Design and application of a microwave moisture meter

by Joseph Lacy Kowalski

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Electrical Engineering
Montana State University

Abstract:
A specific application of microwave techniques to the measurement of moisture content of fuel materials of the forest floor is discussed in this paper. The principle of absorption of electromagnetic energy passed through a layer of water is used to derive the equation for calculating the moisture content of a given sample. Detailed experimental and theoretical study showed the attenuation of microwave energy in water is a strong function of the temperature of the water. A plot of calculated attenuation verses temperature and a table of the derived multiplying factor (k) used in the moisture meter equation are given and compared to experimental results.

It was observed experimentally that the method used for oven drying as a check on the moisture meter was not consistant. It was found to be necessary to remove the moisture from the air in the oven to allow the sample materials to dry out completely. This was achieved by placing a drying agent (calcium sulfate) in the oven. The drying agent absorbed the moisture, in the air and allowed the sample material to dry out completely.

Methods of further study to determine the accuracy of the meter and improvements that could be made on the moisture meter are. given in the last two chapters of this paper.

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Date July 12, 1974

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A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree

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Electrical Engineering

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ABSTRACT

A specific application of microwave techniques to the measurement of moisture content of fuel materials of the forest floor is discussed in this paper. The principle of absorption of electromagnetic energy passed through a layer of water is used to derive the equation for calculating the moisture content of a given sample. Detailed experimental and theoretical study showed the attenuation of microwave energy in water is a strong function of the temperature of the water. A plot of calculated attenuation verses temperature and a table of the derived multiplying factor (k) used in the moisture meter equation are given and compared to experimental results.

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CHAPTER I

INTRODUCTION

The need for accurate, continuous moisture monitoring equipment in the production of paper, textile, flour and various other products has brought about the use of microwave techniques to measure moisture levels where direct contact with the material is undesirable [1,2].

The technique of measuring moisture is based on the fact [3] that the amount of microwave energy absorbed is a function of the amount of water present. Therefore, by transmitting microwave energy through a sample and measuring the difference in transmitted and received energy, the moisture content of the sample can be determined.

This investigation was undertaken to determine how the absorption of microwave energy behaved as a function of moisture content of several particular materials. Also, part of the work was concerned with finding other variables that would have to be considered to obtain a portable microwave moisture meter that could be used by the Forest Service to measure moisture content of fuels on the forest floor with at least as good if not better accuracy than methods presently being used.

CHAPTER II

PRINCIPLE AND DESIGN OF MICROWAVE MOISTURE METER

This chapter discusses the principle of the absorption of electromagnetic energy in water and how this principle is applied in the design of a moisture meter.

A. Microwave Absorption in Water

1. Absorption at Resonance Frequency

The absorption of microwaves in water is due to a resonance of the water molecule with the microwave signal [4]. Several authors have shown that microwave absorption in water peaks out about 22,000 MHz [3,5]. The shape of the absorption peak was first determined by Becker and Aulter [5] for water vapor. It has been shown that the attenuation for pure water is 40 dB/cm at a frequency of 10,000 MHz [6]. Above 10,000 MHz the conductivity of water is independent of its salt content and therefore the absorption of electromagnetic energy is independent of salt content [6]. Figure (1) gives a plot of the loss factor of pure water verses frequency [4]. It is seen then from Figure (1) that the choice of frequency to obtain a high loss factor and hence good sensitivity for the meter would be in the microwave frequency range.

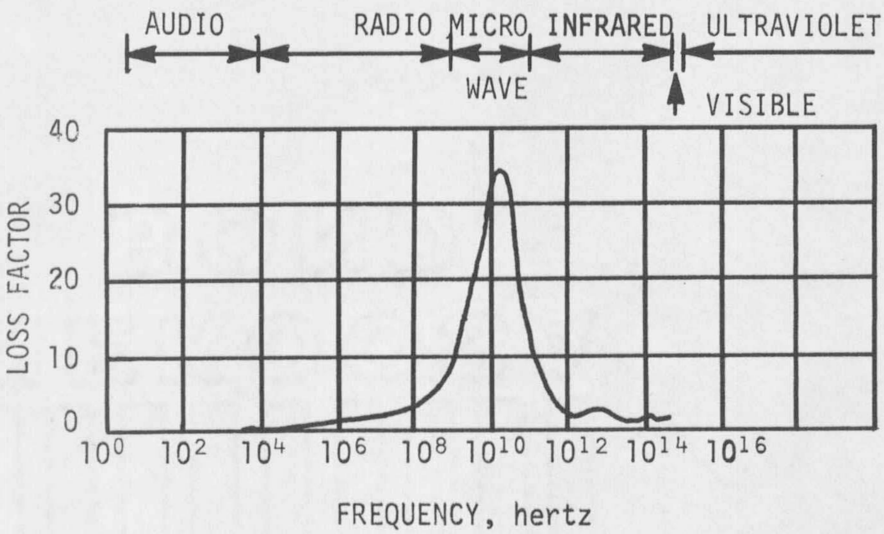


Figure 1. Loss Factor for Pure Water vs. Frequency.

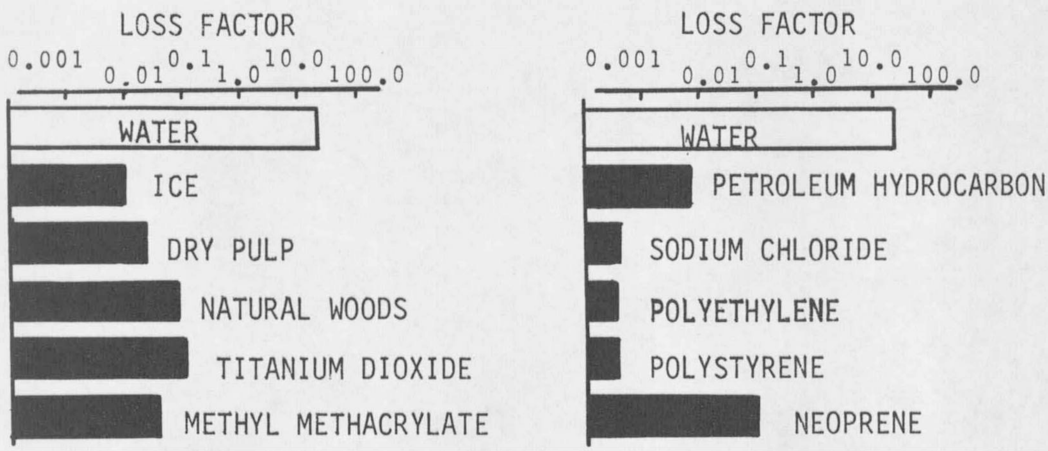


Figure 2. Loss Factor of Water and Prevalent Materials at K-Band Microwave.

2. Absorption of Microwaves in Materials Containing Water

Since the interest of this study was measuring moisture content of materials, the question of how electromagnetic waves were attenuated by water contained in specific materials was raised. If the attenuation of microwaves due to water contained in specific materials was much greater than the attenuation due to the materials themselves the amount of water present could be related directly to the attenuation measured.

The fact that the absorption of microwaves in materials is proportional to the loss factor of the material [4] implies that the loss factor of water is much higher than that of the specific materials of interest. Figure (2) compares the loss factor of water to various other materials [4]. The figure shows that a ratio of 100 to 1 between water and base materials should exist. This means that a similar ratio should exist for the absorption of water and the base material.

Theoretically then the moisture content of a sample of material could be determined from the attenuation of a microwave signal passed through it. Therefore, for a moisture meter, a source of microwave signal plus a means of guiding the signal through the sample material and measuring the received signal at the other side of the sample is needed.

B. Components of Moisture Meter

1. Microwave Components

The heart of the microwave moisture meter is its source of microwave energy. The requirement that the moisture meter be portable placed restrictions on the choice of microwave source. The source had to be small, lightweight, and most of all had to be powered by a dc voltage source. A Gunn oscillator was chosen as the source because it is small, lightweight and requires only a 12 volt dc power supply. The Gunn oscillator chosen operates at 10,525 MHz. This frequency was selected so that the effects due to salts in the water could be ignored as previously stated.

Microwave horns are used to transmit and receive the microwave signal. The horns are placed approximately 2 inches apart. Each horn has an apature area of 2.5" x 2.25" = 5.625 square inches, and each has a gain of approximately 9 db over a dipole antenna.

For detection of the microwave signal a standard 1N23 silicon diode detector is used. The diode detector rectifies the microwave signal and has a dc voltage output proportional to the microwave input level.

A precision rotary vane attenuator is used to set the level of microwave signal that is transmitted into the sample. The accuracy of the attenuator is $\pm 2\%$ of db reading or ± 0.1 db whichever is greater over a 0 to 50 db range. The scale on the attenuator can be read to the nearest tenth of a db in the 10 to 50 db range.

2. Electronic Components

The electronics of the meter are composed of a modulator, amplifier, and power source (two six volt batteries connected in series). The modulator supplies a 1 KHz square wave with its low level at 0 volts and high level at 12 volts. The modulator drives the Gunn oscillator which in turn outputs a 10,525 MHz signal modulated by a 1 KHz square wave. The diode detector then has a 1 KHz square wave output. This output is fed to the amplifier (tuned to 1 KHz) which has a variable gain of 0 to 40 db. The amplifier in turn drives a current meter which is used to set a reference level on the received signal.

Appendix I contains pictures of the Gunn oscillator, horns, diode detector, precision attenuator, modulator and amplifier. Appendix II contains the schematics and specifications of the modulator and amplifier.

C. Construction Details of Moisture Meter

Figure (3) is a block form representation of the moisture meter in terms of its microwave and electronic components. Several authors show similar diagrams of moisture meters that work on the same principle of attenuation measurements [6,7,8].

The moisture meter being discussed in this investigation was designed and built by Dr. Bruce R. McLeod, of Montana State University. The first model was rather large and difficult to carry in the field.

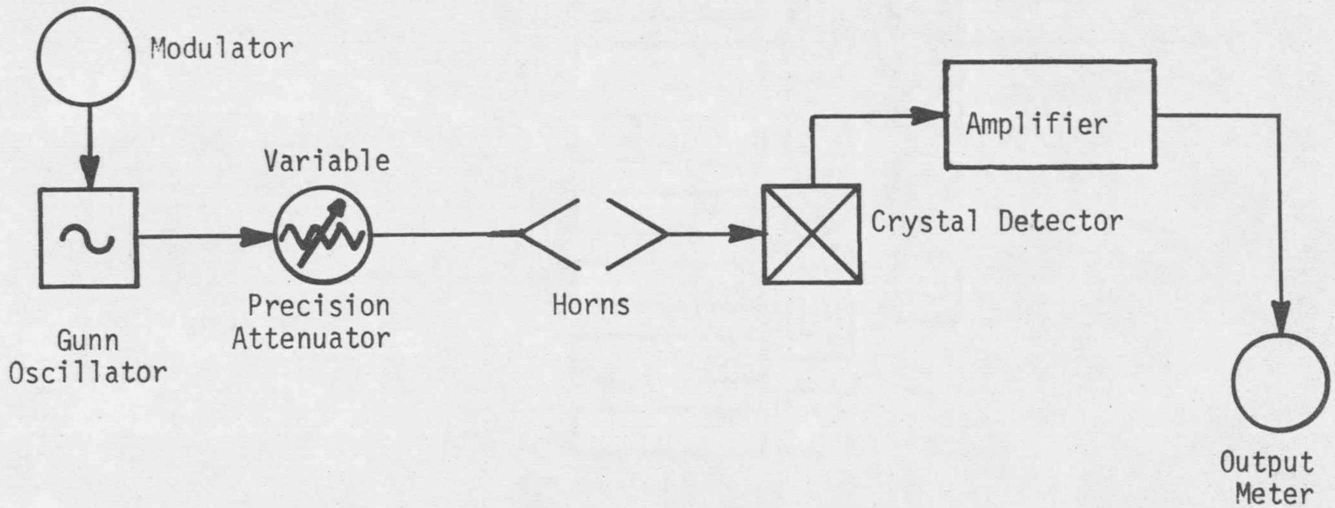


Figure 3. Block diagram of microwave moisture meter.

The second model shown in Figure (4) was built approximately 2 years later in 1973. It is much smaller and easier to carry in the field. Figure (5) shows a rear view of the front panel and inside view of the case with batteries in place. A design convenience of the moisture meter is that all the parts are attached to the removable top panel making repairs very easy. Since it is important that the measurement be consistant from sample to sample, a guide is attached to the bottom of the case in which the sample box fits. Thus, the sample box is held in very nearly the same place for every measurement.

It was found experimentally that glass tape was the best way of fastening the front and back faces to the sample box. Epoxy and various other glues were tried but none held up as long as the glass tape. The sample box dimensions are 5" x 5" x 2".

D. Calculation of % Water from Attenuation and Weight

The equation for relating the moisture content of a sample material to its weight and attenuation of microwave energy was derived by Dr. Bruce R. McLeod. The derivation of the equation given below can be found in Appendix III.

$$\% \, H_2O = \frac{100}{k \frac{w}{x} - 1} \qquad (1)$$

where k = Multiplying Factor
w = Weight of Sample
x = Measured Attenuation

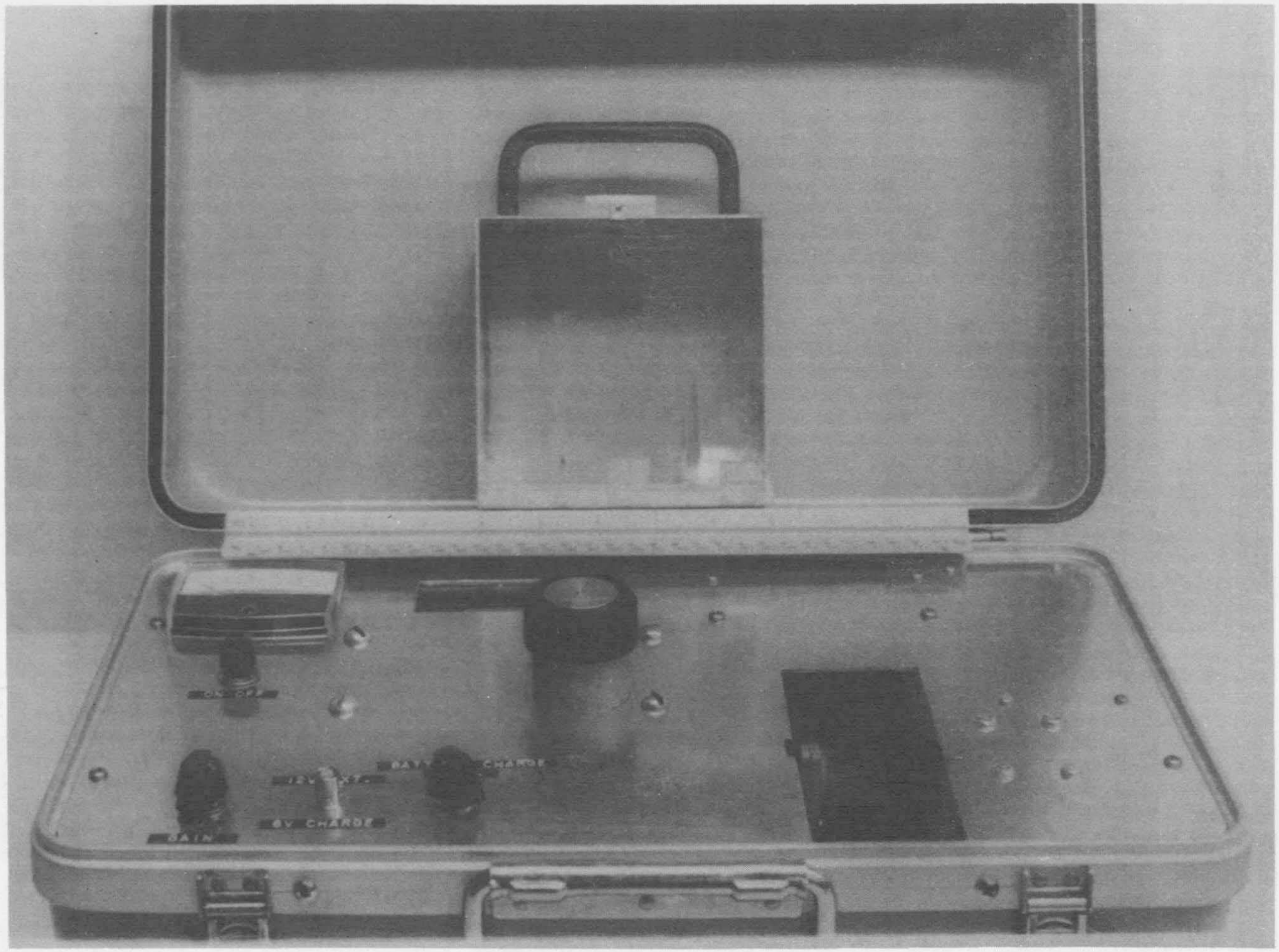


Figure 4. Top View of the Microwave Moisture Meter
Showing Test Cell and Meter Controls.

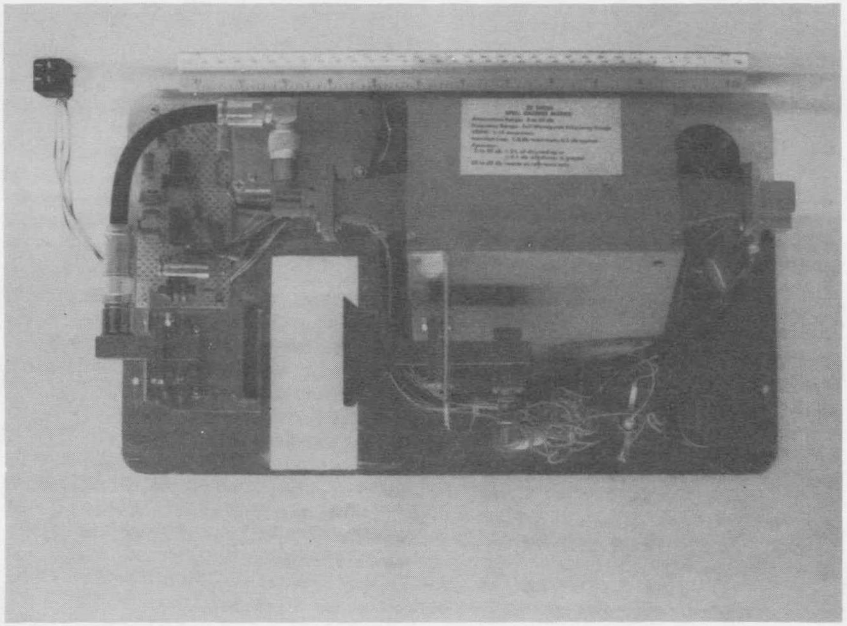


Figure 5(a). Inside View of the Microwave Moisture Meter Showing Electronics and the Microwave Gear.

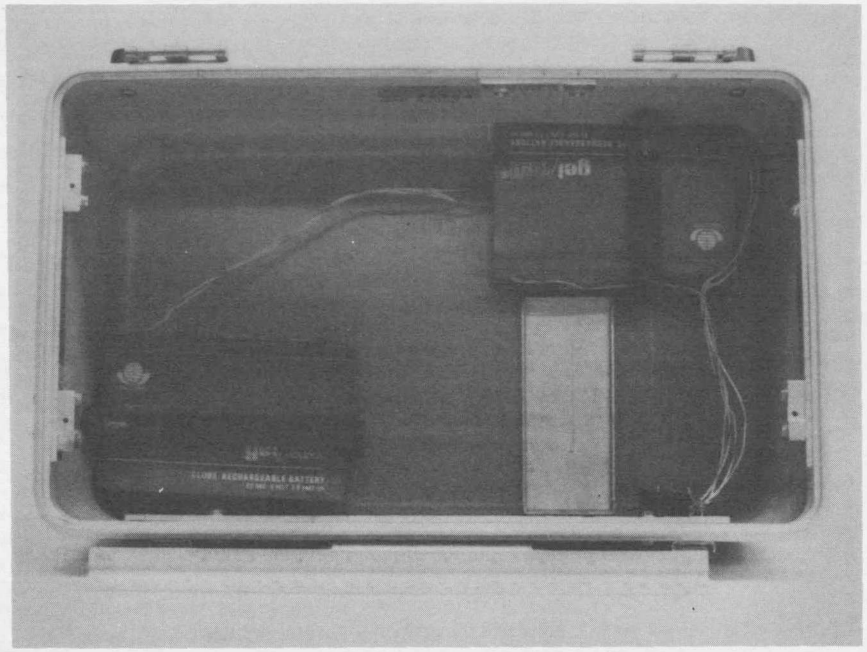


Figure 5(b). Inside View of the Microwave Moisture Meter Showing the Two Six Volt Rechargeable Batteries.

