A Direct Fuel Moisture Measuring Instrument: An Aid for Scheduling Prescribed Fires

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INTRODUCTION

IT has been known for some time that microwave absorption due to a molecular resonance in water offers a possible means of measuring moisture content in various materials. The maximum absorption point in the frequency spectrum due to water is about 22 GHz (22 x 10^9 cycles per second). However, most research and development of microwave moisture sensors has taken place in the 2 to 12 GHz range since equipment is easily available and the absorption is still sufficient to give a clear indication of water in that frequency range.

The papers written in this area show the wide variety of materials to which microwave moisture sensing has been applied. Many articles that discuss this subject refer to a paper by A. Watson (1962) of the Building Research Station in Gaston, England as the first detailed effort to study the use of microwaves to sense moisture in industrial materials. In particular, Watson was interested in the moisture in building materials such as cement walls and cement blocks. A second paper by Watson (1963) presented further data on his work and data about microwave absorption by pure water, how frequency effects this absorption and how minerals and salts in the water effect microwave absorption. Several sets of data are presented showing test results on tobacco, wheat, foundry sand, and minced meat. It is interesting to note that all these data indicate a linear attenuation versus percent moisture relationship. Watson (1963) mentions briefly that sample packing and the direction in which the microwave beam is "shined" through a sample are important but does not pursue these points at any length. Neville Rance (1965) reported on his efforts to introduce microwave moisture sensing to British industry. He notes that in many cases it was difficult to calibrate his gear against the "standard" being used because of errors inherent in the "standard". Hall, Sproson, and Gary (1970) reported on their studies using microwave moisture measurement on coal, B. L. Dalton (1971) discussed applications of microwaves to industrial processes and a survey of moisture instrumentation was published in January of 1972 (Surv. Humid. Moist. Instrum., 1972). Busker (1968) studied microwave absorption in tobacco, textiles, ground wood, and various clays. Lowery and Kotak (1967) studied absorption in solid pieces of lumber. Husted and Shaw (1964) examined absorption in various building materials and Suresh, et. al. (1967) studied binding water in soils with microwaves. Microwave moisture sensing has even been used to test for water in pastries (Ince and Turner, 1965). Enough work has been done in this area of research to warrant at least five review papers (Surv. Humid, Moist. Instrum., 1972; Taylor, 1965; Summerhill, 1967; McLeod and March, 1970; McLeod, 1973). This paper discusses the results obtained from the first 2 years of a continuing research program designed to explore the uses of microwave as a forest and watershed management tool.

THEORY

As previously mentioned, the principle on which microwave sensing is based is that a natural resonance frequency in the rotation spectrum of the water molecule occurs at about 22 GHz (22×10^9 cycles per second). At this frequency (and frequencies close to it) microwave energy is strongly absorbed by water molecules present in a material. By measuring how much microwave energy is absorbed in a known amount of thickness of material, one can, by calibration or calculation, ascertain the percent of water in the sample. The process sounds quite simple until some of the problems are pointed out. A few of these problems are:

1. The packing of the sample in the test cell.
2. Obtaining uniform filling of the test cell.
3. Lack of uniformity in the sample material.
4. Removing the sample from its natural site.
5. Sample drying during testing.
6. Obtaining a small, lightweight source of microwave energy.
7. Designing a small, lightweight piece of test gear to do the necessary microwave measurements in the field.

Of these problems, the first is the most serious. The microwave beam loses energy in proportion to the total amount of water in the path of the beam. If twice as much sample of a given percent moisture is packed into the beam area, the signal loss will double even though the percent moisture of the sample is constant. The accuracy of the attenuation measurement (and hence the accuracy of the meter) then depends on the operator's judgment i.e., on how much he packs the material into the test cell. To avoid this problem a calculation process was developed.

Consider the relationship used to calculate the "dry weight" percent moisture content of a sample of material.

$$P = \frac{H\,(100)}{W-H} \qquad (1)$$

where

P=percent moisture
H=the water in the sample in grams
W=wet weight of the sample.

From Watson's work (1963) a value of attenuation for pure water between the horn antennas was taken as 40 db/centimeter, thus for the 5.08 cm. width of the sample cell a total of 203 db. If less water is present, the attenuation decreases accordingly and hence by measuring the attenuation one can calculate how much water was present in the sample in the volume irradiated by the microwave beam. As a starting point it was assumed that all the energy stayed in the volume outlined by the horn antennas. If the total weight of material in the box is known, one can write (using 1 cm^3 of water weighs 1 gram)

$$H = V_h \frac{X \text{ grams}}{203 \text{ db}} \qquad (2)$$

$$W = \frac{V_h}{V_B} W_T \qquad (3)$$

where
X = measured attenuation in db
W_T = total weight of the sample material filling the box in grams
V_B = volume of the test box in $(cm)^3$
V_h = volume outlined by the horn antennas.

