Microwave sterilization of weed seeds
by Stanley Mark Gliko

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

Abstract:
The subject of this thesis is to determine the amount of microwave energy needed to kill cereal grains such as spring wheat under harvest conditions. In order to determine the behavior of the cereal grains under microwave exposure the dielectric constant, loss tangent, attenuation constant and reflection coefficient were measured as functions of moisture content. From the experimental data, it was determined that the dielectric constant, loss tangent, attenuation constant and reflection coefficient were all functions of moisture content. Once this information was obtained, the seeds were exposed to a high power pulse microwave system and to a continuous wave cavity oven. From the high power pulse tests, no kill point was found for spring wheat. From the microwave oven tests, a kill point was determined as a function of moisture content for spring wheat.

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Date 14 Jan. 1982

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A thesis submitted in partial fulfillment
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Approved:

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ABSTRACT

The subject of this thesis is to determine the amount of microwave energy needed to kill cereal grains such as spring wheat under harvest conditions. In order to determine the behavior of the cereal grains under microwave exposure the dielectric constant, loss tangent, attenuation constant and reflection coefficient were measured as functions of moisture content. From the experimental data, it was determined that the dielectric constant, loss tangent, attenuation constant and reflection coefficient were all functions of moisture content. Once this information was obtained, the seeds were exposed to a high power pulse microwave system and to a continuous wave cavity oven. From the high power pulse tests, no kill point was found for spring wheat. From the microwave oven tests, a kill point was determined as a function of moisture content for spring wheat.

CHAPTER I

INTRODUCTION

Because "saline seep" is becoming an increasing problem in the farm lands throughout the world, several methods of alternate farm practices are being adapted to minimize the saline seep problem. One such practice is to eliminate summer fallowing (unseeded plowed land). With this change, cereal grains which have fallen off the tail board of a combine will grow in the unplanted area. This volunteer recropped grain is undesirable and must be eliminated in order to successfully stop summer fallowing. Due to the impracticality of removing the seeds from the straw which have fallen from the tailboard of the combine, an alternate method which would expose the seeds and straw to high energy microwaves in order to kill the seeds was proposed by Dr. Jim Sims (1). The purpose of this thesis is to investigate Dr. Sims' theory by determining the necessary microwave parameters of various cereal grains and the amount of energy needed to kill the seeds. This project was divided into two major areas:

* Low Power Measurements
* High Power Measurements

In the Low Power Measurements, the amount of energy reflected and absorbed as a function of moisture content was determined for wheat, oats and barley. In addition, the relative dielectric constant and loss tangent was determined for wheat, oats and barley as a function of moisture content.

In the High Power Measurements, a pulsed system and a continuous wave system were used to find a kill point for the seeds. In the pulsed system the duty cycle, power, pulse width and time of exposure were varied to find the optimum kill point as a function of grain moisture content. In the continuous wave system, a microwave oven was used to find the kill point as a function of exposure time and percent moisture. By these tests, the amount of energy needed to kill the seeds was determined.

CHAPTER II

LOW POWER MEASUREMENTS

In determining the microwave properties of the seeds, it is desirable to take into account the moisture content of the seeds. This is necessary because the high loss and highly polarizable nature of water (2) causes attenuation and concentration of the electromagnetic fields. Due to this consideration, the low power tests were completed as functions of moisture content of the seeds.

In order to maintain a standard in determination of moisture content throughout the following experiments, drying tests were performed on spring wheat (Levi type). The procedure for the tests was as follows:

(1) Measure the weight of the container

(2) Measure the weight of the seeds and the container before drying (wet weight)

(3) Put $CaSO_4$ Anhydrous (a desiccant) in the oven to absorb the moisture.

(4) Put seeds into the oven and maintain temperature between 100-110 °C for several hours.

(5) Measure the weight of the seeds and container at different time intervals.