As can be seen from the equation the attenuation should go up as the weight of the material goes up for a fixed percent of moisture content. This would mean that the measurement should be independent of packing density as long as the material is uniform in moisture content and the packing of the material in the box is uniform.

The remainder of this paper deals with the work done to determine the accuracy of the moisture meter and if there were any factors that might introduce significant error into moisture content measured with the meter.

CHAPTER III

TECHNIQUES OF GATHERING AND ANALYZING DATA

This chapter explains the procedure for using the moisture meter, techniques used for gathering data, its analysis, and the effects of various factors on the accuracy of the measurement techniques.

A. Method of Making Measurements

1. Measurement Techniques for the Moisture Meter

Since the function of the moisture meter was to measure the attenuation of microwave energy in a sample of material, the level of microwave energy being received without the sample present must be set before inserting the sample between the horns. The level of received signal was set by placing the empty sample box between the horns, presetting the precision attenuator to 30 db and then adjusting the variable gain amplifier so that the output meter was preset to a reference point (such as full scale). The 30 db range permits a wide range of moisture level readings. The sample box was then uniformly filled with the material to be measured and inserted back between the horns. If there was water present in the sample material, the output meter read down scale (i.e. less signal received) and the attenuator was adjusted to give full scale reading on the output meter. The amount of attenuation in (db) is the difference between the first and final settings of the attenuator. The sample box is then weighted and the percent of water in the sample can then be calculated.

Below is a brief step-by-step summary of the procedure used for making a moisture measurement.

Step 1: Set attenuator to 30 db and place empty sample box between horns.

Step 2: Turn on power and adjust gain on amplifier so that the output meter reads full scale.

Step 3: Fill sample box and place back in case.

Step 4: Turn on power and adjust the attenuator so that the output meter again reads full scale.

Step 5: Note difference in first and final setting on attenuator, weight material, and calculate percent of water content.

2. Materials Being Investigated

Since the moisture meter will probably be used by the Forest Service to measure moisture content of fuels on the forest floor, all the data taken was on these materials. The fuel materials can be broken up into three major categories. The first is the upper layer which is composed of the sticks. Sticks are defined as any branches that are broken from the parent tree and are not connected to anything that is still rooted in the ground. For this investigation only sticks up to one quarter inch in diameter were measured. The next layer down, (visually the surface layer) is called the litter layer. Litter is composed of leaves, pine needles and small twigs. The lowest layer (which is next to the ground surface) is the duff layer. The duff is the several previous year's litter layers which have decomposed to finely ground particles. Figure (6) shows pictures of duff, litter and sticks and Figure (7) shows a cross section of a litter-duff layer emphasizing the separation of layers.

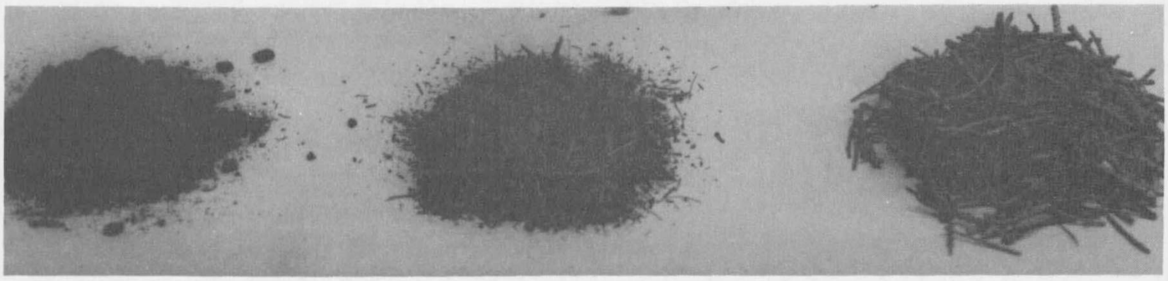
3. Filling Sample Box

Since the equation for percent of moisture was derived assuming uniform packing density of the material in the sample box it is important to achieve uniform packing in the field. It was observed that the best method of filling the box was to add the sample material a handful at a time. Then, while holding the sample box flat and level it was shaken back and forth so that the material spread out in a uniform layer. This was done until the material was level with or above the box edge. Now the box lid was closed, packing the material in a nearly uniform fashion.

If the material contained lumps it was necessary to break up these lumps before putting the material into the box. This was done by rubbing the material between the hands while adding it to the box.

B. Oven Dry Techniques for Checking Moisture Meter

The oven dry technique of determining the moisture content of materials is widely used as a standard [9]. The method consists essentialy of weighing a sample, drying it in an oven for some specified



Duff Litter Sticks

Figure 6. View of the Three Types of Materials Found on the Forest Floor.

Figure 7. Side View of Forest Floor Layer Showing the Separation in the Duff Litter Layer.

period of time and then weighing the sample again. The difference in weights is the weight of water evaporated from the sample. The moisture content is then calculated using the following formula:

$$\%\ \text{water} = \frac{\text{water weight}}{\text{wet sample weight - water weight}} \times 100 \qquad (2)$$

For all the oven dry data taken during this investigation, 15 hours was the minimum oven time with the oven temperature set at 5°C below the local boiling point of water. The reason for staying below the local boiling point of water is to prevent other volatiles in the sample from being liberated [9].

After a measurement was taken on a sample with the moisture meter a part of this sample was put in a small sample can and put through the oven dry process. The material for the oven dry sample was taken from the center of the sample box. This was done so that the material directly between the horns was being used in the oven and also for the meter.

To reduce the error caused by non-uniform packing in the sample box, five to six measurements were taken on one sample. The attenuation readings were then averaged and this average was then used to calculate the percent moisture content. It was observed each time the sample material was dumped out and repacked that the attenuation loss got smaller. This was caused by the material drying out in the air during the dumping and repacking.

Since the above method was obviously introducing error it was decided a better method would be to gather enough material in the first place to make at least five separate measurements with the moisture meter and to make an oven dry measurement for each moisture meter measurement. With this method better consistancy of measurements was observed with respect to the moisture content of a set of samples from the same batch of material.

C. <u>Collection of Data at Lubrecht Forest</u>

1. <u>Moisture Meter Project</u>

Two summers were spent at Lubrecht Forest taking data with the moisture meter. Lubrecht Forest is owned and operated by the University of Montana at Missoula, Montana. The forest land is used primarily by the forestry school and fire labs to conduct various research projects.

The first summer of taking data resulted in efforts to decrease the size of the moisture meter to make it easier to carry in the field. The second summer was used to test the new and smaller meter and collect more data points for analyzing the accuracy of the meter.

Much of the time was spent in the field collecting duff, litter and stick samples. The samples were collected and put in plastic bags so that the water would not evaporate before the samples could be taken back to the lab. Usually enough of each material was collected to make three or four measurements on each material (approximately 800 grams).

At the lab at Lubrecht there was a large oven and a scale for use in carrying out the oven dry measurements. When the samples were brought in each day from the field, measurements were made with the moisture meter and oven dry samples were taken and run through the drying process. For measurements in the field, a hand held scale was used to weigh the sample box and material. A slide rule was used to calculate the percent of moisture.

2. <u>Prescribed Burning Project</u>

The moisture content of the sticks was measured each day in the field as well as in the lab. This information was used by the Northern Forest Fire Labs at Missoula, Montana in determining when they could run a controlled burn safely and effectively. An effective burn was defined as a fire which burned through the forest leaving the larger trees essentially uneffected. With the forest floor cleaned, the larger trees can grow unhampered by the small scrub trees.

A section of Lubrecht was sectioned off into 32 plots. The prescribed burning project used the plots for running test burns to determine the conditions necessary for effective burning as defined previously.

One criteria necessary for proper burning is that the sticks be at a specific moisture level. Since the moisture content has been observed to change in just a few hours it is necessary to be able to measure the moisture content just prior to starting the burn. This is where the microwave moisture meter can play a key role. The measurement can be made right in the field taking only the time required to gather the sample while other methods take several hours and are impossible to use in the field.

D. Analysis of Data Using a Computer Program

1. Description of Program

The program was written in Fortran IV for running on the Sigma 7 computer at Montana State University. The program makes comparisons between the calculated percent from the moisture meter and the measured oven dry percent of a sample. Data cards were punched containing the type of material, year taken, attenuation, weight, and the oven dry percent corresponding to each measurement. The program then sorts the data by type and year. The moisture meter percents are calculated using equation (1). The multiplying constant used in the calculation is read in on another control card. The program then calculates the multiplying constant (k) that will yield the measured oven dry percent (using the attenuation and weight found from the moisture meter measurement). The data is ordered according to increasing calculated percent for each material group. A data number, attenuation, weight, calculated percent, oven dry percent and calculated k is printed out in a table for each material type.

The program calculates the mean and standard deviation of the k values. A plot is done of calculated percent on the y axis and oven dry percent on the x axis. A line x = y is drawn on the same graph so that the scatter of calculated versus oven dry percents around the line of equal calculated and oven dry percents (x = y) can be observed. The program also tabulates how many and how far the calculated percents fall above or below the corresponding oven dry percents.

The purpose of the program was to determine the expected accuracy of the microwave moisture measurement technique and what could be done to improve the accuracy. A listing of the mainline program, subroutines, and input data can be found in Appendix IV. The output tables are in Appendix V.

2. Analysis of Program Output

The output table for 1972 data shows that 55% of all calculated moisture percents were below the corresponding oven dry percents while 64% of the 1973 calculated percents were below the oven dry percents. For both years 80.9% of all calculated moisture percents were within 5% of the corresponding oven dry percent while only 20% of all calculated percents were within 1% of their corresponding oven dry values. This was not good enough accuracy for the moisture meter (assuming the oven dry measurements were correct). The fact that 60% of all the calculated moisture levels were below the corresponding oven dry value and 40% being above suggested no obvious changes in the formula for calculating the moisture content. It was observed that the moisture meter was very consistant for sets of measurements from the same batch of material. It is also observed that the oven dry technique was consistant for sets of samples from the same batch of material. Figures 8 - 13 give a visual comparison of oven dry and calculated percents. The plots are separated into type of material and year. It is observed that although there are many points that lie off the line of equal percent, the points for the most part are in a region directly around the line of equal percent.

The calculated mean k values give no new insight into the problem because of the fact that the standard deviations are relatively large. Thus, 63% of the calculated k values fall in a relatively large range of values around the mean value.

All of the above pointed toward a need for a re-evaluation of both the microwave and oven dry techniques of measuring the moisture content of the sample materials.

E. Temperature Effects on Measurements

1. Methods of Determination of Effects

The derivation of the equation for percent of moisture as a function of attenuation and weight of sample material used the principle of attenuation of microwave energy in water. A value of 40 db of attenuation per centimeter of pure water was used in the derivation.