Now equation (1) can be written as

$$P = \frac{V_h (X/203)}{\frac{V_h}{V_B}(W_T) - V_h (X/203)} \qquad (4)$$

By factoring out the term

$$V_h (X/203)$$

from numerator and denominator one is left with

$$P = \frac{1}{\frac{W_T}{V_B}\left(\frac{203}{X}\right) - 1} \qquad (5)$$

Note now that the term W_T/V_B is the density of the sample material in the box and also note that the volume "seen" by the horns cancelled out. The expression can be rearranged very slightly to read

$$P = \frac{1}{\frac{a\,W_T}{X} - 1} \qquad (6)$$

where

$$a = \frac{203}{V_B} = \text{a constant.}$$

Now the only stipulation to the operator is that the test cell be full. If he just fills the box, the attenuation term (X) is a given value depending on moisture content and the material weight. If the operator packs the box just as full as he can, X goes up but so does W_T and this ratio remains constant since the box volume remains constant. For the same box used in the first field tests the constant (a) in (6) was calculated to be 0.173. The field trials showed the data from the meter and data from the oven drying standard agreed best for a six inch square test cell when

a=0.173 for 0—.25″ sticks
a=0.156 for duff
a=0.19 for litter.

There is also an alternate way to avoid the sample packing problem that is useful in some applications. This method uses the material whose moisture is to be measured in its natural state. That is, the horn antennas that are used to launch and receive the microwave signal are placed so the undisturbed material is between the horns. The horns are fixed semi-permanently and the moisture content (proportional to the signal loss between the horns) is monitored as a function of time. There is no packing problem since the sample material is never placed in a test cell. The calibration procedure for this method requires measuring a sample of the material and fixing its moisture content via an independent means (i e. oven drying or the other type of microwave moisture meter) at the start of the monitoring period. Then if the attenuation versus moisture content curve is known, the microwave moisture monitor can monitor the percent moisture content of the sample as a function of time. The results of field testing such a unit are discussed in a later section.

APPLICATION AND RESULTS

From the literature search conducted during the first part of this work, it was obvious that almost any dielectric material that was a poor conductor could be measured for moisture content using microwaves. Microwaves were and are being used to sense moisture in such diverse materials as tobacco, soap chips, small grains, meat, paper, rug fiber and on and on. The concentration for this study was to be in measuring materials commonly found in forested watershed regions and specifically (at first) in the litter and duff layers on the forest floor. One of the reasons for picking these specific materials was to work in cooperation with the Northern Forest Fire Laboratory at Missoula and the University of Montana's Forestry Department on a special project involving prescribed burning in standing green forests. Other reasons for picking the litter and duff were that both of these materials are fairly uniform in composition; they typically range from 5 percent moisture content during the dry season to 150 percent or more moisture content (using percent as defined in equation 1) during the early spring or late fall months, and these materials are easy to obtain in large quantities from a variety of areas. These materials have been shown in a number of other studies to be quite important in reforestation, water runoff, and the ability of fire to start and/or advance.

As the work progressed it was decided to include other materials in the work primarily because the prescribed burning project had need of the information. Microwave moisture data has been obtained on 0 to ¼ inch dead sticks in the burn areas and also on ¼ to ½ inch dead sticks. Work has also been done on monitoring moisture on a real time basis in the upper duff layer with some very interesting results.

THE MICROWAVE MOISTURE MEASURING METER

As outlined above, the basic measurement is one of measuring the loss of microwave power as the microwave signal passes through the sample being measured. The first design criteria was to pick a frequency at which the absorption would be high enough to obtain significant loss in a reasonable sample thickness but also low enough to have the necessary gear available and fairly cheap. The frequency of 10.525 GHz was chosen because small, cheap sources of microwave energy were becoming available at this frequency (Gunn oscillators) and a 2 inch sample thickness was sufficient to get good moisture readings on 5 percent to over 100 percent moisture material. The Gunn source was especially attractive in that the power supply for this source could be a 12 volt battery and hence field operation of the gear was assured. The rest of the necessary gear is shown in Figure 1 in block diagram form. Figures 2 through 5 show various photographs of the actual meter.

The measurement process is one of setting a given level on the display meter with the precision attenuator set on 30 db with the test cell empty. The cell is then filled with the material to be measured, weighed and inserted between the horns and the precision attenuator reset so as to regain the previous level on the display meter. The difference in the two precision attenuator settings is the microwave signal loss expressed in decibels.

