6	42.3	42.8	42.5	41.9	43.4
			10.01	43.5	42.6	41.9	44.2	43.0	43.4	43.2	42.4	44.0
45%	1.9	1.6	0.91	25.7	25.0	25.6	25.0	25.5	24.7	25.3	25.3	25.2
			1.00	26.4	25.8	26.3	25.8	26.3	25.4	26.0	26.1	26.0
			1.11	27.1	26.5	27.1	26.4	27.0	26.2	26.7	26.8	26.8
			1.23	27.9	27.2	27.8	27.2	27.8	27.0	27.5	27.6	27.7
			1.36	28.6	27.9	28.6	27.8	28.5	27.8	28.3	28.4	28.6
			1.50	29.2	28.6	29.2	28.6	29.1	28.4	29.0	29.1	29.3
			1.66	29.9	29.2	30.0	29.1	29.8	29.2	29.7	29.9	30.1
			1.83	30.4	29.8	30.6	29.7	30.5	29.7	30.2	30.5	30.8
			2.02	30.9	30.4	31.1	30.2	31.0	30.3	30.8	31.2	31.3
			2.23	31.5	31.0	31.7	30.7	31.5	30.8	31.4	31.8	31.9
			2.47	32.2	31.6	32.3	31.2	32.1	31.3	31.9	32.5	32.6
			2.74	32.9	32.1	33.1	32.0	32.8	32.0	32.6	33.1	33.2
			3.02	33.4	32.7	33.8	32.5	33.2	32.6	33.2	33.7	33.9
			3.33	33.9	33.2	34.3	33.1	33.8	33.3	33.8	34.2	34.5
			3.68	34.4	33.6	34.9	33.7	34.4	34.0	34.4	34.8	35.0

TABLE V (Continued)

Moisture	Probe Voltage	Amps	Time (Min.)	Replicate 1 Runs 1 ($T_2 - T_1$, in $^{\circ}$F.)	Replicate 1 Runs 2	Replicate 1 Runs 3	Replicate 2 Runs 1 ($T_2 - T_1$, in $^{\circ}$F.)	Replicate 2 Runs 2	Replicate 2 Runs 3	Replicate 3 Runs 1 ($T_2 - T_1$, in $^{\circ}$F.)	Replicate 3 Runs 2	Replicate 3 Runs 3
			4.08	35.1	34.1	35.3	34.1	35.1	34.5	34.9	35.4	35.6
			4.52	35.8	34.8	35.8	34.7	35.7	35.1	35.5	35.9	36.1
			4.98	36.2	35.3	36.3	35.2	36.2	35.6	35.9	36.4	36.6
			5.50	36.7	35.8	36.8	35.7	36.6	36.1	36.4	36.9	37.0
			6.08	37.2	36.2	37.3	36.2	37.0	36.6	36.9	37.4	37.7
			6.72	37.6	36.6	37.8	36.7	37.6	37.0	37.5	37.9	38.2
			7.44	38.1	37.1	38.4	37.2	38.2	37.5	38.1	38.5	38.7
			8.21	38.6	37.6	38.8	37.6	38.6	37.8	38.6	39.0	39.1
			9.08	39.1	38.1	39.3	38.1	39.3	38.5	39.1	39.6	39.7
			10.01	39.7	39.0	39.8	38.8	39.8	39.1	39.9	40.2	40.2
65%	2.6	2.2	0.91	33.6	32.5	32.7	34.5	33.4	33.4	33.5	33.6	33.7
			1.00	33.8	32.8	33.0	34.7	33.6	33.7	33.7	33.8	33.9
			1.11	34.0	33.1	33.5	35.0	33.8	34.0	34.0	34.1	34.2
			1.23	34.2	33.4	33.8	35.1	34.2	34.3	34.3	34.4	34.5
			1.36	34.5	33.7	34.1	35.3	34.5	34.7	34.7	34.7	34.8
			1.50	34.8	35.0	34.4	35.6	34.8	34.9	35.0	35.0	35.1
			1.66	35.2	35.2	34.7	35.8	35.0	35.1	35.3	35.5	35.5
			1.83	35.8	35.0	35.0	36.3	35.3	35.5	35.6	35.8	35.7
			2.02	36.0	35.1	35.3	36.6	35.8	35.8	35.8	36.0	36.0
			2.23	36.3	35.2	35.5	36.9	36.2	36.2	36.2	36.2	36.3