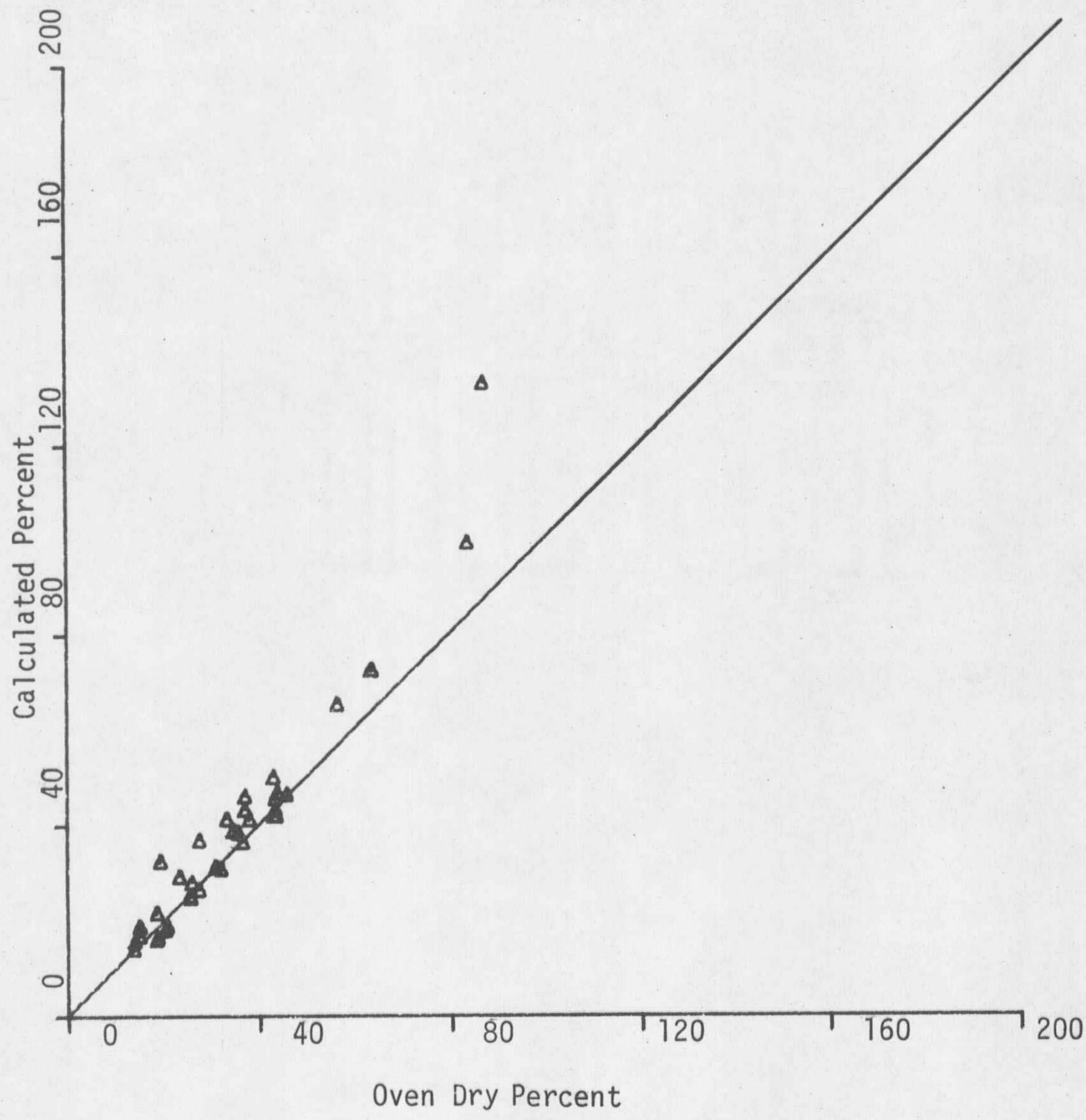


Figure 8

SCATTER PLOT OF OVEN DRY % AND CALCULATED %
FOR DUFF. 1972 DATA. JLK

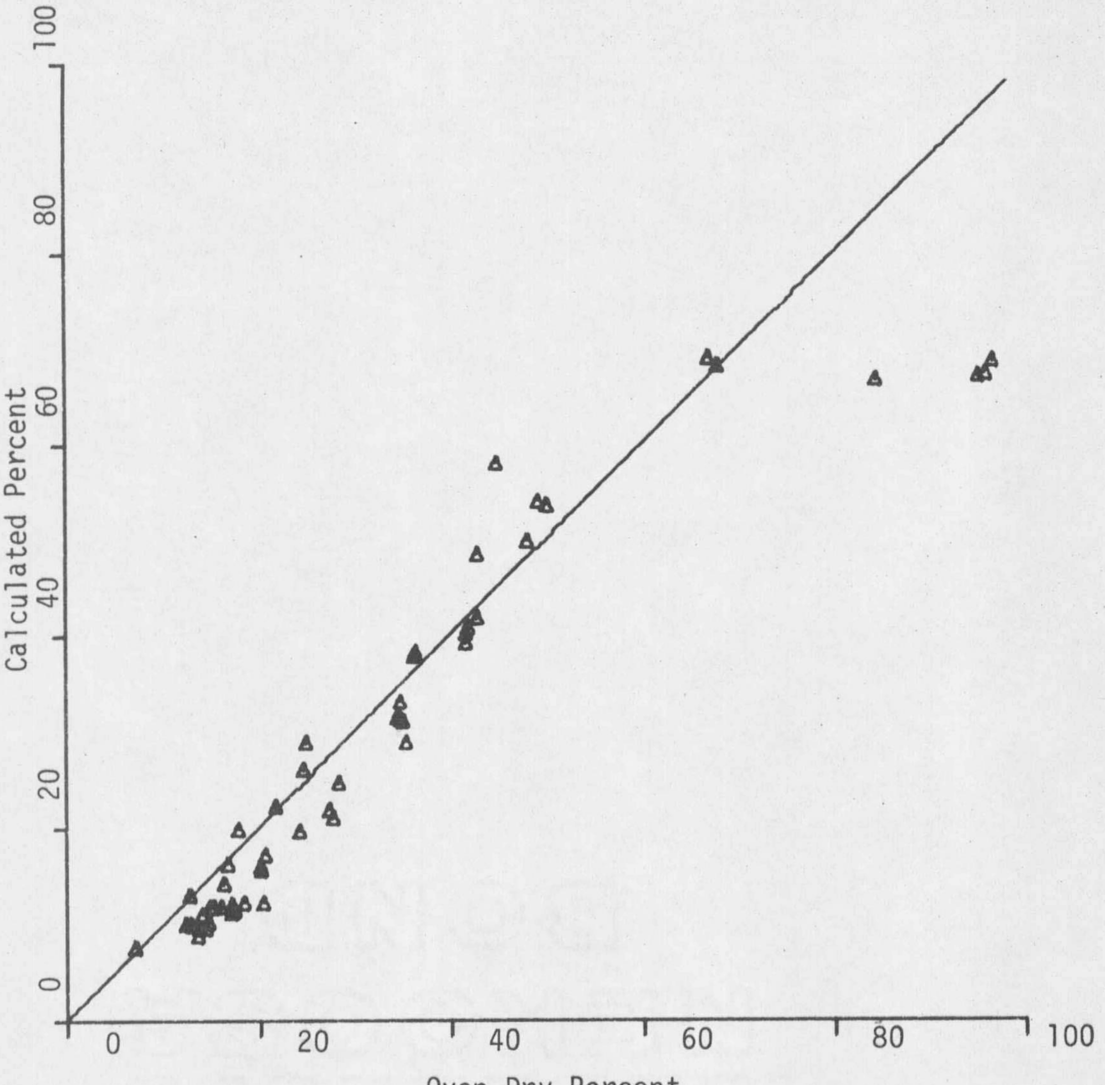


Figure 9

SCATTER PLOT OF OVEN DRY % AND CALCULATED %
FOR LITTER. 1972 DATA. JLK

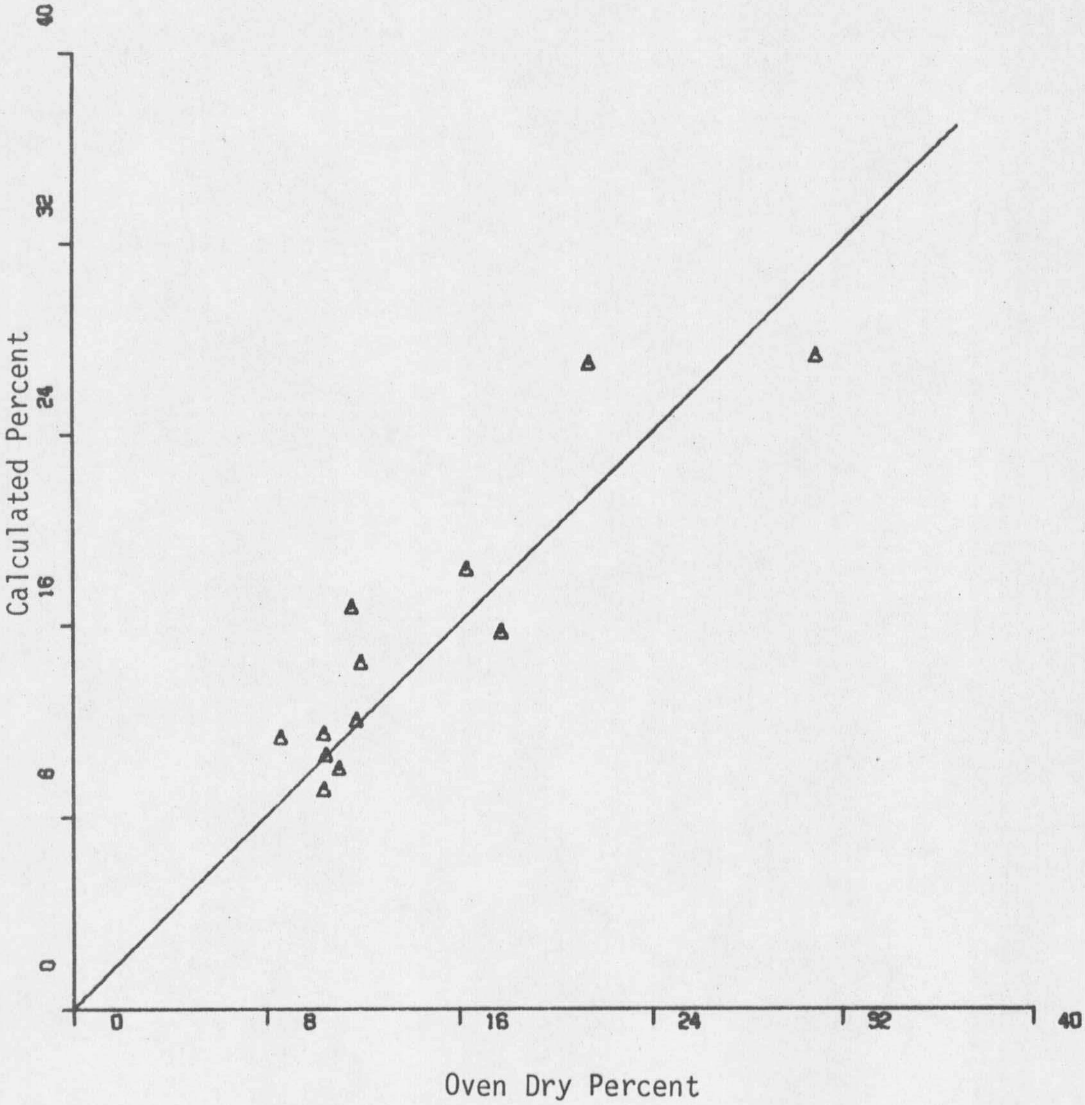


Figure 10

SCATTER PLOT OF OVEN DRY % AND CALCULATED %
FOR STICKS. 1972 DATA. JLK

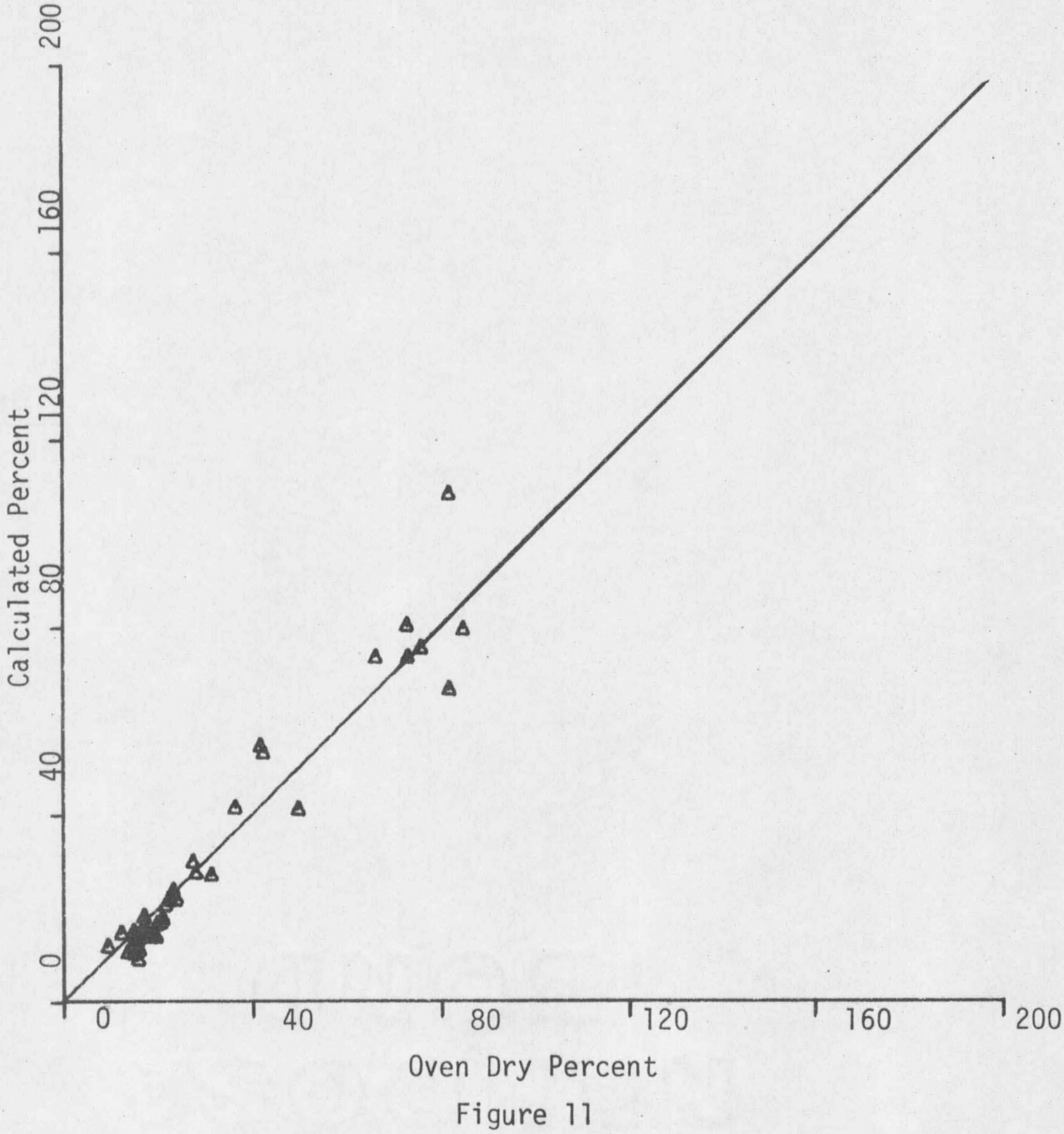


Figure 11

SCATTER PLOT OF OVEN DRY % AND CALCULATED % FOR DUFF. 1973 DATA. JLK

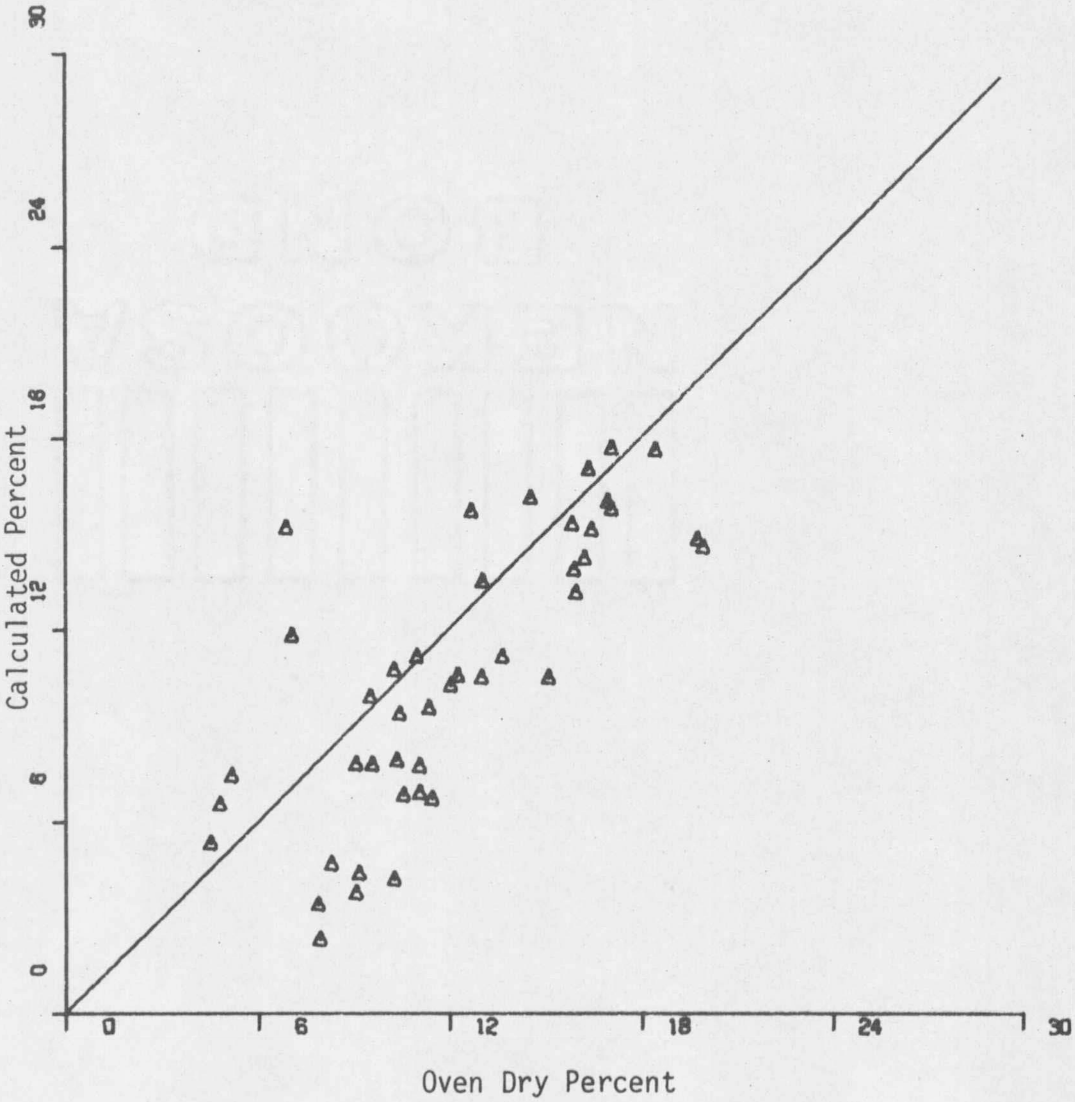


Figure 12

SCATTER PLOT OF OVEN DRY % AND CALCULATED %
FOR LITTER. 1973 DATA. JLK

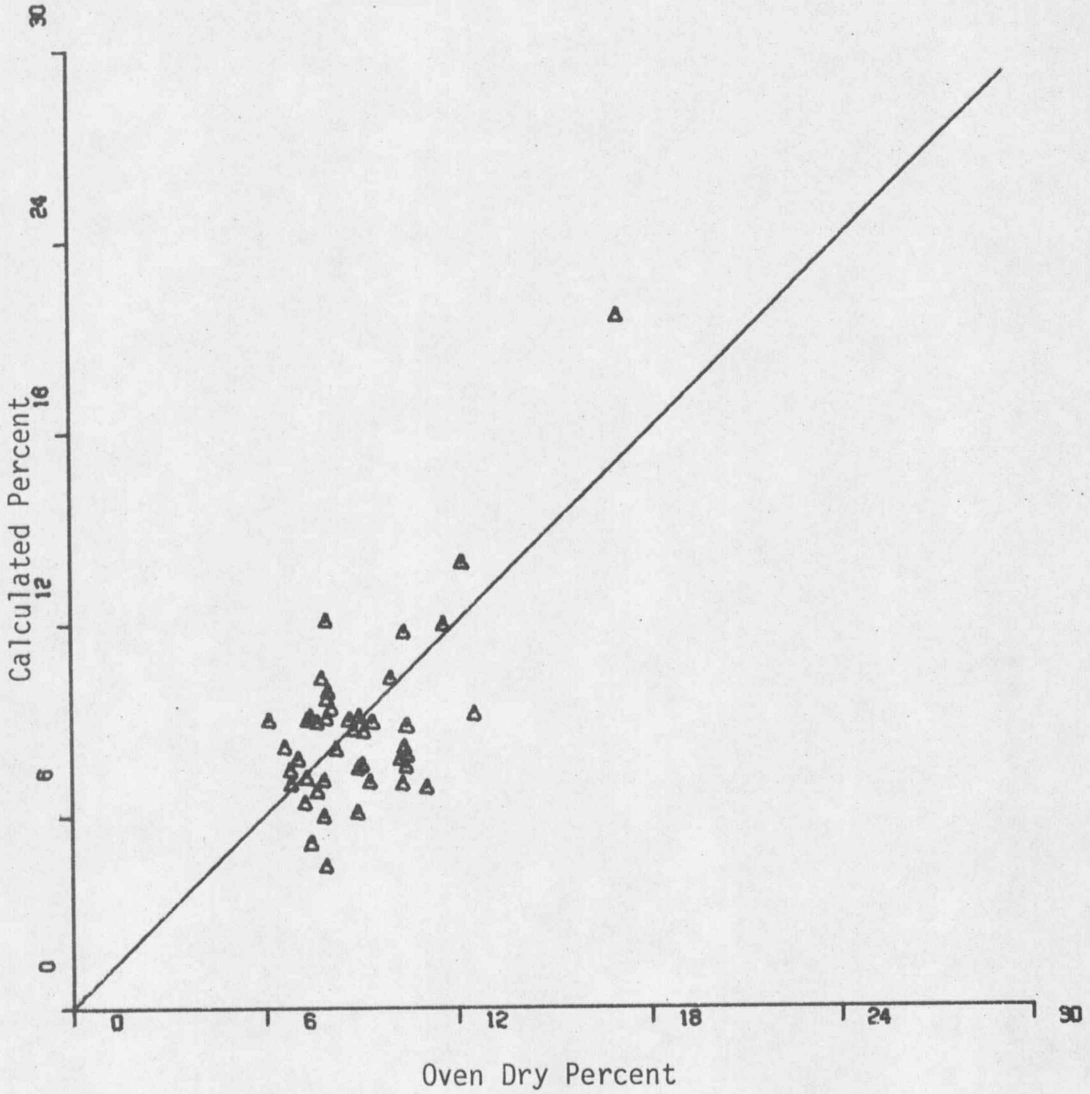


Figure 13

SCATTER PLOT OF OVEN DRY % AND CALCULATED %
FOR STICKS. 1973 DATA. JLK

Assuming that the value of attenuation in water is a constant there should be no charge necessary in the equation. Since it has already been observed that above 10 GHz the attenuation of water is independent of salt content [6] this was ruled out as a variable for improving the moisture meter in this discussion.

In researching various papers it was observed that several authors stated that temperature had an effect on the attenuation of water [3,4,7,8,10,11,12]. The majority of the articles agreed that the effect of an increase in temperature is a decrease in attenuation. Various explanations were given as to the reason for the temperature effects but no data was available giving the attenuation in db/cm as a function of temperature.

To correct for any error in the moisture meter data due to temperature changes, the attenuation of water as a function of temperature had to be determined. There were three approaches that could be taken to determine the temperature effects:

Method one is to measure the moisture content of a sample material at different temperatures using both microwave and oven dry techniques. If there is a temperature effect the oven dry and microwave measurements will differ as a function of temperature (if the same k value is used for all the moisture meter calculations). The measured oven dry percent, sample weight, and attenuation at a specific temperature can be used to calculate k at specific temperatures. The attenuation in db/cm of water at various temperatures can then be calculated from the k value.

Method two is probably the most direct but also the most difficult. This method requires measuring the attenuation of water as a function of temperature using microwave techniques. The k value can then be calculated as a function of temperature.

Method three is the easiest and doesn't require any lab work. This last technique is just applying electromagnetic field theory and deriving an equation for the attenuation of a microwave energy in water.

Once the attenuation of water as a function of temperature is determined, the equation for percent of water can be changed to contain the temperature of the material as one of the variables. The three methods will now be discussed in the order listed.

a. <u>Measurements Made on Sample Material</u>

The measurement of moisture level was done on litter over a temperature range of 15°C to 50°C in steps of 5°C. The sample was placed in the oven for a half hour period with the oven set at a desired temperature. The sample was then taken out and a measurement made with the moisture meter and an oven dry sample taken. It was observed from the first set of data that the sample was drying out too much to give accurate results at the highest temperature. There wasn't any consistancy in the way the calculated k values changed with temperature.

Therefore, on the next run a pan of water was also placed in the oven to prevent the sample from drying out and a thermometer was placed in the sample. The sample wasn't taken out until the material had reached the temperature desired.

Tables 1 and 2 are data tables of two runs over a temperature range of 15°C to 50°C in steps of 5°C. Table 1 is a set of data taken on litter and Table 2 is a set of data taken on sticks. Each table shows the temperature measured attenuation, weight, oven dry percent, and calculated k value.

The data taken on the sticks show a strong tendancy for the k value to increase as the temperature goes up. This would correspond to an increase in attenuation as the temperature goes up which is opposite of what was expected. This inconsistancy might be due to uneven heating of the material in the oven (i.e. temperature gradient existing with higher temperature at outer edge of sample and decreasing toward center of sample). A moisture gradient could also exist with higher moisture level at center of sample decreasing toward the outer edge. Both of these factors could account for the apparently incorrect data that was obtained.

b. <u>Direct Measurement on Water</u>

The goal of this method was to measure the attenuation of a microwave signal passing through a one centimeter layer of water as a function of temperature. The method used is exactly the same as the

Table 1

Moisture Measurements made on Litter as a Function of the Sample Material Temperature

Temperature	Attenuation	Weight	Oven Dry %	Cal. k
15°C	6.0	116.8	16.40	.365
20°C	5.6	117.7	17.65	.317
25°C	6.9	131.5	16.87	.364
30°C	6.2	118.5	15.20	.397
35°C	6.1	115.9	15.95	.383
40°C	5.8	118.9	15.38	.366
45°C	5.5	128.8	14.76	.332
50°C	5.2	120.6	14.87	.333

Table 2

Moisture Measurements Made on Sticks as a Function of the Sample Material Temperature

Temperature	Attenuation	Weight	Oven Dry %	Cal. k
15°C	2.8	155.9	12.98	.156
20°C	2.9	157.6	10.76	.189
25°C	3.3	164.1	12.87	.176
30°C	4.4	164.5	12.04	.249
35°C	7.8	164.0	13.78	.393
40°C	7.9	156.9	13.94	.412
45°C	7.1	164.6	13.33	.366
50°C	4.6	164.0	7.27	.414

the technique used to measure the attenuation of the sample materials in the moisture meter. Figure (14) is a block diagram of bench set-up used in the first measurements. A Hewlett Packard Model 8090B Sweep Oscillator was used as the source of microwave energy. An isolator was used to prevent the reflected wave from reaching the source and the frequency meter was used to check the frequency of the source signal. The frequency of the source was set at 10.525 GHz, the frequency of the Gunn oscillator used in the moisture meter. The slotted line was used to measure the standing-wave ratio (SWR).

A test cell to hold the water was made out of .25 inch plexiglass. The inside dimensions of the cell are 1 cm. x 5" x 5". The test cell was centered between an open-ended waveguide (one end of slotted line) and a horn. The horn was on the receiving side and waveguide was the transmitting side. This was done so that most of the transmitted energy would be received by the horn.

The temperature of the water was set by regulating hot and cold tap water. The temperature of the water was measured at the tap and again in the cell. It was observed that the tap water had to be higher than the temperature desired for the measurement because of cooling of the water as it was poured into the cell.