When these procedures were completed, the following equation was used to calculate the percent moisture content:

$$\%\text{moisture} = \frac{(\text{wet weight of the seeds})-(\text{dry weight of the seeds})}{\text{wet weight of the seeds}}\times 100$$

Figures 1 and 2 on pages 5 and 6 shows the drying process for two different samples of spring wheat. As can be observed from the two figures, very little drying takes place after the twenty-fourth hour. With this in mind, the following criterion to determine percent moisture will be used:

(1) Dry seeds at 100-110^{0}C

(2) Dry seeds for 24 hours

Because percent moisture of storage grain is usually less than 10%, water must be added to some of the test seeds in order to obtain energy reflected and energy absorbed versus percent moisture characteristics that are desired. In order to do this, the following standard was used to increase the percent moisture for each data point. One gram of H_2O was added to 30 grams of seeds at storage value for each data point. That is to say, one data point would have one gram of H_2O per 30 grams of seeds; the next data point would have 2 grams of H_2O per 30 grams of seeds and etc. Once the water was added to the seeds, the seeds would be placed into a sealed container and allowed to absorb the water. Because it was observed that after the twenty-fourth hour the seeds above 30% moisture would begin to germinate, the seeds would remain in the sealed containers at most twenty-four hours before any tests were performed on them. This procedure would allow maximum time for the seeds to absorb the water without introducing the extra factor