The results obtained with the microwave moisture meter were obtained primarily during June through September of 1972 and 1973 at the Lubrecht State Forest near Missoula, Montana. The meter was used extensively to obtain basic data and also to provide fuel moisture data for the prescribed burns. The graphs in Figures 6, 7 and 8 summarize a comparison of the data taken with the meter and data

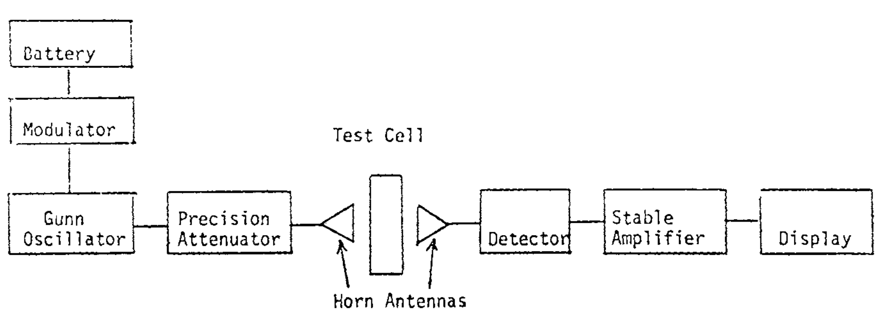


Fig. 1. Microwave moisture meter.

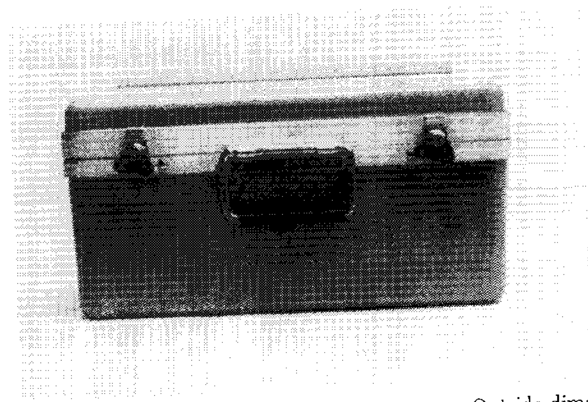


Fig. 2. Outside front view of the microwave moisture meter. Outside dimensions: 17 inches by 10.5 inches by 8.5 inches. Weight: 26 pounds.

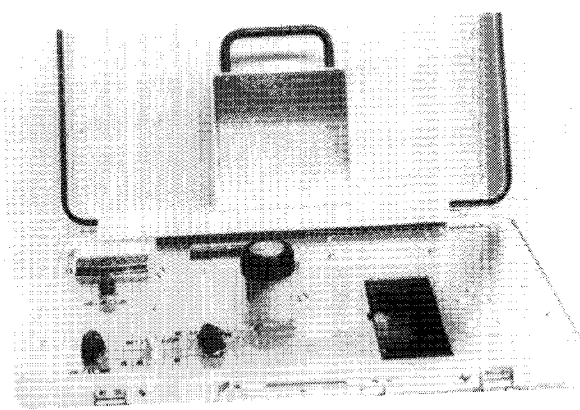


Fig. 3. Top view, cover open of the microwave moisture meter showing test cell and meter controls.

taken on the same material using oven drying. The data are separated to show the comparison for litter, sticks and duff. The standard was taken to be oven drying. For the data shown, a sample large enough for the microwave moisture meter (about 150-200 grams)

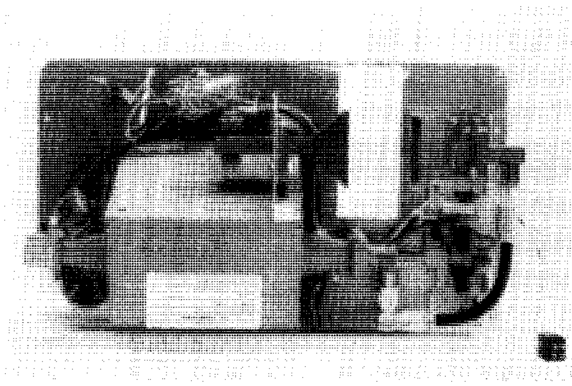


Fig. 4. Inside view of the microwave moisture meter showing electronics and the microwave gear.