For each temperature the total attenuation and SWR were measured. The SWR was used to calculate the db of reflected energy. This value was subtracted from the total measured attenuation leaving the value

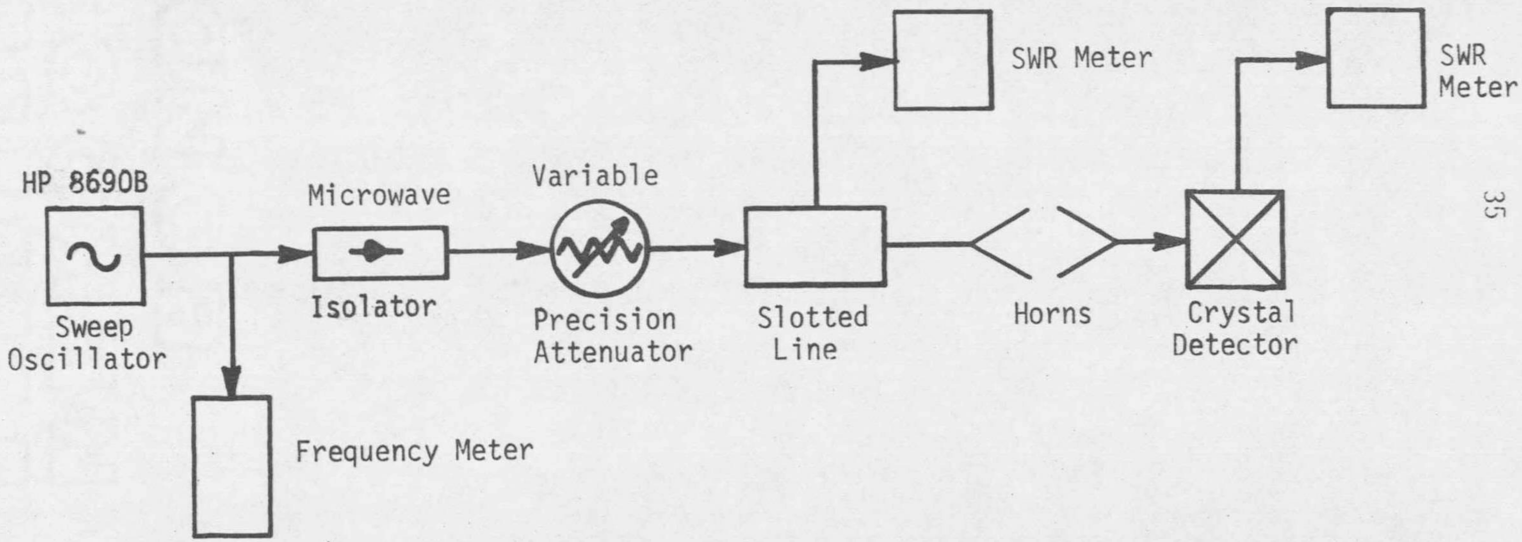


Figure 14. Block diagram of bench set-up for measuring microwave attenuation in water.

of attenuation due to absorption of electromagnetic energy in the water. The procedure for the above calculations is given in Appendix VI.

After making three sets of measurements from 15°C to 50°C in steps of 5°C it was observed that the level of the water in the cell changed the amount of measured attenuation. This was due to reflection of the signal off the water air interface at the top of the cell back down into the cell.

To avoid the problem of reflection, the horn on the receiving side of the cell was replaced by another open ended waveguide. The waveguide did not receive the reflected signal as strongly as the horn. It was observed that the height of the water still effected the measurements. A layer of microwave absorbing material was placed on top of the cell to decrease the level of reflection. The effect of the reflection was still observed to be the same. The absorbing material did not reduce the reflection to a level low enough to obtain consistant measurements.

A new cell was made out of .125 cm thick plexiglass to reduce any refraction that might be caused by the plane wave not being normally incident on the plexiglass layer. The cell was also made 5" x 6.25" inside width and height. The added height helped reduce the amount of reflection but changes of three to five db were still observed between different sets of measurements at the same temperature.

The next approach was to build a new cell out of .125 cm thick plexiglass again but to make its inside thickness .5 cm instead of 1 cm. This presented a smaller water air surface for reflections and also reduced the overall cell thickness. The width and height were again 5" inside dimension. The measurements were still being made with the cell between two open-ended waveguides.

Two sets of measurements were made over the temperature range and both sets of data came out extremely close with no noticeable reflection taking place off the top surface of water. There was a problem with the measured attenuation in that the values were too high at room temperature where the attenuation was known to be 40 db/cm at 25°C [13]. The measured value of 53.45 db/cm pointed toward some other effects coming into play. It was concluded that the placement of the two waveguides so close together was setting up an interaction causing the signal to lose its plane wave characteristics through the water layer.

The next step was to replace both waveguides with horns to preserve the plane wave propagation through the cell. The horns had an apature area of 1.55" x .9". Again, the horns were centered on the cell and adjusted for maximum received signal. Two sets of measurements were made, one at 10.5 GHz and another at 10.525 GHz. Both sets agreed closely with each other and to the 40 db/cm value at 25°C. Figure (15) shows the final lab setup that was used to make the measurements. The measured values of attenuation match with the known value at 25°C, but the rest of the points still have to be verified before any final changes can be made in the moisture meter equation (eq. (1)). The next section will discuss calculation of the attenuation in water from a fields point of view.

c. Theoretical Calculations

The attenuation constant of an electromagnetic plane wave traveling in a lossy dielectric material can be calculated as a function of the dielectric constant, loss tangent and frequency of electromagnetic energy. One author used this approach to calculate the attenuation of a signal in a given thickness of dielectric material such as water [13]. The derivation of this equation relating attenuation to the thickness, dielectric constant, loss tangent and frequency of signal is in Appendix VII. The final equation follows below:

$$A = 8.686 \pi \frac{\ell}{\lambda o} \sqrt{\varepsilon_r} \tan \delta \text{ (db)} \qquad (3)$$

The free space wavelength (λo) and thickness of dielectric layer (ℓ) are both in centimeters. Given the dielectric constant (ε_r) and loss tangent ($\tan \delta$) the attenuation can be found for a specified frequency and thickness.

Figure 16 is a graph of the loss tangent and dielectric constant of water as a function of temperature at various frequencies. The

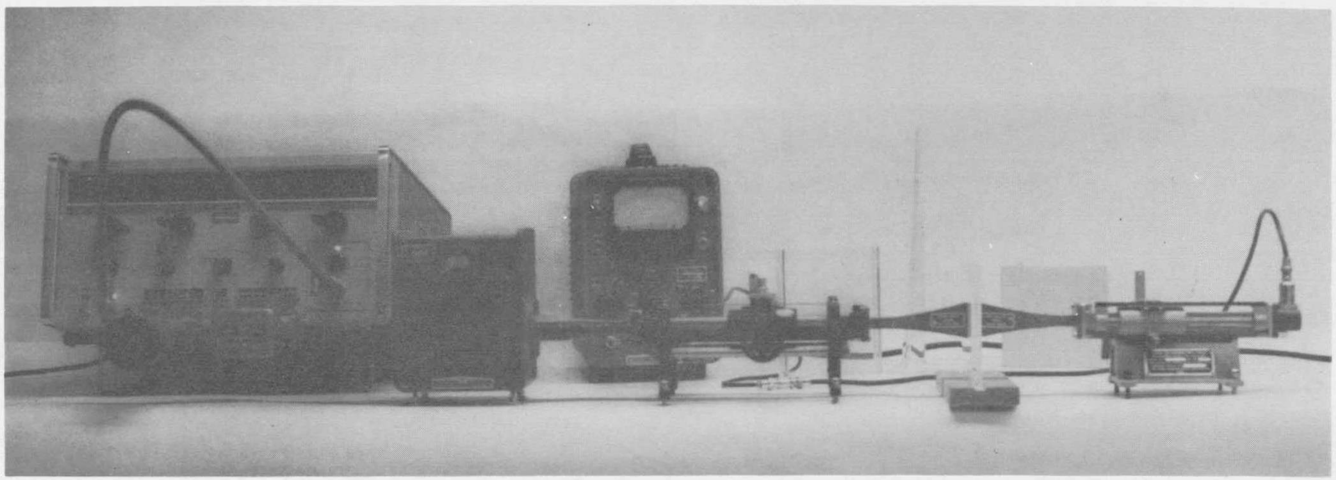


Figure 15. View of the Bench Setup Used to Measure the Attenuation of Microwaves Through a 1-cm Layer of Water.

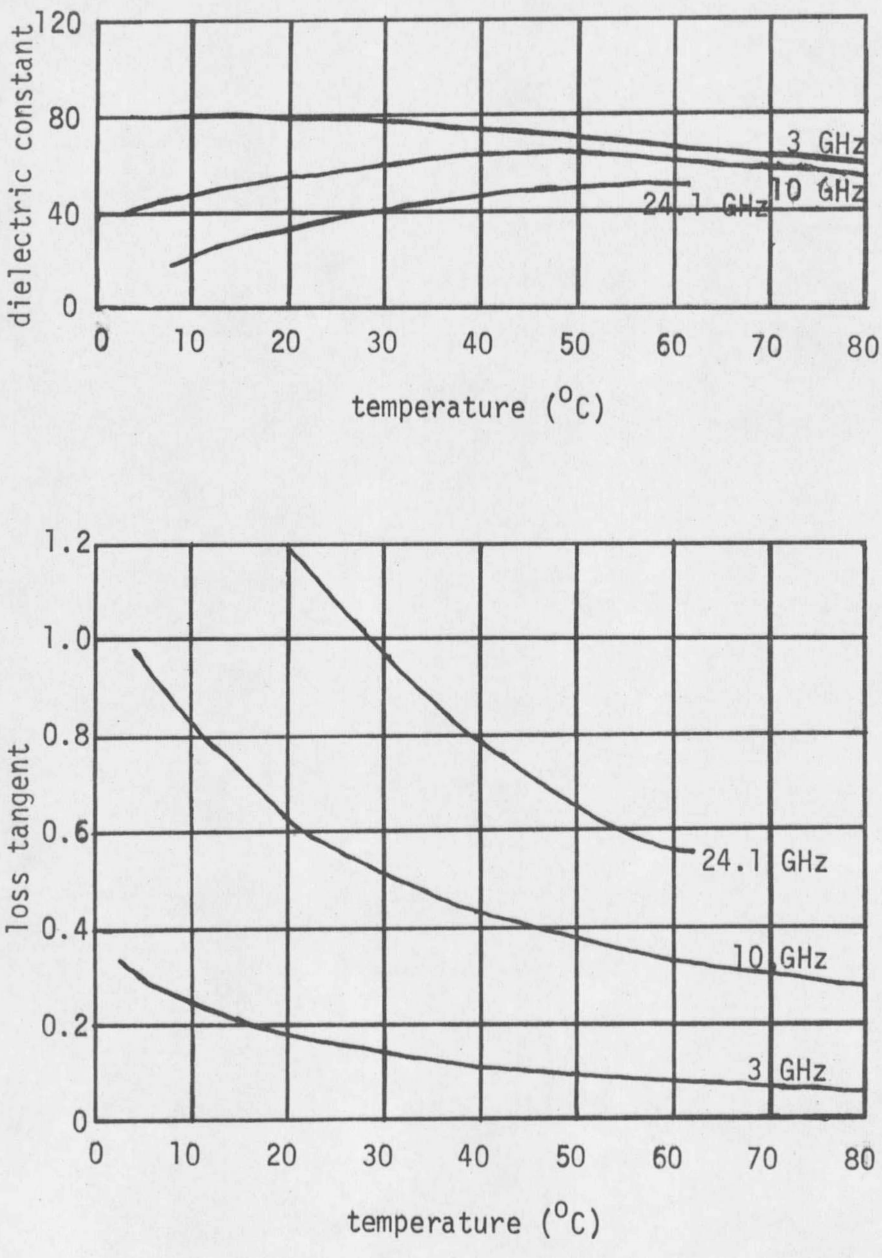


Figure 16. The Variation with Temperature of the Dielectric Constant and Loss Tangent of Water.

dielectric constant and loss tangent were taken off this graph at various temperatures for the 10 GHz frequency. The previous equation was then used to calculate the attenuation of a 10.525 GHz signal in a one centimeter layer of water at various temperatures. Table 3 gives the dielectric constant, loss tangent, and calculated attenuation (db/cm) at various temperatures.

Note that ε_r and tan δ were for 10 GHz rather than 10.525 GHz used in the above calculations but this amounts to only a 5% error in frequency and ε_r and tan δ would show approximately the same amount of change [14].

Table 4 gives the measured and calculated attenuation in db/cm for a signal propagated through water at various temperatures. It is observed that the two values are very close at the various temperatures.

With two methods giving essentially the same values something can now be done to modify the moisture meter equation to take account of the temperature of the material being measured.

2. Modified Moisture Meter Equation Containing Temperature

Now that the attenuation of water as a function of temperature has been determined, the multiplying factor k as a function of temperature can be calculated. This was done and then a least squares solution, given below, was derived for k(T°C). A computer program was written to calculate k for temperatures from 15°C to 50°C in steps

Table 3

Dielectric Constant, Loss Tangent, and Calculated Attenuation of Water at Various Temperatures

Temperature	ε_r	tan δ	Attenuation
15°c	51.2	.723	49.53 db
20°C	54.4	.640	45.20 db
25°C	56.0	.561	40.20 db
30°C	59.2	.504	37.13 db
35°C	60.8	.465	34.72 db
40°C	62.4	.432	32.67 cb
45°C	62.4	.400	30.25 db
50°C	62.4	.376	28.44 db

Table 4

Measured and Calculated Attenuation of Water at Various Temperatures

Temperature	Measured Attenuation	Calculated Attenuation
$15^{o}C$	49.50	49.53
$20^{o}C$	45.54	45.20
$25^{o}C$	40.96	40.20
$30^{o}C$	38.04	37.13
$35^{o}C$	34.86	34.72
$40^{o}C$	31.78	32.67
$45^{o}C$	29.46	30.25
$50^{o}C$	26.66	28.44

of one degree using the least squares solution. The attenuation for water over the same temperature range was calculated from the calculated k values. Figure (17) is a plot of k verses temperature and Figure (18) is a plot of attenuation through one centimeter of water verses temperature. Table 5 gives the value of k over the 15 to 50 degree range in one degree steps.

$$k(T°C) = .3944 - (6.414 \times 10^{-3})\, T + (3.714 \times 10^{-5})\, T^2 \qquad (4)$$

When a measurement is made on a sample, the temperature is taken and the multiplying factor k for that temperature is taken off Table 5. The correct moisture content can then be calculated. The use of the table for finding the correct k value will definitely be more appealing for use in the field by the forester than using equation (4) to calculate k.

F. <u>Error in Oven Dry Measurements</u>

Several questions were raised during the course of this work concerning the oven dry technique of measuring moisture in materials. Is 15 hours enough time to drive all the water out of the samples? What happens if many very wet samples are put in the oven. Will they dry out completely in 15 hours?

For one set of oven dry measurements it was observed that there were water droplets on the inside of the oven door after the materials had been in the oven for 15 hours at 95°C. This would mean that the moisture was not getting out of the oven but saturating the atmosphere

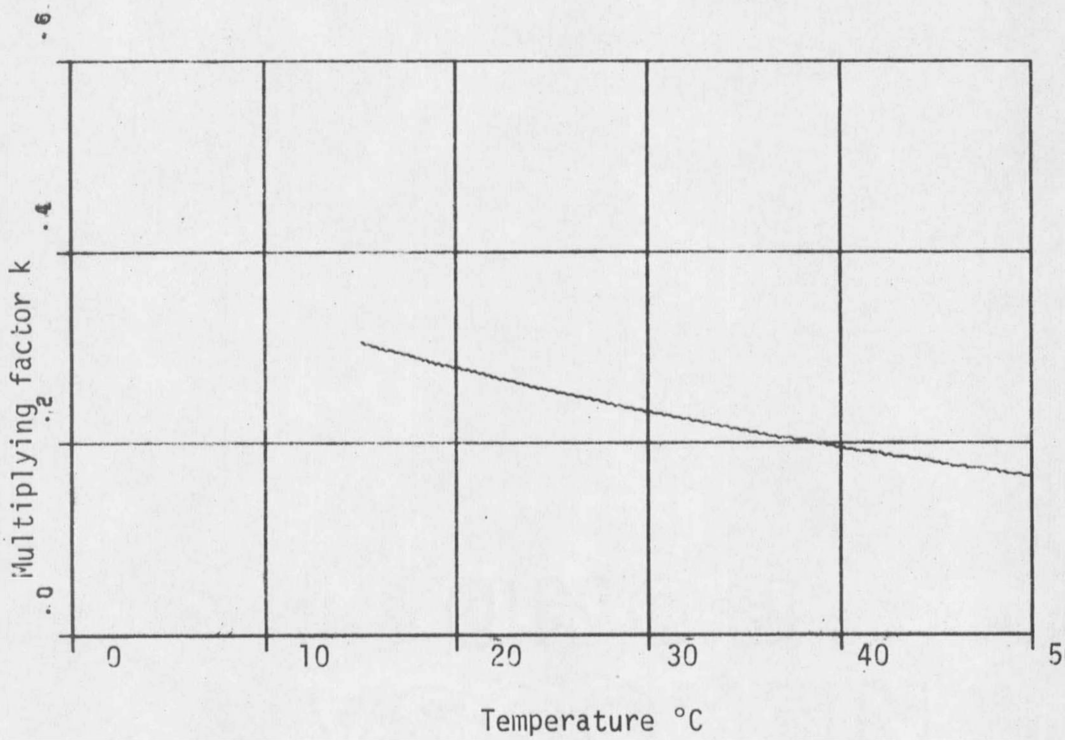


Figure 17

PLOT OF MULTIPLYING FACTOR (K)
VS. TEMPERATURE. JLK

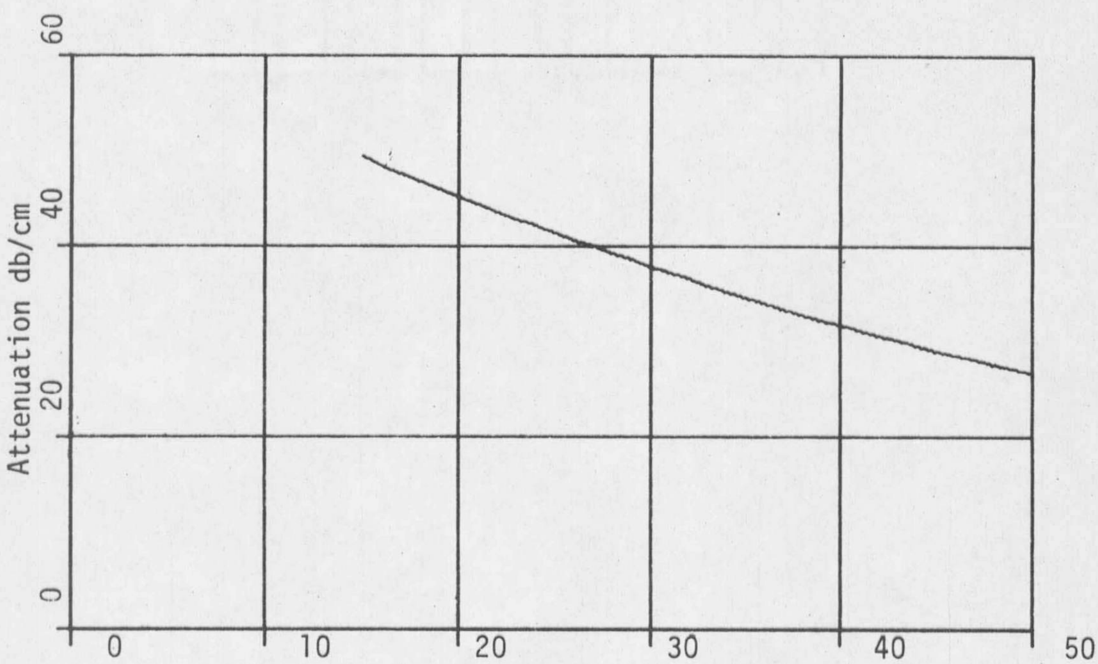


Figure 18

PLOT OF ATTEN. OF MICROWAVE SIGNAL VS. TEMP.
AT 10.525 GHZ. THROUGH 1 CM. OF WATER. JLK

Table 5

Multiplying Factor k at Various Temperatures

Temperature	k Value
15°C	.307
16°C	.301
17°C	.296
18°C	.291
19°C	.286
20°C	.281
21°C	.276
22°C	.271
23°C	.267
24°C	.262
25°C	.257
26°C	.253
27°C	.248
28°C	.244
29°C	.240
30°C	.235
31°C	.231
32°C	.227
33°C	.223
34°C	.219
35°C	.215
36°C	.212
37°C	.208
38°C	.204
39°C	.201
40°C	.197
41°C	.194
42°C	.191
43°C	.187
44°C	.184
45°C	.181
46°C	.178
47°C	.175
48°C	.172
49°C	.169
50°C	.167

in the oven. With the atmosphere saturated, the moisture level of the samples would be the same as the oven air. Therefore, it is obvious that not only is it necessary to drive the water out of the sample material but to also keep the moisture content of the atmosphere of the oven as low as possible.