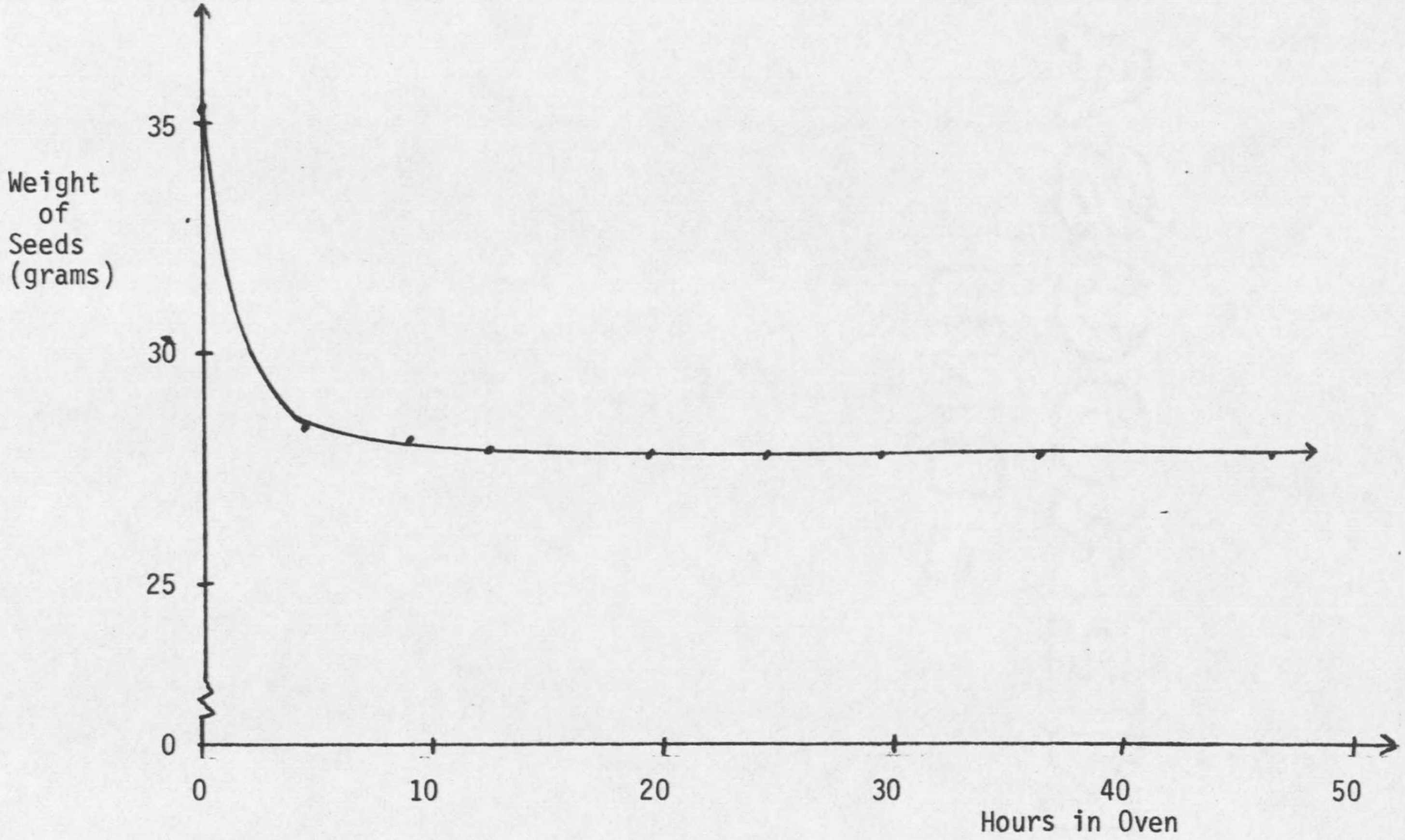

Figure 1 Drying Curve for Spring Wheat

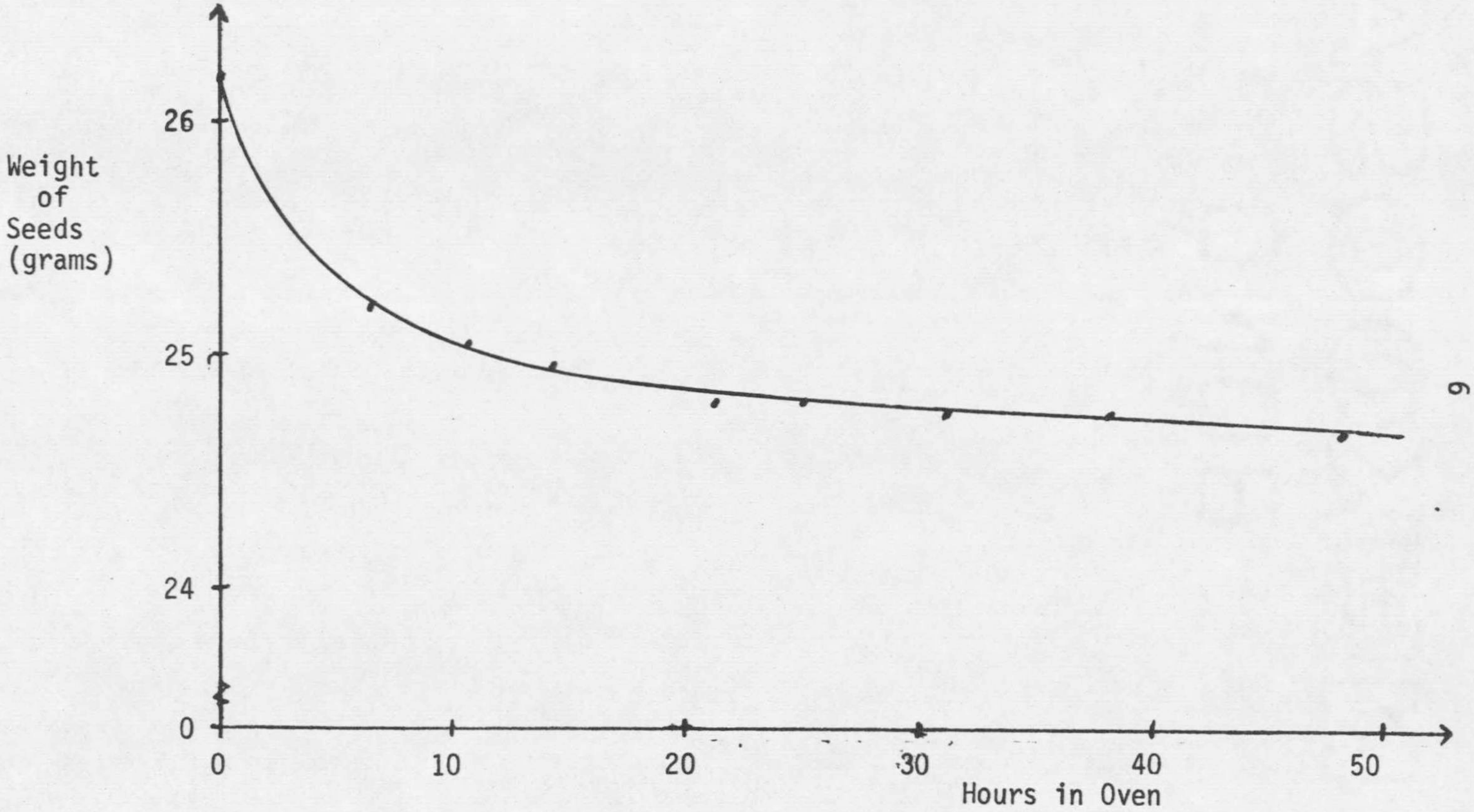

Figure 2 Drying Curve for Spring Wheat

of germinated seeds in the energy reflected and energy absorbed tests. Figure 3 below shows the results of adding water to increase the percent moisture for each data point. As can be observed, the seeds were becoming saturated with the water above the 30% moisture point. Above this point, the seeds would not absorb any additional water and