Fig. 5. Inside view of microwave moisture meter showing the two 6-volt rechargeable batteries.

was taken from a large container of the material under test. The moisture content was measured with the meter and then an oven drying sample (about 15-30 grams) was taken from the central portion of the moisture meter test cell, weighed, and placed in an oven for

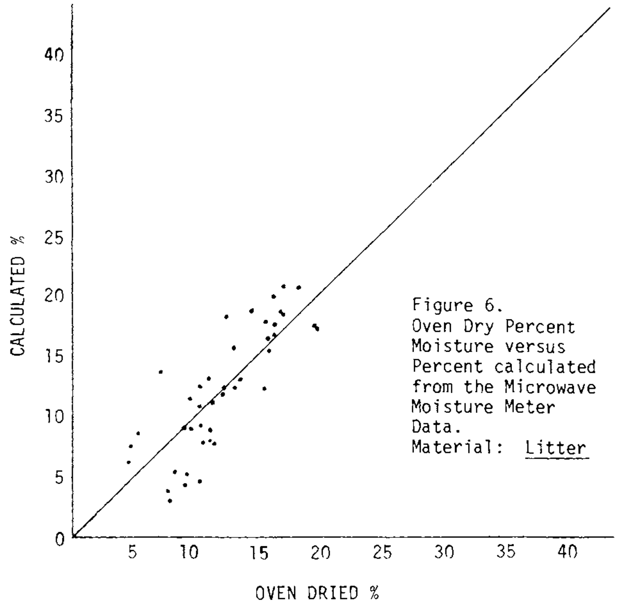


Figure 6.
Oven Dry Percent Moisture versus Percent calculated from the Microwave Moisture Meter Data.
Material: Litter

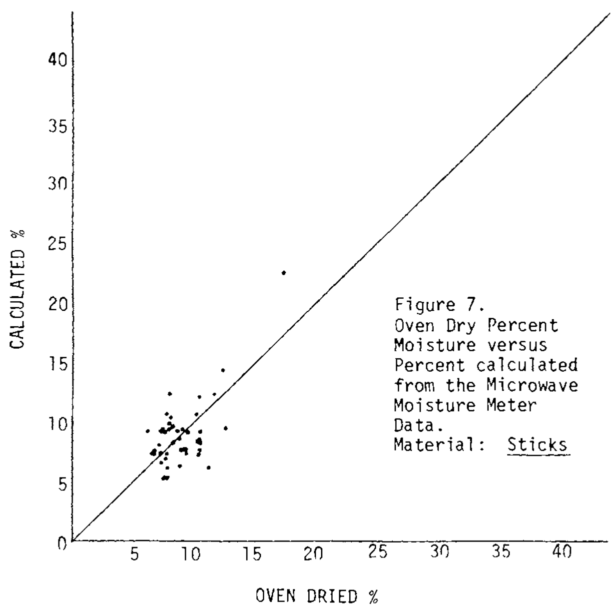


Figure 7.
Oven Dry Percent Moisture versus Percent calculated from the Microwave Moisture Meter Data.
Material: Sticks

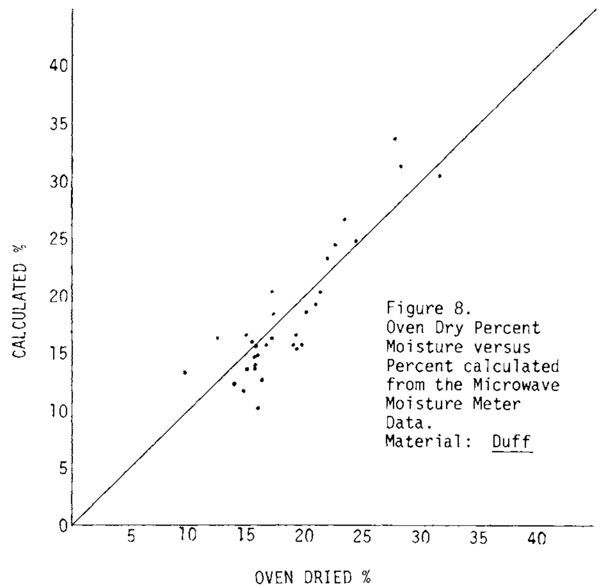


Figure 8.
Oven Dry Percent
Moisture versus
Percent calculated
from the Microwave
Moisture Meter
Data.
Material: Duff

15 hours at a temperature of 95°C. This process was repeated from four to six times for the material with the unknown moisture content.

The data were plotted to show a direct comparison of the moisture meter data and oven drying data. If the two methods gave the same percent moisture, the point would fall on the solid "exact agreement" line. The value of the constant (a) in eq. (6) was adjusted from calculated value of 0.248 for a 5 inch square test cell after studying the first data points for each type of material. It was then held constant for the balance of the data. In all three cases, the data shows some scatter. There are two primary reasons for this. One is temperature variation. It is known that microwave energy absorption by the water in the material is a function of temperature. Since much of the material used in these tests came directly from the forest floor, some temperature variation error could be present in the data. A second reason for the scatter is that the oven drying data also could be in error. It was noted in studying the entire set of oven drying data that some erratic points were present. This might indicate that the oven drying procedure used did not always give the exact moisture content of the material under test. The agreement between the two methods seems to be about ±3% (i.e. all points within about ±3% from the exact agreement line). Further work is under way to study both the temperature variation and the oven drying procedure.