It was initially thought that by placing a vacuum in the oven and setting the oven at a lower temperature the material could be dried out better and faster. This method was tried on five different samples of litter. The samples were left in the oven at 85°C for 15 hours. After the time was up the samples were weighed and percent of moisture calculated. Because moisture was observed on the inside of the oven door the samples were put back in the oven under zero vacuum for another 15 hours. The samples were again weighed and percent of moisture calculated. Table 6 is a list of the data taken. From the table it is observed that the calculated percent moisture contents increased by 2.2 to 3.4 percent. There was no way for the moisture to escape from the oven with a vacuum on it.

What was needed was some way to absorb the moisture driven out of the samples. Thus, the idea of putting a drying agent in the oven with the samples was conceived. Anhydrous calcium sulfate ($CaSO_4$) was found to be a fairly inexpensive drying agent.

The oven was again set at 95°C and three shallow pans containing the drying agent were placed on the upper tray in the oven. The samples to be dried were placed below on the bottom tray. Figure (19) shows the oven with its door open with the pans of drying agent and the samples in plain view. The scale used for weighing all the samples is also shown.

The samples were taken out after 15 hours, weighed, and put back in for another 15 hours. At the end of the second 15 hours, they were again weighed. Table 7 is a list of the data taken. It is observed that the additional 15 hours made no marked difference in the weights. The drying agent was also weighed to check for any absorption of water. The crystals increased in weight by 18.05 grams while the samples decreased by 22.4 grams. From this data the assumption can be made that the samples are dried out completely after 15 hours and that the drying agent is absorbing almost all the moisture driven out of the sample. It can be said now that the best method so far for oven drying to assume accurate results is to use a drying agent in the oven during the drying process.

The drying agent can be reused as many times as necessary by putting it in an oven at a higher temperature, say 120°C to boil off the absorbed moisture. The drying agent adds only a small initial cost to the project.

Table 6

Oven Dry Measurements at 15 Hours and 30 Hours
While Under a Vacuum

Total Weight	Weight 15 Hours	Cal. % of Water	Weight 30 Hours	Cal. % of Water
17.1 gr	15.0 gr	12.3%	14.5 gr	15.2%
21.0 gr	18.7 gr	11.0%	18.1 gr	13.8%
16.9 gr	14.8 gr	12.4%	14.5 gr	14.2%
17.4 gr	15.4 gr	11.5%	14.8 gr	14.9%
18.2 gr	16.3 gr	10.4%	15.7 gr	13.7%

Table 7

Oven Dry Measurements of 15 Hours and 30 Hours
With Drying Agent Present

Total Weight	Weight 15 Hours	Cal. % of Water	Weight 30 Hours	Cal. % of Water
16.6 gr	13.6 gr	18.1%	13.6 gr	18.1%
17.3 gr	14.3 gr	17.3%	14.2 gr	17.9%
15.3 gr	12.7 gr	17.0%	12.7 gr	17.0%
20.8 gr	17.2 gr	17.3%	17.1 gr	17.8%
18.4 gr	15.1 gr	17.9%	15.0 gr	18.5%

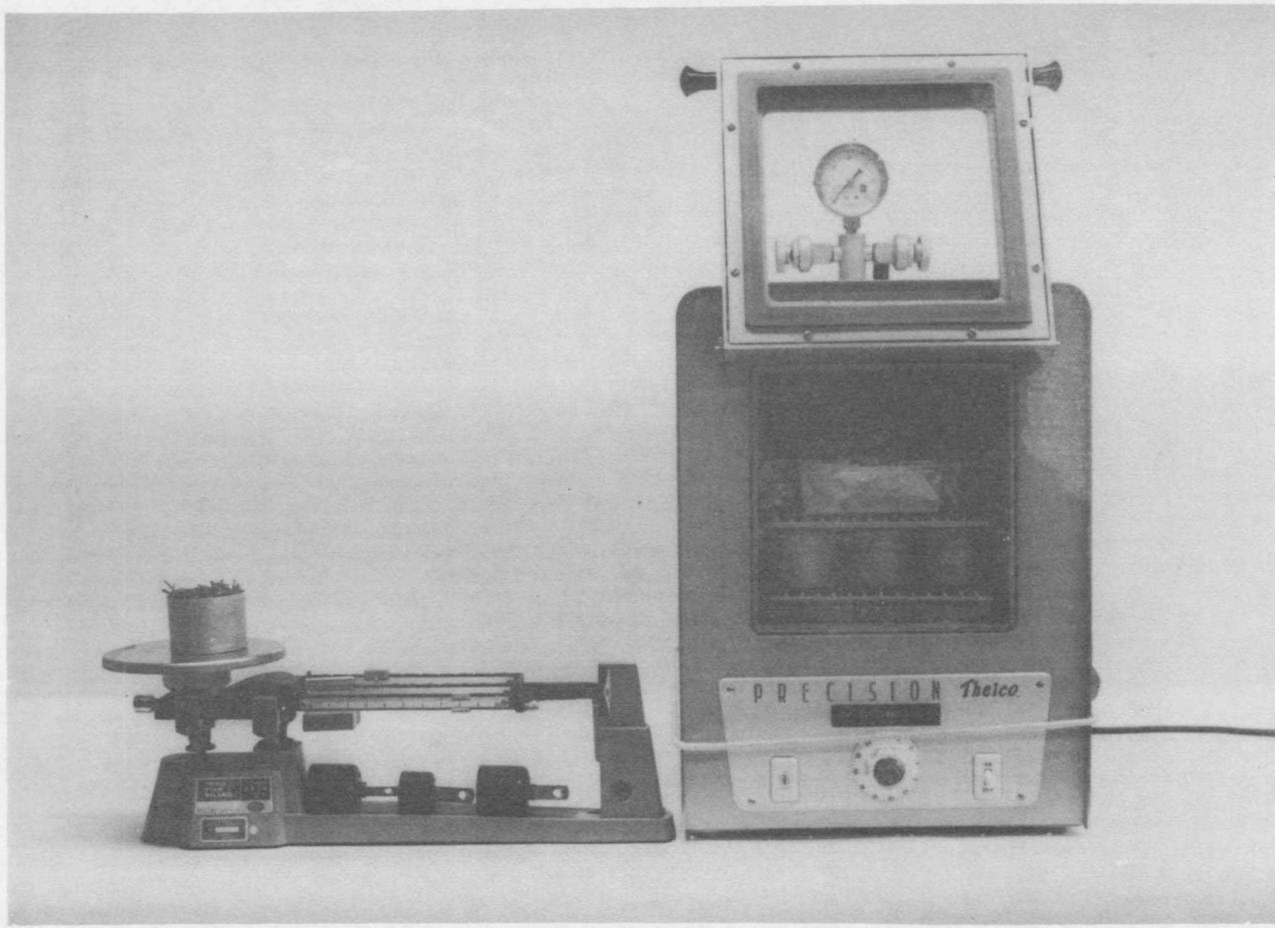


Figure 19. View of Scale and Oven with Door Open Showing Pans Containing Drying Agent on the Upper Shelf of the Oven, and the Drying Cans for the Sample Material on the Bottom Shelf.

CHAPTER IV

SUMMARY OF RESULTS

It has been shown that the moisture content of a material can be calculated from the attenuation of a microwave signal propagating through that material. This principle was then used in building a portable microwave moisture meter. This meter was used in the measurement of the moisture content of fuel materials on the forest floor.

A computer program was written to analyze two years of data taken at Lubrecht Forest. The program showed that there was an additional factor that was influencing the measurements.

The attenuation of the electromagnetic signal in water was shown to be a function of the temperature of the water. This has been shown both experimentally and theoretically. An equation was derived relating the moisture content of a material to the attenuation and temperature of the material.

A better method of oven drying the sample materials was developed. The use of a drying agent in the oven with the sample assures faster and complete drying of the samples.

The next section will give some ideas as to what further investigations should be carried out to check the accuracy of the microwave technique of moisture measurement.

CHAPTER V

CONCLUSIONS

This study was undertaken with the goal of building a microwave moisture meter that could be used by the Forest Service.

The accuracy of the oven dry moisture measurements used in checking the moisture meter was found to be poor. A better method was arrived at which gave better consistency. The oven dry technique should be investigated further to determine the necessary time required to dry a sample and how this time changes with the level of moisture in the material.

The equation relating the moisture content of a sample to attenuation, weight and temperature should be verified. Another summer should be spent collecting data. This time the temperature of the material should be measured and recorded before the microwave moisture measurement is made. The k value can then be found from a table similar to Table 5 of this paper and then the percent of moisture can be calculated.

A subroutine can be added to the data analysis program that will calculate k given the temperature of the sample. This k will be used by the program to calculate the percent of moisture. A better comparison between the oven dry and calculated percents should be seen if the temperature effects are correct.

There are further modifications that could be done to the moisture meter to make it easier to use.

The addition of a built-in electronic scale with digital readout would eliminate the need for carrying a scale along in the field. A pressure transducer load cell would serve as the weight sensor. The analog signal could then be converted to a digital signal for processing to provide a readout in grams. By mounting a small four function calculator on the front panel the calculation would be made faster and more accurately.

The replacement of the precision attenuator with a pin diode attenuator would save in cost, weight and size. The diode attenuator would be calibrated in steps of 10 db from 0 db to 40 db. The meter scale would then be calibrated to read in db. This way the attenuation reading could be read directly off the meter.

All of the above would make the moisture meter a more efficient device to use and also would make it totally self-contained.

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APPENDICES

Appendix I

This section contains the pictures of the Gunn oscillator, diode detector, horns, modulator, and amplifier used in the microwave moisture meter.

Figure (1) shows the amplifier on the left and the modulator right with a HP-45 included to show relative size.

Figure (2) shows a horn with the diode detector attached on the left and another horn with waveguide to coax adaptor and coax cable on the right with HP-45 in the center included scale.

Figure (3) shows the precision attenuator used in the meter.

Figure (4) shows three views of the Gunn oscillator with a fifty cent piece for scale.

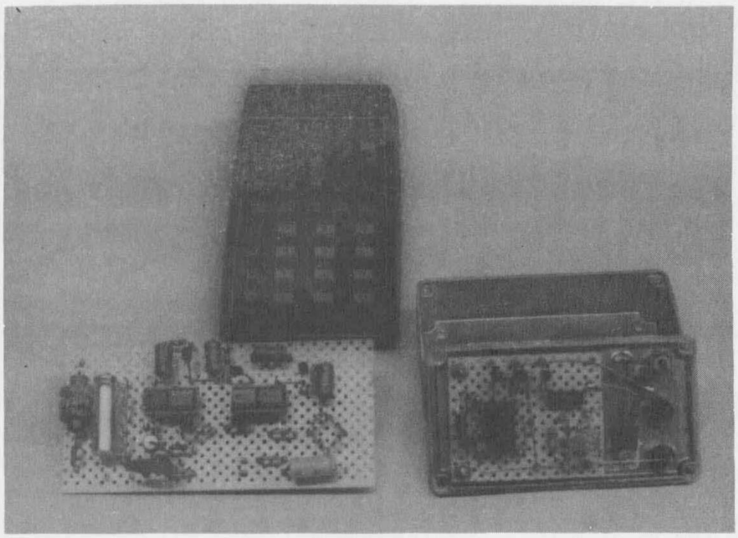


Figure 1. Top View of Amplifier and Modulator.

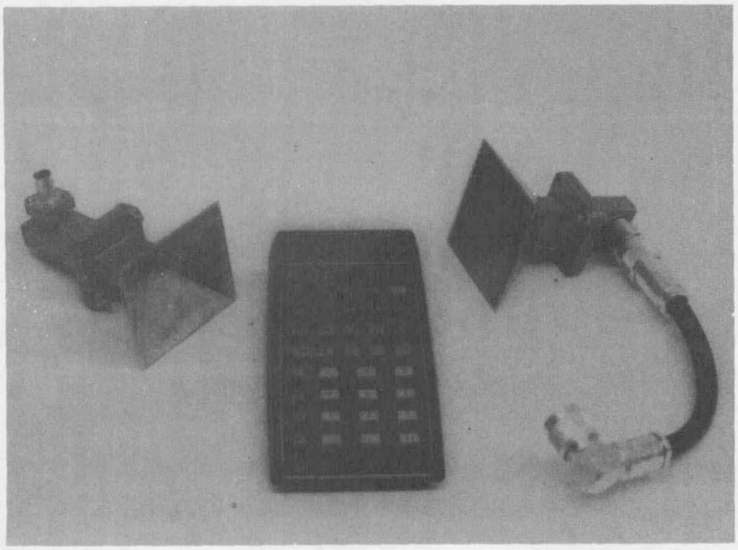


Figure 2. View of Horns, Diode Detector, Coax and Adaptors.

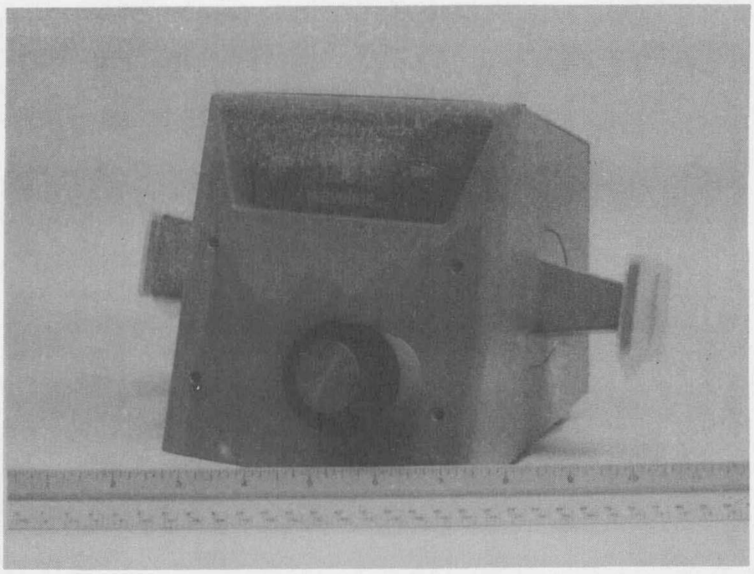


Figure 3. View of Precision Attenuator.

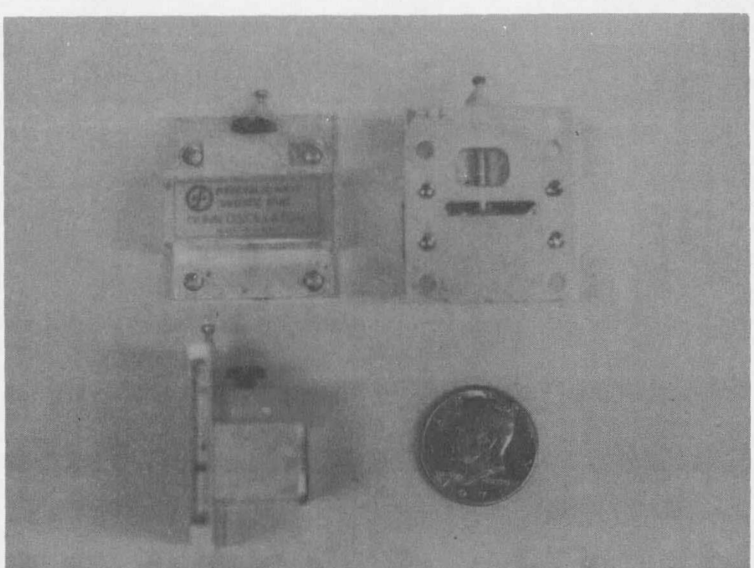


Figure 4. Three Views of Gunn Oscillator.

Appendix II

This section contains the schematics and specifications of the amplifier and modulator used in the microwave moisture meter. The specifications for the circuits are proceeded by the circuit schematics.

Figure 1 is the schematic of the amplifier. The gain of the amplifier is adjusted by the 2.5K potentiometer. The amplifier uses a FET input for high input impedance and low current drain on the source. The FET input is followed by a variable gain operation amplifier (OP. amp) stage which is followed by two active filter stages which were designed for a center frequency of 1KHz. The last active filter stage feeds another OP-amp stage which in turn drives an emitter follower which provides the low output impedance to drive the output meter circuit.

Figure 2 is the schematic of the modulator which was built by Mr. John Rompel, an engineer at Montana State University. The modulator consists of a single 1KHz oscillator and the appropriate interfacing to provide low output impedance with high current capabilities to drive the gunn oscillator.