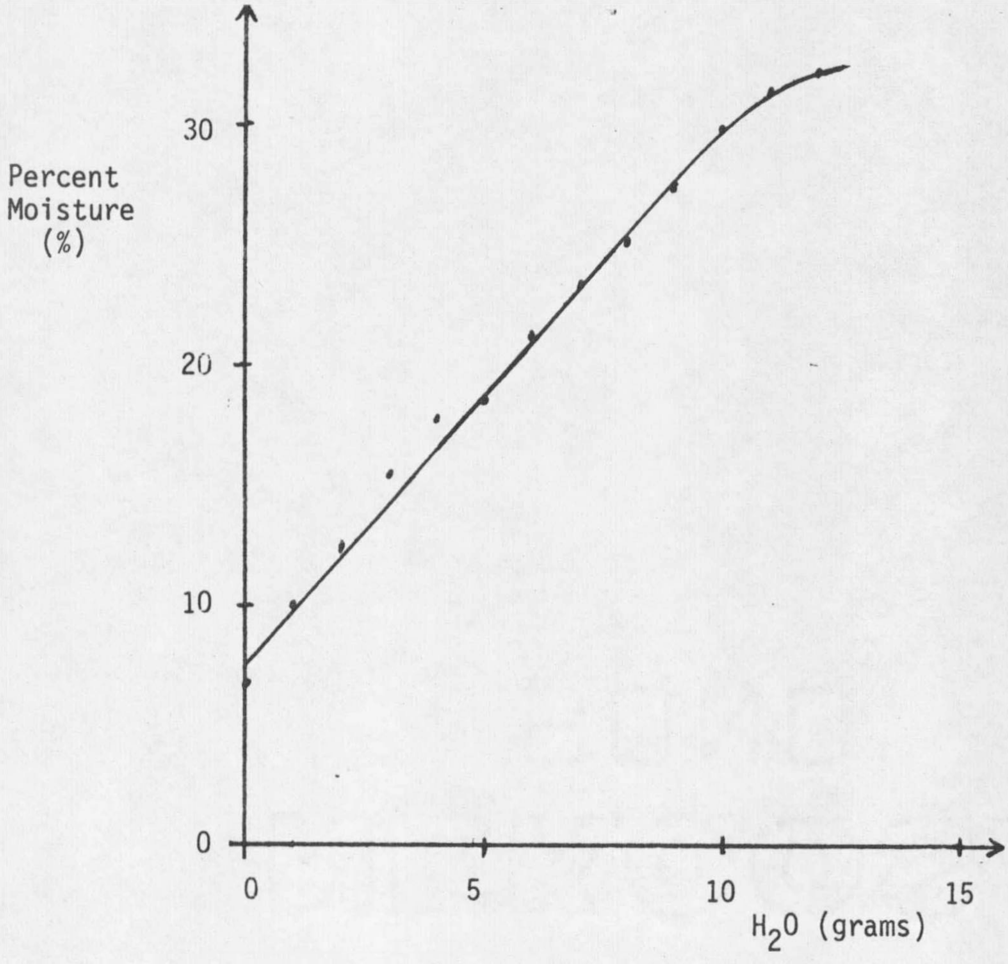

Figure 3 Percent Moisture versus Water Added to Seeds

consequently surface water became noticeable on the seeds. Since surface water (unbounded water) behaves differently than the water inside the seeds (bounded water) due to the different boundary conditions, then the 30% moisture point will be the upper limit in the succeeding tests.

After establishing the procedures to increase and to measure percent moisture of the seeds, the tests to determine experimentally the attenuation (energy absorbed) of the seeds were undertaken. In measuring the attenuation, the substitution method was used (3). See Appendix A for the block diagram of the equipment setup and the list of procedures. By use of the substitution method, the following tests were done.

Depending on various factors, different amounts of seeds will be dispersed from the rear of the combine during harvest. With this in mind, a test was run to determine the relationship between depth of the seed sample versus the amount of energy absorbed. See Figure 4 on page 9 for the results. As can be observed from Figure 4, a linear relationship exists between energy absorbed and depth of sample.

Because the physical orientation of the seeds affects the amount of energy absorbed due to the different boundary conditions the electromagnetic wave encounters, the following test was run to determine if random orientation would affect the amount of energy absorbed. This must be considered because the seeds on the sieves in the combine