THE MICROWAVE MONITORING METER

The microwave moisture monitor consists, in its most simple form, of a source of microwave energy (battery operated), a pair of horn antennas, a detector and a recorder. A line diagram of the unit that was placed in the field during September and October 1973 is shown in Figure 9. The unit was packaged in a lightweight fiberglass case shown in Figure 10 and powered by a 12 volt car battery that was placed in a separate, vented battery case. The monitor was designed to record both the microwave power to the transmit horn as well as the received power. Thus, any source power fluctuations could be substracted out of the resulting data. The unit monitored and re-

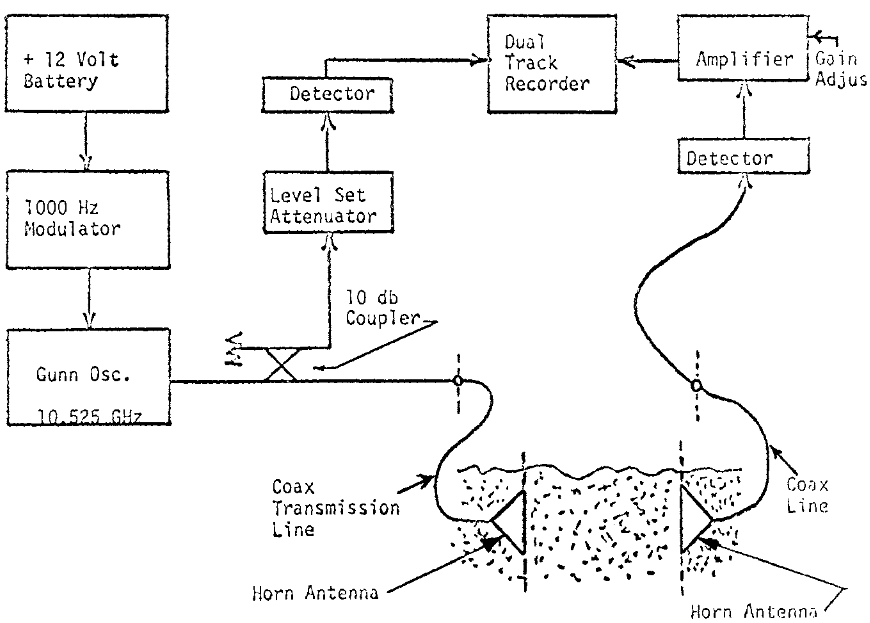


Fig. 9. Fixed moisture monitor.

corded the level of microwave energy being transmitted through the litter layer between the horns.

The unit was installed about 50 feet from a weather station set up near some experimental burning plots at the Lubrecht State Forest, Greenough, Montana. Since the unit was installed in September near the end of a very dry summer, it was assumed that the wetting/ drying cycle of the litter layer being monitored was probably following the local humidity. Data from the microwave monitor recorder tape and from the weather station humidity tape are shown in Figure 11a through 11e. The attenuation data was obtained with the horns set below the surface of the upper litter layer as shown in Figure 9 and with about 14 inches of litter between the horns. Note how fast the litter seems to respond to rainfall (see Thursday Figure 11b at 16-1700 hours and Friday Figure 11c around 1900 hours) and how the litter seems to be still wetting after the humidity has peaked and headed lower (for instance Thursday Figure 11b 0800 to 1000 hours).

These results, while preliminary, do seem to indicate a rapid response of the litter layer to external moisture stimuli. The time lags