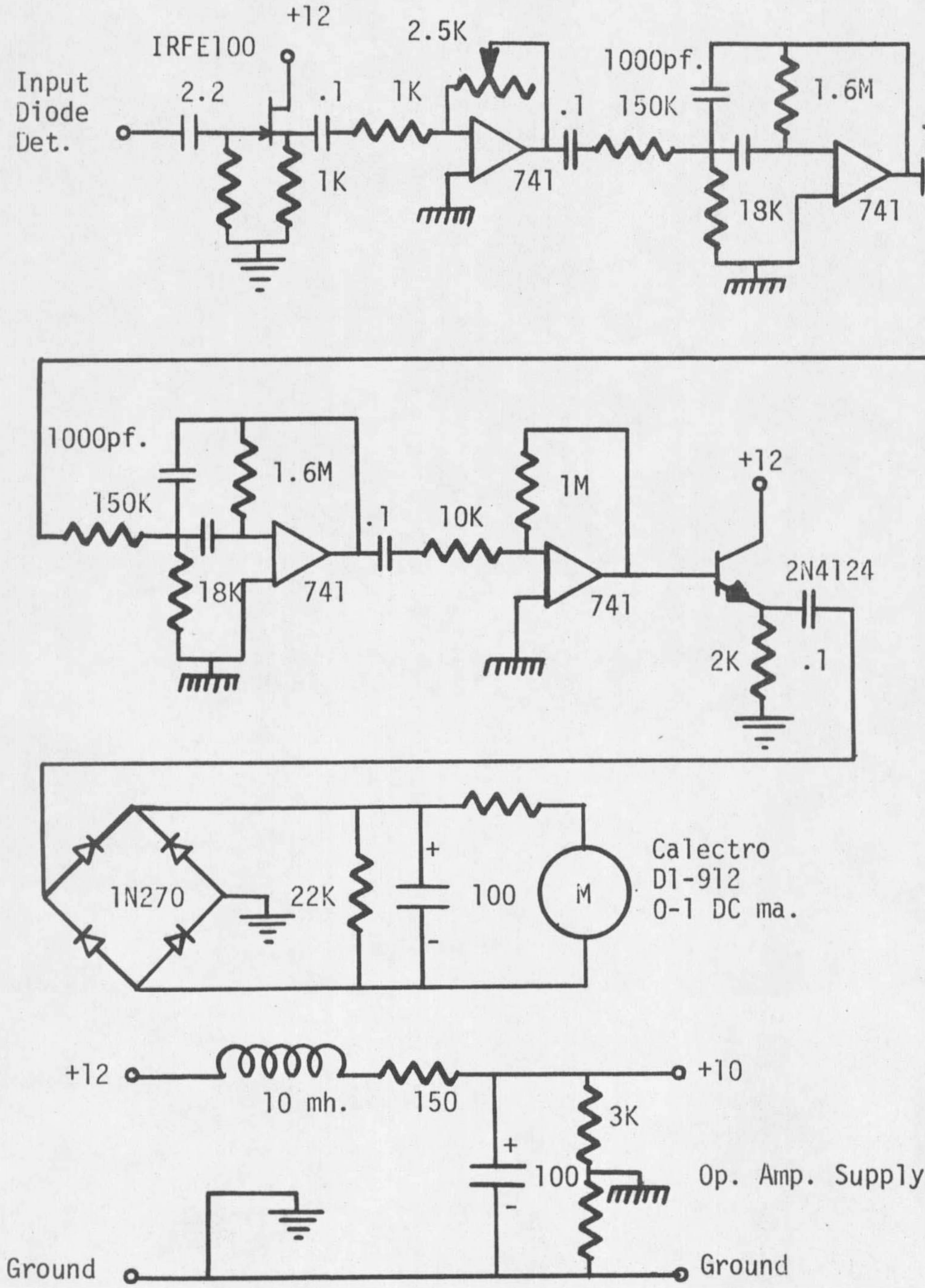


Figure 1. Amplifier Schematic

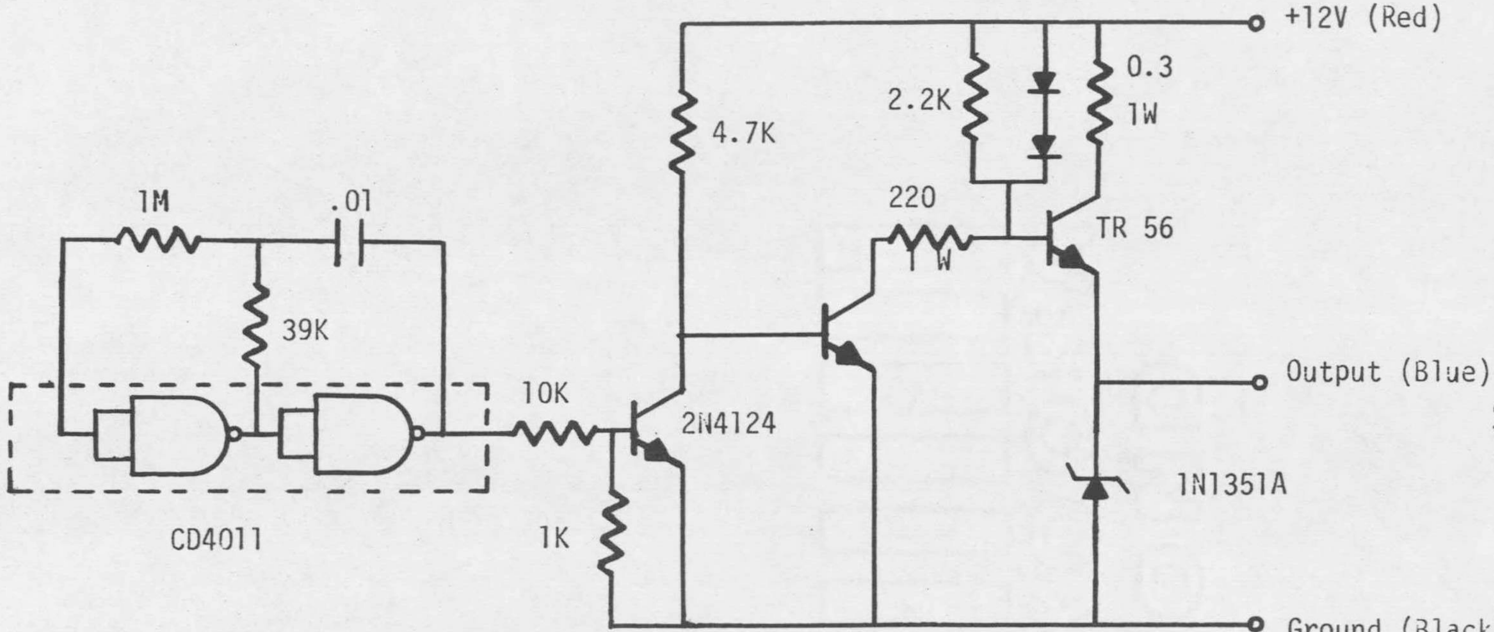


Figure 2. Modulator Schematic

Amplifier Specifications

Gain: 0 to 40 db.

Center Frequency: 1000 Hz.

$Q \simeq 8$

12 Volts Minimum

All Resistors 1/4 Watt Unless Stated Otherwise.

All Capacitors Given in Microfarads Unless Stated Otherwise.

Modulator Specifications

12 Volts Minimum

Output: 1000 Hz. Square Wave

460 ma. Maximum Output Drain

All Resistors 1/4 Watt Unless Stated Otherwise.

All Capacitors Given in Microfarads Unless Stated Otherwise.

Appendix III

This section presents the derivation of the equation used to calculate the moisture content of a sample material given its weight and amount of attenuation of a microwave signal passed through it. The derivation following was first done by Dr. Bruce McLeod at Montana State University.

The value of attenuation of a microwave signal passed through a one centimeter layer of water is 40 db at 25°C. This fact is the heart of the derivation.

Assume that two microwave horns were placed X cm apart. If the area between the horns was filled with water the attenuation measured would be X · 40 db. This would correspond to an "all water" sample. Since the attenuation is to be just due to absorption in the water, the area of water or material is made larger than the horn apature area. This is done to prevent the signal from refracting around the sample and back into the receiving horn.

Now if the water between the horn is replaced by some material containing water and attenuation measured, the percent of water weight seen by the horn would be

$$\%\ H_2O\ \text{weight} = \left(\frac{A_m}{A_t}\right) V_h \times 100 \quad \text{gr}$$

remembering that

$$1\ CC = 1\ \text{gr}\ H_2O$$

where A_m is the attenuation measured, A_t is attenuation for all water, and V_h is the volume seen by the horn.

$$V_h = (\text{Horn apature area})\ (\text{distance between horns})$$

The percent of weight seen by the horn would be

$$\%\ \text{wet weight} = \left(\frac{V_h}{V_t}\right) W_t \times 100$$

where V_t is the total volume of the box containing the sample material and W_t is the total weight of the sample.

The percent of moisture for any sample is given by the following equation:

$$\%H_2O = \frac{H_2O\ \text{weight}}{\text{wet weight} - H_2O\ \text{weight}} \times 100$$

and after substituting in the terms for % H_2O weight and % wet weight seen by the horns the following equation is obtained:

$$\%\ H_2O = \frac{\left(\frac{A_m}{A_t}\right) V_h}{\left(\frac{V_h}{V_t}\right) W_t - \left(\frac{A_m}{A_t}\right) V_h} \times 100.$$

By making the following manipulations the final equation is obtained

$$\% \; H_2O = \frac{\left(\frac{A_m}{A_t}\right)}{\left(\frac{W_t}{V_t}\right) - \left(\frac{A_m}{A_t}\right)} \times 100$$

$$= \frac{100}{\left(\frac{A_t}{V_t}\right)\left(\frac{W_t}{A_m}\right) - 1} .$$

Since A_t and V_t are known the final equation is just

$$\% \; H_2O = \frac{100}{k\left(\frac{W_t}{A_m}\right)-1}$$

where k is a constant in terms of size of the sample box and attenuation of a microwave signal in one centimeter width of water.

For the moisture meter of this study, the horns were looking at a 5.08 cm layer of material and the sample box was 12.7 cm square by 5.08 cm. wide. This gives the following values for A_t and V_t,

$$A_t = (40)\ (5.08) = 203.2\ (\text{db})$$

$$V_t = (12.7)^2\ (5.08) = 819.35\ (\text{cc})$$

and a k value equal to .248.

Appendix IV

The first part of this section contains the listing of the program used to analyze the data taken with the microwave moisture meter. The program listing consists of the mainline program and six subroutines.

The second part of this section contains a listing of the data that was read in on cards for analysis by the program. The data consists of control cards for control of the program and the data cards of 1973 and 1974.

PROGRAM LISTING

```
      DIMENSION A(500),W(500),CP(500),TP(3),DPA(500),DPW(500),IYPE(3),
     *OP(500),IS(500),ID(500),IL(500),ITYPE(500,3),IFORM(3,2),
     *INUM(500),DF(500),X(100),Y(100),IT(24)
      REAL K(500),LK
      INTEGER DS,CC,TYPE/2HD ,2HL ,2HS /
      IFORM(1,1)=4HDUFF
      IFORM(1,2)=4H
      IFORM(2,1)=4HSTIC
      IFORM(2,2)=4HKS
      IFORM(3,1)=4HLITT
      IFORM(3,2)=4HER
C THIS PROGRAM WILL SEPRATE DATA ACCORDING TO YEAR AND
C TYPE AND THEN CALCULATE THE K VALUES AND PERCENT OF
C MOISTURE VALUES, AND DELTA P FOR A AND DELTA P FOR W.
C
C DATA VALUES AND CALCULATED VALUES ARE AS FOLLOWS.
C A=ATTEN., W=WEIGHT,CP=CAL. %,OP=OVEN DRY %,D(N)=
C DELTA % FOR ERROR ANALYSIS,K=MULTIPLYING FACTOR
C TP=TIME PERIOD,DPA&DPW DELTA VALUES,IS,ID,&IL ARE
C THE ORDERED ARRAYS OF DATA
C
C READ DATA CARDS.
C THE FIRST CARD WILL CONTAIN THE DATASET CODE,COMMAND
C CODE,TIME PERIOD,K VALUES, AND UP TO FOUR DELTA %
C VALUES. DS=0 END OF DATA, DS=1 MORE DATA
C CC=0 ANALYZE DATA SEPERATELY CC=1 ANALYZE TOGETHER
C
C THE DATA CARDS WILL CONTAIN  TYPE,TIME PERIOD,
C ATTENUATION, WEIGHT, OVEN DRY %.
C
      ILAST=0
 4    READ(105,5)DS,CC,(TP(I),I=1,3),DK,LK,SK,D
 5    FORMAT(2I2,3A2,3F5.3,F4.2)
      IBLANK=2H
      J=1
 3    READ(105,2)(ITYPE(J,I),I=1,3),A(J),W(J),OP(J)
 2    FORMAT(3A2,2X,2F7.2,F8.5)
      INUM(J)=J
      IF(ITYPE(J,1).EQ.IBLANK)GO TO 20
      J=J+1
      N=J
      GO TO 3
20    I=1
      J=1
      M=1
      NO=N-1
      DO 10 L=1,NO
```

```
      IF(ITYPE(L,1).EQ.TYPE(1))GO TO 30
      IF(ITYPE(L,1).EQ.TYPE(2))GO TO 40
      IS(I)=L
      I=I+1
 10   CONTINUE
      GO TO 50
 30   ID(J)=L
      J=J+1
      GO TO 10
 40   IL(M)=L
      M=M+1
      GO TO 10
C
C NOW CALCULATE THE FUEL MOISTURE
C SAVE  I=STICKS, J=DUFF, M=LITTER
C
 50   I=I-1
      J=J-1
      M=M-1
      CALL PERCENT(A,W,DK,ID,J,CP)
      CALL PERCENT(A,W,LK,IL,M,CP)
      CALL PERCENT(A,W,SK,IS,I,CP)
C
C NOW ORDER SETS ACCORDING TO INCREASING CALCULATED
C PERCENT VALUES.
C
      CALL SORT(IS,I,CP)
      CALL SORT(ID,J,CP)
      CALL SORT(IL,M,CP)
C
C NOW CALCULATE THE ACTUAL K VALLES GIVEN OVEN DRY PERCENT,
C ATTENUATION, AND THE SAMPLE WEIGHT.
C
      DO 60 N=1,NO
      K(N)=(1.0+OP(N))/(OP(N)*(W(N)/A(N)))
 60   CONTINUE
      TK=LK
      ALOW=0
      AHIGH=0
      CALL PRINT(IFORM,TP,1,J,ID,A,W,CP,OP,K,DK)
      CALL PSORT(CP,OP,J,ID,IFORM,TP,1,SN,SG)
      CALL STAT(K,J,ID)
      ALOW=ALOW+SN
      AHIGH=AHIGH+SG
      CALL PRINT(IFORM,TP,3,M,IL,A,W,CP,OP,K,LK)
      CALL PSORT(CP,OP,M,IL,IFORM,TP,3,SN,SG)
      CALL STAT(K,M,IL)
      ALOW=ALOW+SN
```

```
      AHIGH=AHIGH+SG
      CALL PRINT(IFORM,TP,2,I,IS,A,W,CP,OP,K,SK)
      CALL PSORT(CP,OP,I,IS,IFORM,TP,2,SN,SG)
      CALL STAT(K,I,IS)
      ALOW=ALOW+SN
      AHIGH=AHIGH+SG
      COUNT=J+M+I
      PLOW=(ALOW/COUNT)*100
      PHIGH=(AHIGH/COUNT)*100
      WRITE(108,100)(TP(IA),IA=1,2),PLOW,PHIGH
  100 FORMAT(1X,/,'% OF SCATTER OF DATA FOR ',2A2,/1X,F5.2'% OF ALL POIN
     *TS ARE BELOW OVEN DRY PERCENT'/,1X,F5.2,'% OF ALL POINTS ARE ABOVE
     * OVEN DRY PERCENT')
      WRITE(108,110)
  110 FORMAT(1X,/,67'=')
      WRITE(108,120)
  120 FORMAT(1H1)
      CALL PGRAPH(CP,OP,J,ID,ILAST)
      CALL PGRAPH(CP,OP,M,IL,ILAST)
      CALL PGRAPH(CP,OP,I,IS,ILAST)
  999 IF(DS.EQ.1)GO TO 4
      END
```

```
      SUBROUTINE PERCENT(A,W,DK,ID,J,CP)
      DIMENSION A(500),W(500),ID(500),CP(500)
      DO 10 I1=1,J
      I=ID(I1)
      B=((W(I)/A(I))*DK)=1
      CP(I)=100/B
   10 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SORT(IS,I,CP)
      DIMENSION IS(500),CP(500)
      IF(I.EQ.1) GO TO 20
 1    I1=1
 2    IF(CP(IS(I1)).LE.CP(IS(I1+1)))GO TO 5
      GO TO 10
 5    I1=I1+1
      IF(I1.EQ.I) GO TO 20
      GO TO 2
10    I2=IS(I1)
      I3=IS(I1+1)
      IS(I1)=I3
      IS(I1+1)=I2
      GO TO 1
20    RETURN
      END
```

```
      SUBROUTINE PRINT(IFORM,TP,I1,J,ID,A,W,CP,OP,K,C)
      DIMENSION IFORM(3,2),TP(3),ID(500),A(500),W(500),CP(500),
     *OP(500)
      REAL K(500)
      WRITE(108,10)(IFORM(I1,I),I=1,2),(TP(I),I=1,2)
 10   FORMAT(1H1,20X,'ERROR ANALYSIS',/2X,'TABLE OF OVEN DRY%, CALCULATE
     *D%, AND CALCULATED K.',/22X,2A4,2A2)
      WRITE(108,15)C
 15   FORMAT(8X,'K VALUE USED IN CALCULATIONS IS=',F4.3,//)
      WRITE(108,20)
 20   FORMAT(1X,'DATA#',2X,'ATTENUATION(A)',2X,'WEIGHT(W)',3X,
     *'CLC(%)',5X,'OD(%)',5X,'K')
      WRITE(108,30)
 30   FORMAT(1X,5'=',2X,14'=',2X,9'=',2X,6'=',5X,5'=',4X,
     *3'=',//)
      CO=0
      CN=0
      DO 40 K1=1,J
      K2=ID(K1)
      WRITE(108,45)K2,A(K2),W(K2),CP(K2),OP(K2),K(K2)
 45   FORMAT(1X,I3,5X,F8.2,7X,F8.2,3X,F7.2,3X,F7.2,3X,F4.3)
      CN=CN+1
      IF(CN.EQ.5)GO TO 50
 40   CONTINUE
      GO TO 100
 50   WRITE(108,70)
 70   FORMAT(2H  )
      CO=CO+1
      CN=0
      IF(CO.EQ.5)GO TO 80
      GO TO 40
 80   WRITE(108,10)(IFORM(I1,I),I=1,2),(TP(I),I=1,2)
      WRITE(108,15)C
      WRITE(108,20)
      WRITE(108,30)
      CO=0
      GO TO 40
100   RETURN
      END
```

```
      SUBROUTINE PSORT(CP,OP,J,ID,IFORM,TP,I1,SN,SG)
      DIMENSION CP(500),ID(500),OP(500),TP(3),IFORM(3,2),DF(500)
      DL1=0
      DL2=0
      DL5=0
      DLG=0
      DG1=0
      DG2=0
      DG5=0
      DGG=0
      B=J
      DO 10 K1=1,J
      K2=ID(K1)
      DF(K1)=OP(K2)-CP(K2)
   10 CONTINUE
      DO 20 K=1,J
      IF(DF(K).LT.0.)GO TO 100
      IF(DF(K).GT.1.)GO TO 30
      DL1=DL1+1
      GO TO 20
   30 IF(DF(K).GT.2.)GO TO 40
      DL2=DL2+1
      GO TO 20
   40 IF(DF(K).GT.5.)GO TO 50
      DL5=DL5+1
      GO TO 20
   50 DLG=DLG+1
      GO TO 20
  100 IF(ABS(DF(K)).GT.1.) GO TO 60
      DG1=DG1+1
      GO TO 20
   60 IF(ABS(DF(K)).GT.2.)GO TO 70
      DG2=DG2+1
      GO TO 20
   70 IF(ABS(DF(K)).GT.5.)GO TO 80
      DG5=DG5+1
      GO TO 20
   80 DGG=DGG+1
   20 CONTINUE
      WRITE(108,110)(IFORM(I1,I),I=1,2),(TP(I),I=1,2)
  110 FORMAT(1H1,10X'VARIATION OF CALCULATED PERCENT AROUND OVEN DRY'
     *'PERCENT'/30X,2A4,2A2,////)
      ST1=DL1+DG1
      ST2=DL2+DG2
      ST5=DL5+DG5
      STG=DLG+DGG
      P1=(ST1/B)*100
      P2=(ST2/B)*100
```

```
      P5=(ST5/B)*100
      PG=(STG/B)*100
      SN=DL1+DL2+DL5+DLG
      SG=DG1+DG2+DG5+DGG
      PTL=(SN/B)*100
      PTG=(SG/B)*100
      WRITE(108,120)
120   FORMAT(1X,'ABS(OD(%)=CAL(%))'2X'% OF MEASUREMENTS'2X'#CAL(%)<OD(%)
     *',2X,'#CAL(%)>OD(%)')
      WRITE(108,125)
125   FORMAT(1X,17'=',2X,17'=',2X,13'=',2X,13'='/)
      WRITE(108,130)P1,DL1,DG1
130   FORMAT(5X,'0% TO 1%',12X,F5.2,'%',14X,F3.0,12X,F3.0)
      WRITE(108,135)P2,DL2,DG2
135   FORMAT(5X,'1% TO 2%',12X,F5.2,'%',14X,F3.0,12X,F3.0)
      WRITE(108,140)P5,DL5,DG5
140   FORMAT(5X,'2% TO 5%',12X,F5.2,'%',14X,F3.0,12X,F3.0)
      WRITE(108,145)PG,DLG,DGG
145   FORMAT(4X,'GREATER 5%',11X,F5.2,'%',14X,F3.0,12X,F3.0)
      WRITE(108,150)
150   FORMAT(1X,/,67'='/)
      WRITE(108,155)PTL,PTG
155   FORMAT(1X,F5.2,'% OF MEASUREMENTS WERE LOWER THAN OVEN DRY PERCENT
     *'//,1X,F5.2,'% OF MEASUREMENTS WERE HIGHER THAN OVEN DRY PERCENT')
      WRITE(108,150)
      RETURN
      END
```

```
      SUBROUTINE PGRAPH(CP,OP,J,ID,ILAST)
      DIMENSION CP(500),OP(500),ID(500),X(100),Y(100),IT(24)
      REAL MCP,MOP,MAX
C FIRST FIND PERCENT TO BE PLOTTED
      ILAST=ILAST+1
      NUMPTS=J
      LABEL=4H
      MCP=0
      MOP=0
      DO 10 K=1,J
      K1=ID(K)
      IF(CP(K1).GT.MCP)GO TO 40
      GO TO 30
   40 MCP=CP(K1)
   30 IF(OP(K1).GT.MOP)GO TO 50
      GO TO 10
   50 MOP=OP(K1)
   10 CONTINUE
      IF(MCP.GT.MOP)GO TO 60
      MAX=MOP
      GO TO 70
   60 MAX=MCP
   70 MAX=MAX/10
      IMAX=MAX+1.
      IMAX=IMAX*10
      YMAX=IMAX
      XMAX=IMAX
      XSCALE=XMAX/6
      YSCALE=YMAX/6
C PLOT OVEN DRY ALONG X AXIS
      DO 110 K=1,J
      K1=ID(K)
      X(K)=OP(K1)
      Y(K)=CP(K1)
  110 CONTINUE
      READ(105,20)(IT(I),I=1,24)
  20  FORMAT(12A4/12A4)
      CALL DRAW(X,Y,NUMPTS,1,1,LABLE,IT,XSCALE,YSCALE,0,0,6,6,0,LAST)
      XN=XMAX/J
      DO 120 I=1,J+1
      X(I)=XN*(I-1)
      Y(I)=XN*(I-1)
  120 CONTINUE
      IF(ILAST.EQ.6)LAST=4HLAST
      CALL DRAW(X,Y,NUMPTS,3,0,LABLE,IT,XSCALE,YSCALE,0,0,6,6,0,LAST)
      RETURN
      END
```

```
      SUBROUTINE STAT(K,J,ID)
      DIMENSION ID(500)
      REAL K(500),MEAN,MS
C
C FIRST DETERMIN MEAN VALUE OF K'S.
C
      TOK=0
      DO 10 I=1,J
   10 TOK=K(ID(I))+TOK
      MEAN=TOK/J
C
C STANDARD DEVIATION IS MEAN SQUARE MINUS
C SQUARE MEAN SQUARE ROOT.
C
      SM=MEAN**2
C
C NOW MEAN SQUARE
C
      TKS=0
      DO 20 I=1,J
   20 TKS=(K(ID(I)))**2+TKS
      MS=TKS/J
      DEV=(ABS(SM=MS))**.5
       WRITE(108,30)MEAN,DEV
   30 FORMAT(1X,//,1X,'MEAN VALUE OF K IS ',F4.3,/,1X,'STANDARD DEVIATIC
     *N OF K IS ',F4.3)
      WRITE(108,40)
   40 FORMAT(1X,/,67'=')
      RETURN
      END
```