TABLE V (Continued)

				Replicate								
				1			2			3		
Moisture	Probe Voltage	Amps	Time (Min.)	Runs 1 ($T_2 - T_1$, in °F.)	Runs 2 ($T_2 - T_1$, in °F.)	Runs 3 ($T_2 - T_1$, in °F.)	Runs 1 ($T_2 - T_1$, in °F.)	Runs 2 ($T_2 - T_1$, in °F.)	Runs 3 ($T_2 - T_1$, in °F.)	Runs 1 ($T_2 - T_1$, in °F.)	Runs 2 ($T_2 - T_1$, in °F.)	Runs 3 ($T_2 - T_1$, in °F.)
			2.47	36.5	35.5	35.8	37.1	36.4	36.5	36.6	36.5	36.5
			2.74	36.8	35.8	36.2	37.4	36.6	36.6	36.8	36.8	37.0
			3.02	37.2	36.1	36.3	37.9	36.9	36.8	37.1	37.1	37.2
			3.33	37.4	36.4	36.5	38.2	37.2	37.4	37.4	37.3	37.5
			3.68	37.7	36.6	36.8	38.6	37.5	37.6	37.7	37.6	37.8
			4.08	38.0	37.0	37.5	39.0	37.8	37.7	37.9	37.8	38.1
			4.52	38.3	37.2	37.8	39.3	38.1	38.0	38.3	38.0	38.4
			4.98	38.6	37.5	38.1	39.8	38.4	38.4	38.7	38.3	38.9
			5.50	39.1	37.8	38.3	40.1	38.8	38.8	39.1	38.7	39.1
			6.08	39.3	38.2	38.8	40.4	39.0	39.0	39.3	39.1	39.5
			6.72	39.8	38.3	39.1	40.7	39.3	39.4	39.6	39.4	39.8
			7.44	40.1	38.6	39.5	41.0	39.6	40.3	40.0	39.7	40.0
			8.21	40.4	39.3	39.8	41.2	39.9	40.4	40.3	40.2	40.4
			9.08	40.8	39.4	40.1	41.6	40.2	40.6	40.6	40.4	40.7
			10.01	41.1	39.7	40.4	41.8	40.5	40.7	40.9	40.7	41.0
85%	2.6	2.2	0.91	34.5	34.2	34.0	32.8	33.2	32.5	32.6	32.4	31.7
			1.00	34.8	34.5	34.2	33.1	33.4	32.8	32.8	32.6	31.9
			1.11	35.1	34.8	34.5	33.4	33.7	33.1	33.0	32.8	32.1
			1.23	35.4	35.0	34.8	33.7	33.9	33.4	33.2	33.1	32.4
			1.36	35.7	35.5	35.2	33.9	34.2	33.6	33.6	33.4	32.7

TABLE V (Continued)