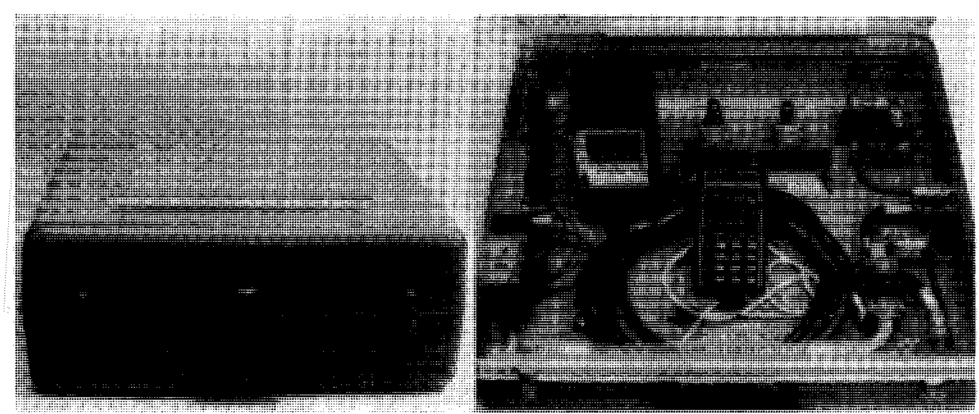
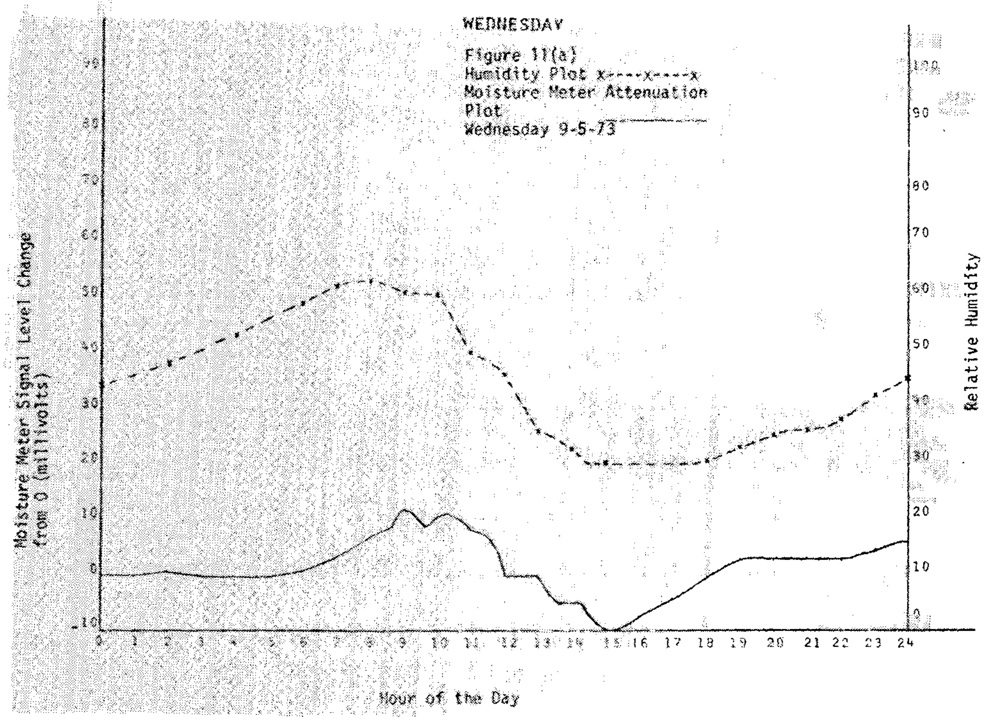
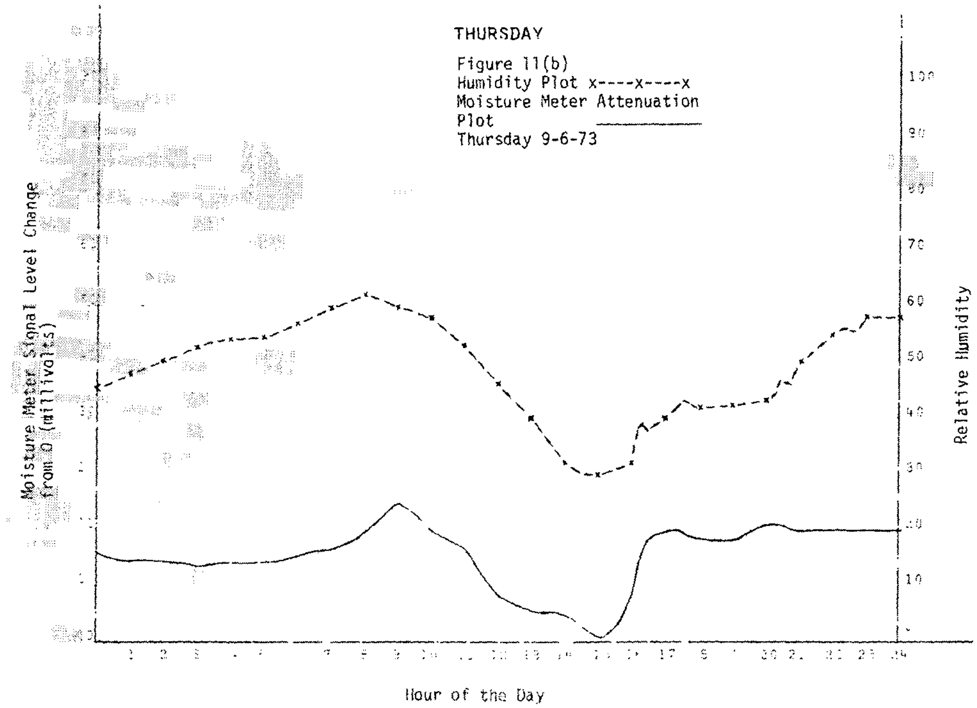
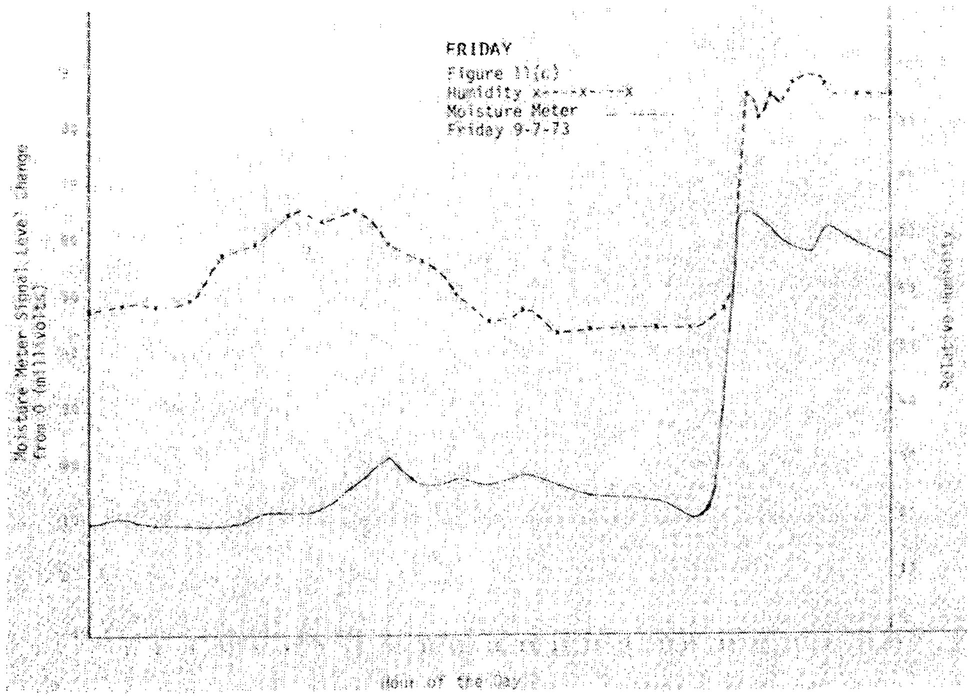
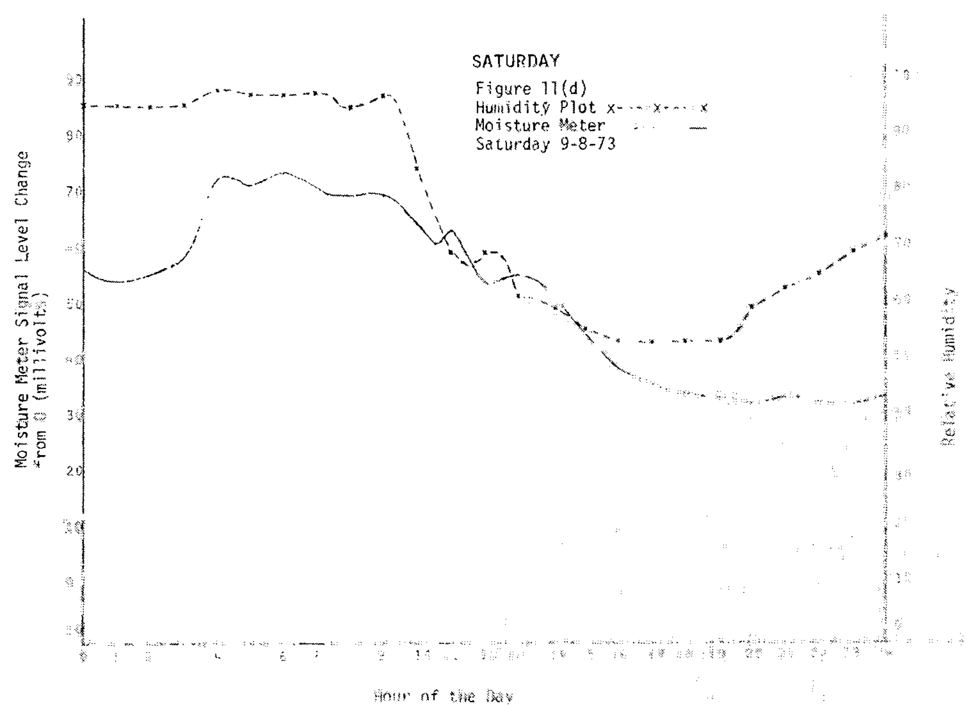