INPUT DATA LISTING
FOR 1972

1	OSU72	.156	.210	.173	.05
L	72	3.16	142.0	16.10	
D	72	7.36	214.0	26.30	
D	72	8.2	179.0	33.70	
L	72	3.40	152.0	15.37	
D	72	9.6	227.0	27.85	
L	72	4.7	194.0	12.85	
D	72	21.47	241.0	87.50	
L	72	5.84	153.0	21.85	
D	72	12.65	242.0	43.50	
L	72	5.51	159.0	24.30	
S	72	7.76	211.0	21.50	
L	72	4.16	140.7	16.80	
D	72	15.17	406.0	31.30	
D	72	13.10	399.00	27.90	
D	72	12.90	412.0	26.10	
D	72	13.83	436.0	25.90	
D	72	10.20	408.0	21.10	
D	72	10.43	436.0	20.60	
D	72	19.35	295.0	64.00	
D	72	22.36	341.0	63.90	
L	72	23.22	276.0	84.50	
L	72	15.74	266.0	41.80	
L	72	3.7	175.0	14.10	
L	72	3.6	185.0	14.80	
L	72	12.13	244.0	35.20	
L	72	12.60	267.0	35.50	
L	72	11.97	155.0	45.00	
L	72	13.17	192.0	43.00	
D	72	11.00	254.0	36.00	
D	72	12.80	292.0	35.10	
D	72	8.2	231.0	23.70	
D	72	10.00	261.0	19.75	
D	72	6.95	277.0	15.30	
D	72	7.02	311.0	15.20	
D	72	5.95	277.0	14.30	
*	72	9.43	254.0	31.00	
D	72	6.73	242.0	18.80	
L	72	6.9	159.0	24.70	
L	72	4.35	233.0	14.50	
D	72	5.57	289.0	14.15	
L	72	3.9	149.0	16.40	
D	72	19.07	245.0	84.00	
D	72	15.30	366.0	37.00	
L	72	3.25	145.0	14.90	
S	72	6.4	344.0	11.80	
S	72	4.9	337.0	10.45	
S	72	5.8	325.0	10.45	

S	72	4.8	305.0	11.10
S	72	6.9	316.0	12.00
L	72	3.03	201.4	7.20
S	72	4.6	278.0	10.55
L	72	3.13	182.0	13.70
D	72	12.23	259.0	37.50
L	72	10.57	209.0	34.70
L	72	4.0	184.0	17.50
L	72	4.6	202.0	17.20
D	72	19.25	311.7	56.90
S	72 2	6.46	241.0	16.40
D	72	11.03	223.3	37.50
D	72	8.33	183.0	38.40
L	72	3.55	153.6	20.50
L	72	5.07	122.0	28.40
S	72	5.33	227.0	17.84
L	72	3.45	180.0	12.40
L	72	19.78	231.0	96.70
L	72	21.20	251.0	95.20
L	72	23.63	279.0	96.00
L	72	19.10	224.0	68.00
L	72	21.06	245.4	67.00
L	72	21.06	245.4	67.00
L	72	12.60	218.0	36.30
L	72	13.60	234.0	36.50
L	72	3.7	193.0	12.95
L	72	4.0	214.0	13.85
L	72	6.67	215.0	20.70
L	72	7.07	242.0	20.20
L	72	7.3	257.0	20.30
L	72	15.41	210.0	50.20
L	72	17.12	232.0	49.30
L	72	18.20	260.0	48.20
L	72	4.62	211.0	17.30
L	72	4.9	213.0	18.50
L	72	8.02	212.0	27.40
L	72	8.92	244.0	27.80
L	72	11.77	225.0	34.90
L	72	12.83	255.0	34.50
L	72	15.11	244.0	43.00
L	72	16.90	277.0	42.00
D	72	14.70	318.0	44.00
D	72	17.30	367.3	43.90
D	72	18.10	392.0	43.50
D	72	13.43	271.5	46.20
D	72	17.86	364.0	43.90
D	72	8.5	391.0	18.85
D	72	9.3	416.0	19.10

D	72	13.97	377.0	32.40
S	72	5.18	294.0	8.65
L	72	10.30	219.0	25.00
L	72	5.3	152.0	17.90
L	72	14.60	242.0	41.80
S	72	7.2	290.0	11.60
D	72	14.87	298.0	44.20
L	72	4.14	193.0	17.25
L	72	11.87	237.0	34.90
L	72	3.45	180.0	12.40
S	72	5.33	227.0	17.84

SCATTER PLOT OF OVEN DRY % AND CALCULATED % FOR
DUFF. 1972 DATA. JOE KOWALSKI JUNE 1974
SCATTER PLOT OF OVEN DRY % AND CALCULATED % FOR
LITTER. 1972 DATA. JOE KOWALSKI JUNE 1974
SCATTER PLOT OF OVEN DRY % AND CALCULATED % FOR
STICKS. 1972 DATA. JOE KOWALSKI JUNE 1974

INPUT DATA LISTING
FOR 1973

0	OSU73	.248	.248	.248	.C5
L	73	2.8	87.40	19.80	
D	73	24.95	193.10	82.00	
S	73	2.30	144.9	7.69	
D	73	25.6	232.4	85.0	
L	73	2.60	82.1	20.00	
S	73	2.50	122.6	7.69	
D	73	23.9	240.3	82.00	
D	73	25.25	239.8	73.20	
S	73	2.9	138.5	12.60	
D	73	29.5	266.8	73.00	
D	73	26.2	244.8	76.00	
D	73	28.6	271.2	66.50	
L	73	3.0	80.4	17.10	
L	73	3.6	96.75	18.50	
L	73	2.85	83.1	17.00	
L	73	3.2	88.5	16.40	
S	73	2.8	136.7	6.20	
S	73	2.6	138.3	6.66	
S	73	2.9	173.3	7.35	
S	73	1.9	154.6	7.50	
S	73	1.5	140.5	7.95	
L	73	1.0	95.1	9.20	
L	73	1.0	100.0	10.30	
L	73	1.0	109.2	9.10	
L	73	3.0	99.0	15.95	
D	73	5.0	194.3	16.3	
D	73	3.5	166.2	16.00	
D	73	4.3	177.9	14.80	
S	73	5.0	186.5	8.00	
S	73	3.9	167.4	7.85	
L	73	1.9	104.3	10.40	
L	73	1.5	94.1	10.60	
D	73	5.0	140.5	17.3	
D	73	4.5	145.3	15.90	
S	73	2.5	150.7	7.90	
S	73	2.2	145.8	7.30	
S	73	2.3	163.4	7.90	
L	73	1.7	111.1	4.85	
L	73	1.5	118.9	4.55	
L	73	1.9	110.0	5.20	
D	73	4.6	155.4	15.90	
D	73	4.0	146.3	15.80	
D	73	4.1	140.2	15.60	
S	73	2.9	160.6	10.30	
S	73	2.5	156.0	11.1	
L	73	1.9	87.7	11.40	
D	73	4.1	132.7	19.80	

S	73	3.1	156.2	9.15
S	73	3.2	156.2	8.70
S	73	3.3	159.4	8.00
L	73	2.0	111.7	11.10
L	73	1.9	121.4	11.50
L	73	1.9	117.8	11.10
D	73	9.6	180.3	31.60
D	73	8.6	158.6	28.20
S	73	3.5	159.6	8.00
S	73	3.5	156.3	8.05
S	73	3.8	178.0	8.15
S	73	3.3	177.2	8.30
L	73	2.3	99.5	12.10
L	73	2.7	113.8	12.30
D	73	6.0	187.3	17.10
D	73	5.8	186.2	16.60
S	73	3.4	165.7	7.40
S	73	2.9	168.2	6.85
L	73	2.6	79.3	6.90
L	73	2.5	95.3	7.10
D	73	8.1	252.0	12.50
D	73	7.2	269.2	9.70
S	73	3.0	144.5	7.47
S	73	3.0	166.6	7.10
S	73	2.6	158.6	6.87
L	73	2.0	111.4	9.60
L	73	2.5	117.4	10.47
L	73	2.0	110.7	9.09
D	73	5.0	129.2	17.22
D	73	4.5	137.3	15.00
D	73	4.7	149.8	15.35
S	73	4.2	158.0	11.64
S	73	2.8	149.0	10.42
S	73	4.1	157.0	10.42
S	73	2.7	165.0	10.36
L	73	2.6	90.0	15.99
L	73	2.1	89.0	15.16
L	73	2.6	84.0	16.26
L	73	3.1	95.0	16.49
D	73	10.5	145.0	50.06
D	73	10.6	145.0	36.61
D	73	10.9	124.0	42.12
D	73	11.4	132.0	42.76
S	73	3.3	142.0	10.01
S	73	2.9	144.0	10.50
S	73	2.9	159.0	10.51
S	73	2.9	166.0	10.49
L	73	2.6	88.0	13.08

L	73	2.2	93.0	13.05
L	73	3.0	89.0	12.74
L	73	2.5	100.0	13.73
D	73	6.9	143.0	23.4
D	73	6.8	151.0	24.35
D	73	6.6	147.0	22.74
D	73	6.7	156.0	21.97
S	73	3.1	156.0	8.84
S	73	3.3	162.0	9.42
S	73	2.9	165.0	9.10
L	73	2.2	98.0	9.55
L	73	2.8	116.0	10.30
L	73	2.9	116.0	11.03
D	73	9.9	172.0	27.79
D	73	6.3	164.0	21.27
D	73	6.0	164.0	20.98
D	73	5.6	174.0	19.24
S	73	2.5	143.9	8.98
S	73	2.1	146.8	8.96
S	73	2.7	164.3	9.35
L	73	1.4	124.8	8.33
L	73	1.5	262.2	7.95
L	73	1.2	146.3	7.89
D	73	4.5	180.5	13.96
D	73	4.7	167.4	15.72
D	73	4.8	176.0	15.04
S	73	6.5	147.0	17.10
S	73	4.3	141.7	12.24
L	73	3.6	109.1	15.89
L	73	3.8	110.2	14.58
L	73	3.9	115.2	17.1
D	73	6.8	190.3	20.08
D	73	6.0	184.6	19.14
D	73	5.5	177.8	18.96
S	73	2.9	139.5	9.02

SCATTER PLOT OF OVEN DRY % AND CALCULATED % FOR DUFF. 1973 DATA. JOE KOWALSKI JUNE 1974

SCATTER PLOT OF OVEN DRY % AND CALCULATED % FOR LITTER. 1973 DATA. JOE KOWALSKI JUNE 1974

SCATTER PLOT OF OVEN DRY % AND CALCULATED % FOR STICKS. 1973 DATA. JOE KOWALSKI JUNE 1974

Appendix V

This section contains a listing of the output generated by the program. The output consists of the tables of oven dry percents, moisture meter percents, k values and various statical analysis carried out by the program. The output is separated into duff, litter, and sticks for 1973 and 1974.

OUTPUT LISTING

1

ERROR ANALYSIS
TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.
DUFF SU72
K VALUE USED IN CALCULATIONS IS=.156

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(X)	OD(X)	K
40	5.57	289.00	14.10	14.15	.155
35	5.95	277.00	15.97	14.30	.172
94	8.50	391.00	16.19	18.85	.137
95	9.30	416.00	16.73	19.10	.139
34	7.02	311.00	16.92	15.20	.171
18	10.43	436.00	18.11	20.60	.140
17	10.20	408.00	19.08	21.10	.143
33	6.95	277.00	19.17	15.30	.189
37	6.73	242.00	21.69	18.80	.176
15	12.90	412.00	25.11	26.10	.151
16	13.83	436.00	25.52	25.90	.154
14	13.10	399.00	26.66	27.90	.151
2	7.36	214.00	28.28	26.30	.165
31	8.20	231.00	29.46	23.70	.185
96	13.97	377.00	31.15	32.40	.151
13	15.17	406.00	31.50	31.30	.157
32	10.00	261.00	32.56	19.75	.232
43	15.30	366.00	36.61	37.00	.155
5	9.60	227.00	37.19	27.85	.194
29	11.00	254.00	38.43	36.00	.164
30	12.80	292.00	39.08	35.10	.169
60	8.33	183.00	41.20	38.40	.164
3	8.20	179.00	41.57	33.70	.182
91	18.10	392.00	42.04	43.50	.152
89	14.70	318.00	42.11	44.00	.151

1

ERROR ANALYSIS

TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.

DUFF SU72

K VALUE USED IN CALCULATIONS IS=.156

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
90	17.30	367.30	43.25	43.90	.154
53	12.23	259.00	43.41	37.50	.173
93	17.86	364.00	45.88	43.90	.161
59	11.03	223.30	46.34	37.50	.181
92	13.43	271.50	46.43	46.20	.157
102	14.87	298.00	47.03	44.20	.163
9	12.65	242.00	50.39	43.50	.172
57	19.25	311.70	65.53	56.90	.170
20	22.36	341.00	72.51	63.90	.168
19	19.35	295.00	72.55	64.00	.168
42	19.07	245.00	99.58	84.00	.170
7	21.47	241.00	133.14	87.50	.191

1 VARIATION OF CALCULATED PERCENT AROUND OVEN DRYPERCENT
DUFF SU72

ABS(OD(%)-CAL(%))	% OF MEASUREMENTS	#CAL(%)<OD(%)	#CAL(%)>OD(%)
0% TO 1%	18.92%	5.	2.
1% TO 2%	21.62%	4.	4.
2% TO 5%	27.03%	4.	6.
GREATER 5%	32.43%	0.	12.

35.14% OF MEASUREMENTS WERE LOWER THAN OVEN DRY PERCENT

64.86% OF MEASUREMENTS WERE HIGHER THAN OVEN DRY PERCENT

MEAN VALUE OF K IS .166
STANDARD DEVIATION OF K IS .018

1

ERROR ANALYSIS
TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.
LITTER SU72
K VALUE USED IN CALCULATIONS IS=.210

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
50	3.03	201.40	7.72	7.20	.224
52	3.13	182.00	8.92	13.70	.143
39	4.35	233.00	9.76	14.50	.147
74	4.00	214.00	9.77	13.85	.154
64	3.45	180.00	10.04	12.40	.174
105	3.45	180.00	10.04	12.40	.174
73	3.70	193.00	10.05	12.95	.167
24	3.60	185.00	10.21	14.80	.151
23	3.70	175.00	11.20	14.10	.171
103	4.14	193.00	11.38	17.25	.146
55	4.00	184.00	11.55	17.50	.146
81	4.62	211.00	11.64	17.30	.148
1	3.16	142.00	11.85	16.10	.160
4	3.40	152.00	11.92	15.37	.168
44	3.25	145.00	11.95	14.90	.173
56	4.60	202.00	12.16	17.20	.155
82	4.90	213.00	12.30	18.50	.147
61	3.55	153.60	12.37	20.50	.136
6	4.70	194.00	13.04	12.85	.213
41	3.90	149.00	14.24	16.40	.186
77	7.30	257.00	15.64	20.30	.168
76	7.07	242.00	16.16	20.20	.174
12	4.16	140.70	16.39	16.80	.206
75	6.67	215.00	17.33	20.70	.181
10	5.51	159.00	19.76	24.30	.177

1

ERROR ANALYSIS
TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.
LITTER SU72
K VALUE USED IN CALCULATIONS IS=.210

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
99	5.30	152.00	19.91	17.90	.230
84	8.92	244.00	21.08	27.80	.168
83	8.02	212.00	21.97	27.40	.176
8	5.84	153.00	22.21	21.85	.213
62	5.07	122.00	24.67	28.40	.188
38	6.90	159.00	26.05	24.70	.219
98	10.30	219.00	28.86	25.00	.235
26	12.60	267.00	28.99	35.50	.180
25	12.13	244.00	31.02	35.20	.191
104	11.87	237.00	31.32	34.90	.194
86	12.83	255.00	31.51	34.50	.196
54	10.57	209.00	31.72	34.70	.196
85	11.77	225.00	33.17	34.90	.202
71	12.60	218.00	37.97	36.30	.217
72	13.60	234.00	38.27	36.50	.217
22	15.74	266.00	39.23	41.80	.201
100	14.60	242.00	40.31	41.80	.205
88	16.90	277.00	40.95	42.00	.206
87	15.11	244.00	41.82	43.00	.206
28	13.17	192.00	48.51	43.00	.228
80	18.20	260.00	50.00	48.20	.215
78	15.41	210.00	53.71	50.20	.220
79	17.12	232.00	54.18	49.30	.223
27	11.97	155.00	58.16	45.00	.249
21	23.22	276.00	66.84	84.50	.184

1

ERROR ANALYSIS

TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.

LITTER SU72

K VALUE USED IN CALCULATIONS IS=.210

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
66	21.20	251.00	67.28	95.20	.173
67	23.63	279.00	67.59	96.00	.173
68	19.10	224.00	68.36	68.00	.211
65	19.78	231.00	68.85	96.70	.174
69	21.06	245.40	69.11	67.00	.214
70	21.06	245.40	69.11	67.00	.214

1 VARIATION OF CALCULATED PERCENT AROUND OVEN DRYPERCENT
LITTER SU72

ABS(OD(%)-CAL(%))	% OF MEASUREMENTS	#CAL(%)<OD(%)	#CAL(%)>OD(%)
0% TO 1%	8.93%	1.	4.
1% TO 2%	14.29%	4.	4.
2% TO 5%	50.00%	22.	6.
GREATER 5%	26.79%	13.	2.

71.43% OF MEASUREMENTS WERE LOWER THAN OVEN DRY PERCENT

28.57% OF MEASUREMENTS WERE HIGHER THAN OVEN DRY PERCENT

MEAN VALUE OF K IS .188
STANDARD DEVIATION OF K IS .028

1

ERROR ANALYSIS

TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.