				Replicate 1			Replicate 2			Replicate 3		
				Runs			Runs			Runs		
Moisture	Probe Voltage	Amps	Time (Min.)	1	2	3	1	2	3	1	2	3
				($T_2 - T_1$, in °F.)			($T_2 - T_1$, in °F.)			($T_2 - T_1$, in °F.)		
			1.50	36.0	35.5	35.5	34.2	34.5	33.8	34.0	33.7	33.0
			1.66	36.3	35.6	35.7	34.5	34.8	34.2	34.3	34.0	33.3
			1.83	36.4	35.8	35.9	34.7	35.0	34.4	34.6	34.2	33.6
			2.02	36.7	36.1	36.2	35.0	35.4	34.6	34.9	34.5	33.8
			2.23	36.9	36.4	36.5	35.2	35.7	34.8	35.1	34.8	34.0
			2.47	37.2	36.7	36.7	35.6	35.9	35.0	35.4	35.1	34.3
			2.74	37.5	37.1	36.9	35.8	36.1	35.3	35.5	35.4	34.6
			3.02	37.7	37.3	37.2	36.1	36.6	35.6	35.9	35.6	34.8
			3.33	37.9	37.7	37.4	36.2	36.7	35.7	36.1	35.8	35.0
			3.68	38.0	38.0	37.8	36.5	37.0	35.9	36.2	36.1	35.3
			4.08	38.3	38.2	38.0	36.8	37.3	36.1	36.6	36.4	35.5
			4.52	38.7	38.5	38.3	36.9	37.6	36.2	36.7	36.7	35.8
			4.98	39.1	38.8	38.6	37.1	37.8	36.5	37.1	37.0	36.0
			5.50	39.3	39.0	38.8	37.4	37.8	36.6	37.5	37.3	36.3
			6.08	39.4	39.2	39.1	37.9	38.1	36.8	37.6	37.5	36.5
			6.72	39.7	39.4	39.4	37.9	38.2	36.9	37.8	37.8	36.7
			7.44	40.0	39.7	39.7	37.9	38.3	37.9	38.1	38.0	36.9
			8.21	40.4	40.0	39.9	37.9	38.5	37.9	38.1	38.2	37.4
			9.08	40.7	40.2	40.2	37.9	38.6	37.8	38.1	38.5	37.6
			10.01	40.9	40.6	40.6	37.8	38.8	37.8	38.1	38.7	37.8

APPENDIX B

SPECIFIC HEAT AND BULK DENSITY DATA

TABLE VI

ORIGINAL DENSITY AND SPECIFIC HEAT DATA

Moisture	Replicate	Run	Density (lb./Ft.^{3})	Specific Heat (BTU/lb. - $^{\circ}$F.)
25%	1	1	26.9	0.395
		2	27.1	0.385
		3	27.4	0.415
	2	1	25.5	0.447
		2	25.7	0.413
		3	25.7	0.462
	3	1	26.1	0.424
		2	26.3	0.411
		3	26.2	0.401
45%	1	1	33.1	0.615
		2	33.0	0.634
		3	33.0	0.614
	2	1	32.7	0.645
		2	32.3	0.647
		3	32.5	0.656
	3	1	31.9	0.595
		2	32.4	0.598
		3	32.3	0.631
65%	1	1	68.4	0.780
		2	67.7	0.792
		3	68.4	0.788
	2	1	66.6	0.821
		2	66.9	0.814
		3	67.0	0.729
	3	1	66.2	0.791
		2	66.6	0.810
		3	66.7	0.772
85%	1	1	66.0	0.881
		2	66.0	0.932
		3	66.0	0.933
	2	1	65.9	0.910
		2	65.9	0.913
		3	65.9	0.940
	3	1	65.2	0.948
		2	65.2	0.932
		3	65.2	0.910

VITA

Robert Lloyd Houkom

Candidate for the Degree of

Master of Science

Thesis: THERMAL PROPERTIES OF BEEF MANURE

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Fargo, North Dakota, March 29, 1945, the son of Carl and Ilene Houkom; married to Mary Ann Pulse on June 20, 1970; father of Melanie Jeanne, who was born February 9, 1972.

Education: Graduated from West Fargo High School, West Fargo, North Dakota, in May, 1963; received Bachelor of Science degree in Agricultural Engineering from the North Dakota State University in May, 1970; completed the requirements for the Master of Science degree at the Oklahoma State University in May, 1972.

Professional Experience: Graduate Research Assistant, Oklahoma State University, 1970 to 1972.

Professional and Honorary Societies: Student Member American Society of Agricultural Engineers, Member of Tau Beta Pi, Member of Alpha Epsilon, Engineer in Training (North Dakota).