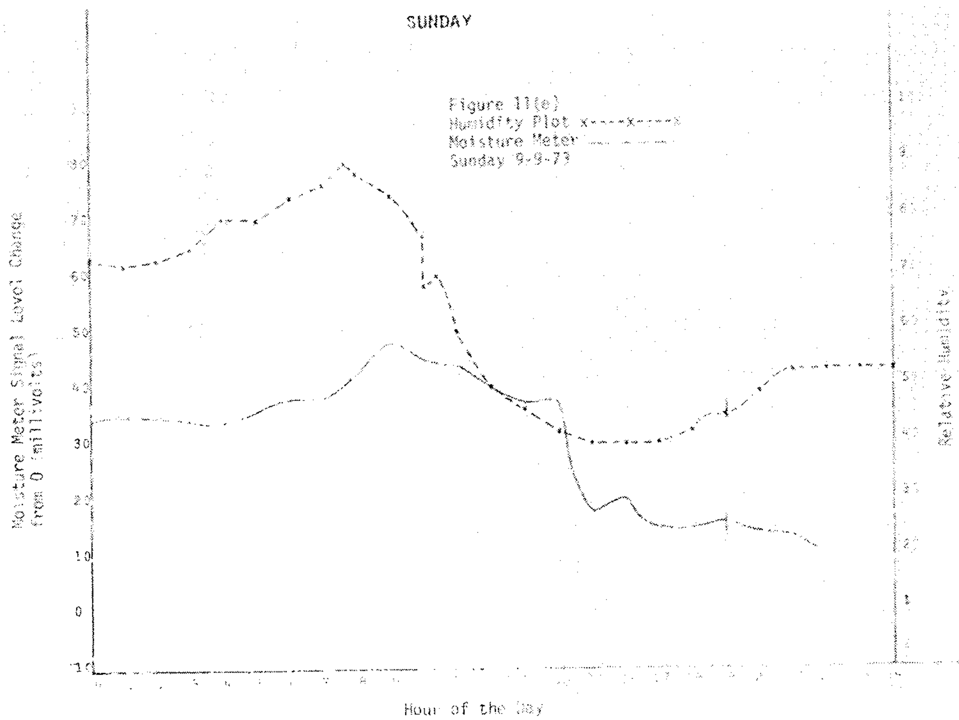
Fig. 10. a) Left: Outside view of the microwave moisture monitoring meter. Dimensions: 21 inches by 20 inches by 9 inches. b) Right: Top view of the monitor with the lid open showing the electronics, recorder, and microwave gear packed for moving the monitor.