STICKS SU72

K VALUE USED IN CALCULATIONS IS= .173

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
46	4.90	337.00	9.18	10.45	.154
48	4.80	305.00	10.01	11.10	.158
51	4.60	278.00	10.58	10.55	.173
97	5.18	294.00	11.34	8.65	.221
47	5.80	325.00	11.50	10.45	.189
45	6.40	344.00	12.05	11.80	.176
49	6.90	316.00	14.44	12.00	.204
63	5.33	227.00	15.70	17.84	.155
106	5.33	227.00	15.70	17.84	.155
101	7.20	290.00	16.76	11.60	.239
58	6.46	241.00	18.34	16.40	.190
11	7.76	211.00	27.00	21.50	.208
36	9.43	254.00	27.32	31.00	.157

1 VARIATION OF CALCULATED PERCENT AROUND OVEN DRYPERCENT
STICKS SU72

ABS(OD(%)-CAL(%))	% OF MEASUREMENTS	#CAL(%)<OD(%)	#CAL(%)>OD(%)
0% TO 1%	15.38%	0.	2.
1% TO 2%	30.77%	2.	2.
2% TO 5%	38.46%	3.	2.
GREATER 5%	15.38%	0.	2.

38.46% OF MEASUREMENTS WERE LOWER THAN OVEN DRY PERCENT

61.54% OF MEASUREMENTS WERE HIGHER THAN OVEN DRY PERCENT

MEAN VALUE OF K IS .183
STANDARD DEVIATION OF K IS .027

% OF SCATTER OF DATA FOR SU72
54.72% OF ALL POINTS ARE BELOW OVEN DRY PERCENT
45.28% OF ALL POINTS ARE ABOVE OVEN DRY PERCENT

1

ERROR ANALYSIS
TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.
DUFF SU73
K VALUE USED IN CALCULATIONS IS=.248

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
27	3.50	166.20	9.28	16.00	.153
28	4.30	177.90	10.80	14.80	.187
119	4.50	180.50	11.18	13.96	.204
26	5.00	194.30	11.58	16.30	.184
69	7.20	269.20	12.09	9.70	.302
121	4.80	176.00	12.36	15.04	.209
42	4.00	146.30	12.39	15.80	.200
120	4.70	167.40	12.77	15.72	.207
43	4.10	140.20	13.37	15.60	.217
41	4.60	155.40	13.55	15.90	.216
47	4.10	132.70	14.23	19.80	.187
129	5.50	177.80	14.25	18.96	.194
34	4.50	145.30	14.27	15.90	.226
63	5.80	186.20	14.36	16.60	.219
78	4.70	149.80	14.48	15.35	.236
62	6.00	187.30	14.83	17.10	.219
68	8.10	252.00	14.89	12.50	.289
112	5.60	174.00	14.91	19.24	.199
128	6.00	184.60	15.08	19.14	.202
77	4.50	137.30	15.23	15.00	.251
33	5.00	140.50	16.75	17.30	.241
127	6.80	190.30	16.83	20.08	.214
111	6.00	164.00	17.31	20.98	.211
110	6.30	164.00	18.33	21.27	.219
76	5.00	129.20	18.49	17.22	.263

1

ERROR ANALYSIS
TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.
DUFF SU73
K VALUE USED IN CALCULATIONS IS=.248

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
102	6.70	156.00	20.95	21.97	.238
101	6.60	147.00	22.11	22.74	.242
100	6.80	151.00	22.19	24.35	.230
99	6.90	143.00	24.16	23.40	.254
54	9.60	180.30	27.34	31.60	.222
55	8.60	158.60	27.98	28.20	.247
109	9.90	172.00	30.22	27.79	.265
87	10.50	145.00	41.24	50.06	.217
88	10.60	145.00	41.80	36.61	.273
90	11.40	132.00	53.43	42.76	.288
89	10.90	124.00	54.91	42.12	.297
7	23.90	240.30	66.96	82.00	.221
8	25.25	239.80	73.79	73.20	.249
12	28.60	271.20	73.98	66.50	.264
11	26.20	244.80	75.92	76.00	.248
4	25.60	232.40	79.91	85.00	.240
10	29.50	266.80	80.46	73.00	.262
2	24.95	193.10	108.77	82.00	.287

1 VARIATION OF CALCULATED PERCENT AROUND OVEN DRYPERCENT

DUFF SU73

ABS(OD(%)-CAL(%))	% OF MEASUREMENTS	#CAL(%)<OD(%)	#CAL(%)>OD(%)
0% TO 1%	18.60%	5.	3.
1% TO 2%	6.98%	2.	1.
2% TO 5%	48.84%	18.	3.
GREATER 5%	25.58%	5.	6.

69.77% OF MEASUREMENTS WERE LOWER THAN OVEN DRY PERCENT

30.23% OF MEASUREMENTS WERE HIGHER THAN OVEN DRY PERCENT

MEAN VALUE OF K IS .232
STANDARD DEVIATION OF K IS .033

1

ERROR ANALYSIS

TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.

LITTER SU73

K VALUE USED IN CALCULATIONS IS=.248

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
117	1.50	262.20	2.36	7.95	.078
118	1.20	146.30	3.42	7.89	.112
24	1.00	109.20	3.83	9.10	.110
23	1.00	100.00	4.20	10.30	.107
22	1.00	95.10	4.43	9.20	.125
116	1.40	124.80	4.74	8.33	.146
39	1.50	118.90	5.36	4.55	.290
38	1.70	111.10	6.58	4.85	.331
52	1.90	121.40	6.74	11.50	.152
32	1.50	94.10	6.87	10.60	.166
53	1.90	117.80	6.96	11.10	.161
40	1.90	110.00	7.49	5.20	.349
51	2.00	111.70	7.78	11.10	.179
73	2.00	111.40	7.80	9.60	.205
75	2.00	110.70	7.86	9.09	.217
31	1.90	104.30	7.93	10.40	.193
74	2.50	117.40	9.39	10.47	.225
46	1.90	87.70	9.57	11.40	.212
106	2.20	98.00	9.95	9.55	.258
60	2.30	99.50	10.28	12.10	.214
84	2.10	89.00	10.51	15.16	.179
96	2.20	93.00	10.54	13.05	.205
61	2.70	113.80	10.58	12.30	.217
107	2.80	116.00	10.78	10.30	.258
98	2.50	100.00	11.21	13.73	.207

1

ERROR ANALYSIS

TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.

LITTER SU73

K VALUE USED IN CALCULATIONS IS=.248

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	CD(%)	K
108	2.90	116.00	11.21	11.03	.252
67	2.50	95.30	11.83	7.10	.396
83	2.60	90.00	13.18	15.99	.210
95	2.60	88.00	13.52	13.08	.255
25	3.00	99.00	13.92	15.95	.220
85	2.60	84.00	14.26	16.26	.221
5	2.60	82.10	14.64	20.00	.190
1	2.80	87.40	14.83	19.80	.194
86	3.10	95.00	15.15	16.49	.231
66	2.60	79.30	15.23	6.90	.508
124	3.60	109.10	15.35	15.89	.241
97	3.00	89.00	15.73	12.74	.298
126	3.90	115.20	15.81	17.10	.232
15	2.85	83.10	16.05	17.00	.236
125	3.80	110.20	16.15	14.58	.271
16	3.20	88.50	17.07	16.40	.257
14	3.60	96.75	17.65	18.50	.238
13	3.00	80.40	17.71	17.10	.256

1 VARIATION OF CALCULATED PERCENT AROUND OVEN DRYPERCENT
LITTER SU73

ABS(OD(%)-CAL(%))	% OF MEASUREMENTS	#CAL(%)<OD(%)	#CAL(%)>OD(%)
0% TO 1%	23.26%	3.	7.
1% TO 2%	25.58%	9.	2.
2% TO 5%	39.53%	14.	3.
GREATER 5%	11.63%	4.	1.

69.77% OF MEASUREMENTS WERE LOWER THAN OVEN DRY PERCENT

30.23% OF MEASUREMENTS WERE HIGHER THAN OVEN DRY PERCENT

MEAN VALUE OF K IS .223
STANDARD DEVIATION OF K IS .077

1

ERROR ANALYSIS

TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.

STICKS SU73

K VALUE USED IN CALCULATIONS IS=.248

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
21	1.50	140.50	4.50	7.95	.145
20	1.90	154.60	5.21	7.50	.176
37	2.30	163.40	6.02	7.90	.192
114	2.10	146.80	6.12	8.96	.174
36	2.20	145.80	6.48	7.30	.222
3	2.30	144.90	6.84	7.69	.222
45	2.50	156.00	6.91	11.10	.160
82	2.70	165.00	7.06	10.36	.174
72	2.60	158.60	7.08	6.87	.255
115	2.70	164.30	7.10	9.35	.192
35	2.50	150.70	7.17	7.90	.227
19	2.90	173.30	7.24	7.35	.244
65	2.90	168.20	7.47	6.85	.269
113	2.50	143.90	7.53	8.98	.211
94	2.90	166.00	7.58	10.49	.184
105	2.90	165.00	7.63	9.10	.211
71	3.00	166.60	7.83	7.10	.272
44	2.90	160.60	7.85	10.30	.193
93	2.90	159.00	7.94	10.51	.192
59	3.30	177.20	8.12	8.30	.243
80	2.80	149.00	8.20	10.42	.199
18	2.60	138.30	8.20	6.66	.301
48	3.10	156.20	8.70	9.15	.237
103	3.10	156.00	8.71	8.84	.245
92	2.90	144.00	8.84	10.50	.212

1

ERROR ANALYSIS

TABLE OF OVEN DRY%, CALCULATED%, AND CALCULATED K.

STICKS SU73

K VALUE USED IN CALCULATIONS IS=.248

DATA#	ATTENUATION(A)	WEIGHT(W)	CLC(%)	OD(%)	K
104	3.30	162.00	8.95	9.42	.237
6	2.50	122.60	8.96	7.69	.286
17	2.80	136.70	9.00	6.20	.351
49	3.20	156.20	9.00	8.70	.256
64	3.40	165.70	9.02	7.40	.298
50	3.30	159.40	9.11	8.00	.279
70	3.00	144.50	9.14	7.47	.299
130	2.90	139.50	9.15	9.02	.251
9	2.90	138.50	9.22	12.60	.187
58	3.80	178.00	9.42	8.15	.283
56	3.50	159.60	9.70	8.00	.296
57	3.50	156.30	9.93	8.05	.301
91	3.30	142.00	10.34	10.01	.255
30	3.90	167.40	10.37	7.85	.320
81	4.10	157.00	11.77	10.42	.277
79	4.20	158.00	12.01	11.64	.255
25	5.00	186.50	12.12	8.00	.362
123	4.30	141.70	13.94	12.24	.278
122	6.50	147.00	21.70	17.10	.303

1 VARIATION OF CALCULATED PERCENT AROUND OVEN DRYPERCENT
STICKS SU73

ABS(OD(%)-CAL(%))	% OF MEASUREMENTS	#CAL(%)<OD(%)	#CAL(%)>OD(%)
0% TO 1%	34.09%	8.	7.
1% TO 2%	31.82%	4.	10.
2% TO 5%	34.09%	11.	4.
GREATER 5%	.00%	0.	0.

52.27% OF MEASUREMENTS WERE LOWER THAN OVEN DRY PERCENT

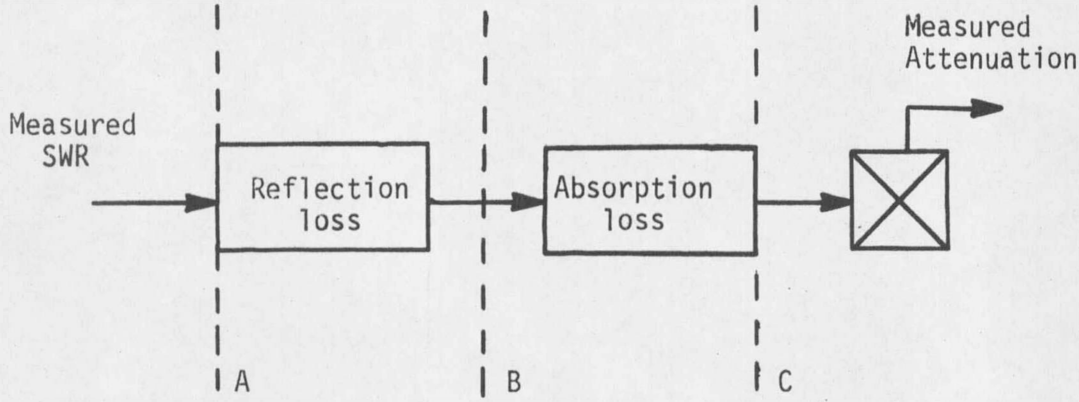
47.73% OF MEASUREMENTS WERE HIGHER THAN OVEN DRY PERCENT

MEAN VALUE OF K IS .244
STANDARD DEVIATION OF K IS .051

% OF SCATTER OF DATA FOR SU73
63.85% OF ALL POINTS ARE BELOW OVEN DRY PERCENT
36.15% OF ALL POINTS ARE ABOVE OVEN DRY PERCENT

Appendix VI

This section shows how the attenuation of an electromagnetic signal in water is calculated from the measured attenuation and SWR. The block diagram below represents the measured attenuation loss in terms of absorption and reflection loss.



The absorption loss would be the measured attenuation minus the reflection loss in db.

The reflection coefficient can be calculated from the SWR using the following equation.

$$|\rho| = \frac{SWR - 1}{SWR + 1}$$

Remembering that

$$|\rho|^2 = \frac{Pr}{Pi}$$

where

$$Pr = \text{Power Reflected at point A}$$

and

$$Pi = \text{Incident Power at point A}$$

the percent of power reflected is found. The percent of power transmitted through to point B is

$$\frac{Pt}{Pi} = 1 - |\rho|^2.$$

The reflection loss in db in then given by

$$A_r = 10 \log (1 - |\rho|^2).$$

The absorption loss between points B and C is

$$A_a = A_m - 10 \log (1 - |\rho|^2(\text{ (db)}$$

where A_m is the measured attenuation.

As an example suppose a total attenuation of 10 db and SWR of 4 is measured. The reflection coefficient is

$$|\rho| = \frac{4 - 1}{4 + 1} = .6$$

and

$$|\rho|^2 = .36 .$$

The reflection loss in db is then

$$A_r = 10 \log (1 - .36)$$

$$A_r = 1.94 \text{ db.}$$

The attenuation due to absorption in the water is then

$$A_a = A_m - A_r$$

$$A_a = 10 - 1.94 \text{ (db)}$$

$$A_a = 8.06 \text{ (db)} \quad .$$

This is the method used to calculate the absorption loss in water at various temperatures.

Appendix VII

This section presents the derivation of the equation used to calculate the attenuation of a microwave signal passed through a dielectric material such as water as a function of its dielectric constant (ε_r), loss tangent (tan δ), thickness (ℓ), and free space wavelength (λo) of the microwave signal.

Starting with Maxwell's equation

$$\nabla x \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

where

$$\vec{J} = \sigma \vec{E}$$

$$\vec{D} = \varepsilon \vec{E}$$

and assuming time variation of the form

$$e^{j\omega t}$$

then

$$\frac{\partial}{\partial t} = j\omega \ .$$

After making appropriate substitutions, the following equation is obtained

$$\nabla \times \vec{H} = (\sigma + j\omega\varepsilon)\vec{E} \ .$$

Letting

$$\varepsilon = \varepsilon_o \varepsilon_r$$

and again rearranging one gets

$$\nabla\times\vec{H} = \varepsilon_o\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_o}\right)j\omega\vec{E}$$

which can be written as

$$\nabla\times\vec{H} = \varepsilon_o\hat{\varepsilon}_r j\omega\vec{E}$$

where

$$\hat{\varepsilon}_r = \left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_o}\right) \tag{1}$$

which is equal to

$$\varepsilon' - j\varepsilon''$$

for a dielectric with finite losses.

Now one can solve for the propagation vector by deriving and solving the wave equation. By taking the curl of

$$\nabla\times\vec{H} = \varepsilon_o\hat{\varepsilon}_r j\omega\vec{E}$$

one gets

$$\nabla\times\nabla\times\vec{H} = \varepsilon_o\hat{\varepsilon}_r j\omega\nabla\times\vec{E}$$

where

$$\nabla\times\nabla\times\vec{H} = \nabla(\nabla\cdot\vec{H}) - \nabla^2\vec{H}$$

and since $\nabla\cdot\vec{B} = 0$

then $\nabla\cdot\vec{H} = 0$

and given
$$\nabla \times \vec{E} = \frac{-\partial \vec{B}}{\partial t}$$

$$\vec{B} = \mu \vec{H}$$

one gets
$$\nabla \times \vec{E} = -j\omega\mu \vec{H}$$

this gives the following equation

$$\nabla^2 \vec{H} + \omega^2 \mu \varepsilon_o \hat{\varepsilon}_r \vec{H} = 0$$

where
$$\mu = \mu_o \mu_r$$

Assuming $\mu_r = 1$ for most dielectric materials we finally get,

$$\nabla^2 \vec{H} + \omega^2 \mu_o \varepsilon_o \hat{\varepsilon}_r \vec{H} = 0$$

where the propagation vector is

$$k = \pm \sqrt{\omega^2 \mu_o \varepsilon_o \hat{\varepsilon}_r} \qquad (2)$$

and we take the negative term for our solution.

By assuming the following form of a traveling wave in the + z direction, one can express the equation of the traveling wave in complex form as

$$E = E_1 e^{-jkz}.$$

and

$$jk = \alpha + j\beta$$

where α is the attenuation constant and β the phase factor.

Substituting in for k from equation (2) and for $\hat{\varepsilon}_r$ from equation (1) one gets

$$\alpha + j\beta = j\omega\sqrt{\mu_o\varepsilon_o}\ \sqrt{\varepsilon_r - \frac{\sigma}{\omega\varepsilon_o}}$$

which can be rearranged to get

$$\alpha + j\beta = j\omega\sqrt{\mu_o\varepsilon_o}\ \sqrt{\varepsilon_r}\ \sqrt{1 - \frac{j\sigma}{\omega\varepsilon_o\varepsilon_r}} \quad . \qquad (3)$$

Remembering that

$$\hat{\varepsilon}_r = \varepsilon' = j\varepsilon''$$

and

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

Equation (3) can be rewritten as

$$\alpha + j\beta = j\omega\sqrt{\mu_o\varepsilon_o}\ \sqrt{\varepsilon_r}\ \sqrt{1 - j\tan\delta} \quad .$$

By applying the binomial expansion to the last right hand term and keeping the first two terms (since $\tan\delta << 1$) one gets

$$\alpha + j\beta \simeq j\omega\sqrt{\mu_o\varepsilon_o}\ \sqrt{\varepsilon_r}\ \left(1 - j\frac{\tan\delta}{2}\right) .$$

Now equating real parts one gets the attenuation constant

$$\alpha = \omega \sqrt{\mu_o \varepsilon_o} \quad \sqrt{\varepsilon_r} \quad \frac{\tan \delta}{2}$$

where

$$\omega = 2\pi f$$

$$\sqrt{\mu_o \varepsilon_o} = \frac{1}{C}$$

$$\frac{f}{C} = \lambda_o \quad .$$

This can be substituted into the above equation to give the following:

$$\alpha = \frac{\pi \quad \sqrt{\varepsilon_r}}{\lambda_o} \tan \delta$$

We now have a propagation wave in + z direction in terms of attenuation constant given as

$$E = D_1 e^{-\alpha z}$$

Since the attenuation is desired as a function of distance into the dielectric layer (in db), the following equation is used:

$$\text{Attenuation} = 20 \log \frac{E_2}{E_1} \text{ (db)}$$

where E_2 is signal at $z = \ell$ and E_1 is equal to signal at $z = 0$.

$$A = 20 \log \frac{E_1 e^{-\alpha\ell}}{E_1}$$

$$A = 20 \log e^{-\alpha\ell}$$

$$|A| = 20 \alpha\ell \log e$$

Remembering that

$$\log e = .4343$$

the attenuation is

$$A = 8.686 \alpha\ell$$

which after substituting in α gives the final equation.

$$A = 8.686 \frac{\pi\ell}{\lambda_o} \sqrt{\varepsilon_r} \tan \delta \text{ (db)} .$$