WEDNESDAY
Figure 11(a)
Humidity Plot x----x----x
Moisture Meter Attenuation Plot
Wednesday 9-5-73
Moisture Meter Signal Level Change from 0 (millivolts)
Relative Humidity
Hour of the Day


THURSDAY
Figure 11(b)
Humidity Plot x----x----x
Moisture Meter Attenuation Plot
Thursday 9-6-73
Moisture Meter Signal Level Change from 0 (millivolts)
Relative Humidity
Hour of the Day


FRIDAY
Figure 11(c)
Humidity x---x---x
Moisture Meter
Friday 9-7-73
Moisture Meter Signal Level Change from 0 (millivolts)
Relative Humidity
Hour of the Day


SATURDAY
Figure 11(d)
Humidity Plot x---x---x
Moisture Meter
Saturday 9-8-73
Moisture Meter Signal Level Change from 0 (millivolts)
Relative Humidity
Hour of the Day



indicated in Figure 11 also agree with very recent and as yet unpublished theoretical work done by Mr. Mike Fosberg of the Rocky Mountain Forest and Range Experiment Station in Ft. Collins, Colorado. A great deal more effort is planned for the microwave moisture monitoring meter to perfect it for field use and to pursue the questions raised as to the actual time lag of forest fuels in their natural settings.

CONCLUSIONS

The results of the research to date have demonstrated the feasibility and usefulness of microwave moisture sensing as a valuable tool in watershed management. Specifically, the portable moisture meter allows rapid, on site measurement of fuel moisture content just before and even during prescribed burns. The accuracy of the meter appears to be at least with ±3 percent of the oven drying standard and there are indications that this is not yet the ultimate accuracy. The fixed monitor has yielded some very interesting data on the actual in situ time lag of litter which, if confirmed, could have a significant impact not only on prescribed burn procedures but also fire danger rating calculations and perhaps fire supression techniques.

Both types of gear are in the development stage at this point but both are being used in actual field operations. Two of the portable moisture meters are being used by the Forest Service. One is in Montana, another will shortly be in Seattle, Washington area. The data from these two units will be available in about a year which will further definitize the meter's accuracy.

The ultimate impact of microwaves as a tool for forest and watershed management is not yet established. The two types of moisture measuring gear discussed in this paper show that new and useful information can be obtained by using microwave techniques in the forest. A number of other possible applications could be listed that include not only moisture sensing but also using microwaves as a diagnostic tool on both controlled burns and wildfires. Microwave gear specifically designed for forest application could become a major research tool and ultimately have an important impact on forest and watershed management.

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