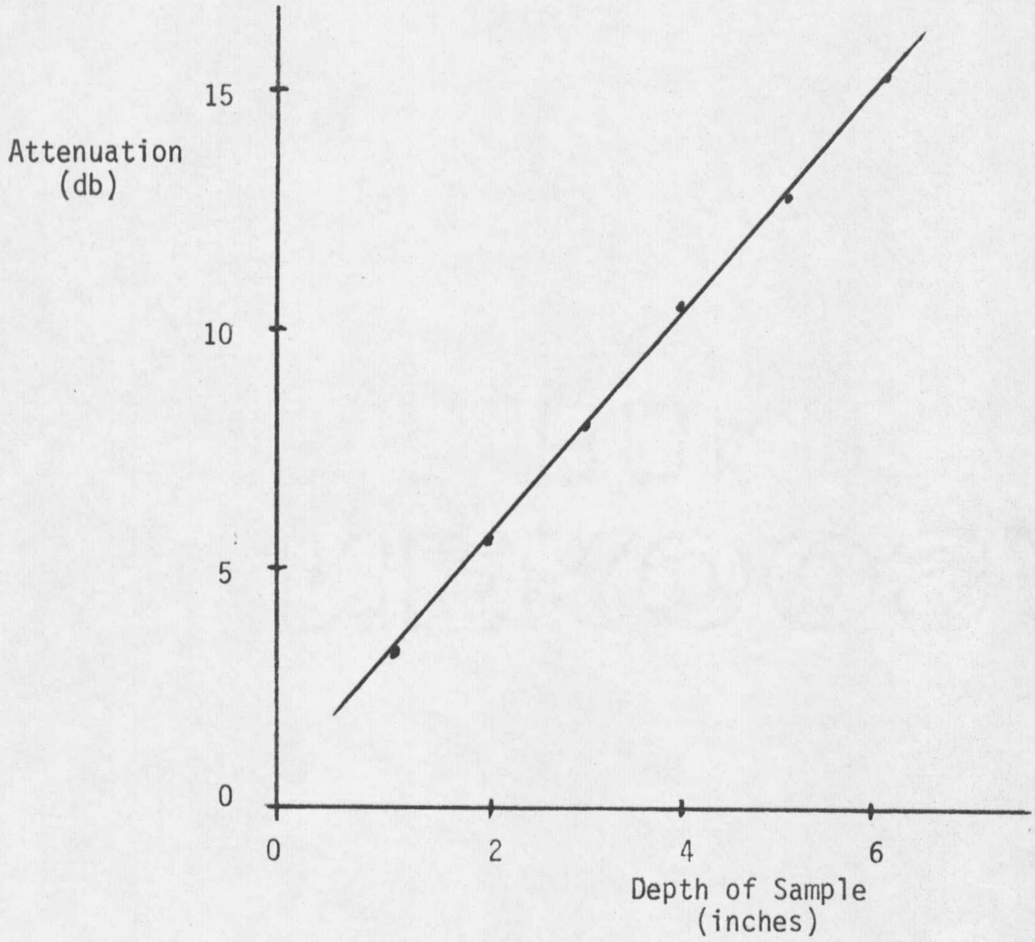

Figure 4 Attenuation versus Depth of Spring Wheat

will be in a random pattern (at least in two axis) due to the conveyor belt action of the sieves. By using the same seeds with three separate random orientations, an attenuation test was run for spring wheat. Table 1 on the next page shows the results. As can be observed from Table 1, the random orientation of the seeds did not

% moisture	Attenuation in db Test 1	 Test 2	 Test 3	Maximum Variation
10.7	5.0	5.0	5.0	0.0
13.4	6.5	6.3	6.3	0.2
16.4	8.7	8.3	8.3	0.4
18.6	11.2	11.5	11.4	0.3
19.2	11.3	11.2	11.6	0.4
22.2	13.0	12.3	12.8	0.7
23.7	14.0	14.0	13.6	0.4
25.6	15.7	15.0	15.1	0.3
28.1	19.6	19.0	19.0	0.6
30.3	21.3	19.4	18.3	3.0

Table 1 Maximum Variation of Attenuation

affect the results of the test except at the 30% moisture level. Because the main focus of these experiments is between 10-12% moisture content (harvest conditions) (4), random orientation will be eliminated from consideration as a factor in the following tests.

The energy absorbed versus percent moisture was obtained for spring wheat, oats and barley at a frequency of 8.682 GHz. The substitution method was used to measure the attenuation and the following relationship was used to convert the measured decibel change to the attenuation constant in nepers per meter. See Appendix B for the derivation of the following equation.

$$\alpha = \frac{\Delta \text{db}}{8.686 \times l}$$

where l = length of sample in meters

After the energy absorbed versus percent moisture tests were completed, a statistical analysis of the data followed. By use of the least squares method (5), an exponential function was fitted to the data points. These results are shown on Figures 5, 6, 7 and 8 on the following four pages. Two different tests (runs) were completed on spring wheat, and as can be observed on Figures 7 and 8, the two curves came out well within experimental error of one another. These results show that the amount of energy absorbed by the seeds is a non-linear function of moisture. Table 2 shows the exponential functions from the least squares curve fit of the data points for spring wheat, oats and barley. Also in the table are the associated correlation coefficients.

Seed Type	Mathematical Function	Correlation Coefficient
Spring Wheat (run 1)	$y = 6.20e^{.0756x}$	.99
Barley	$y = 4.99e^{.0849x}$	.98
Spring Wheat (run 2)	$y = 6.14e^{.0784x}$	.98
Oats	$y = 5.24e^{.0726x}$	.97

where: $y = \alpha_{TE_{10}}$ in nepers/meter

x = percent moisture

Table 2 Mathematical Attenuation Functions

From Figures 5, 6, 7 and 8 and Table 2 it is interesting but not surprising to note that the graphs and the mathematical functions for

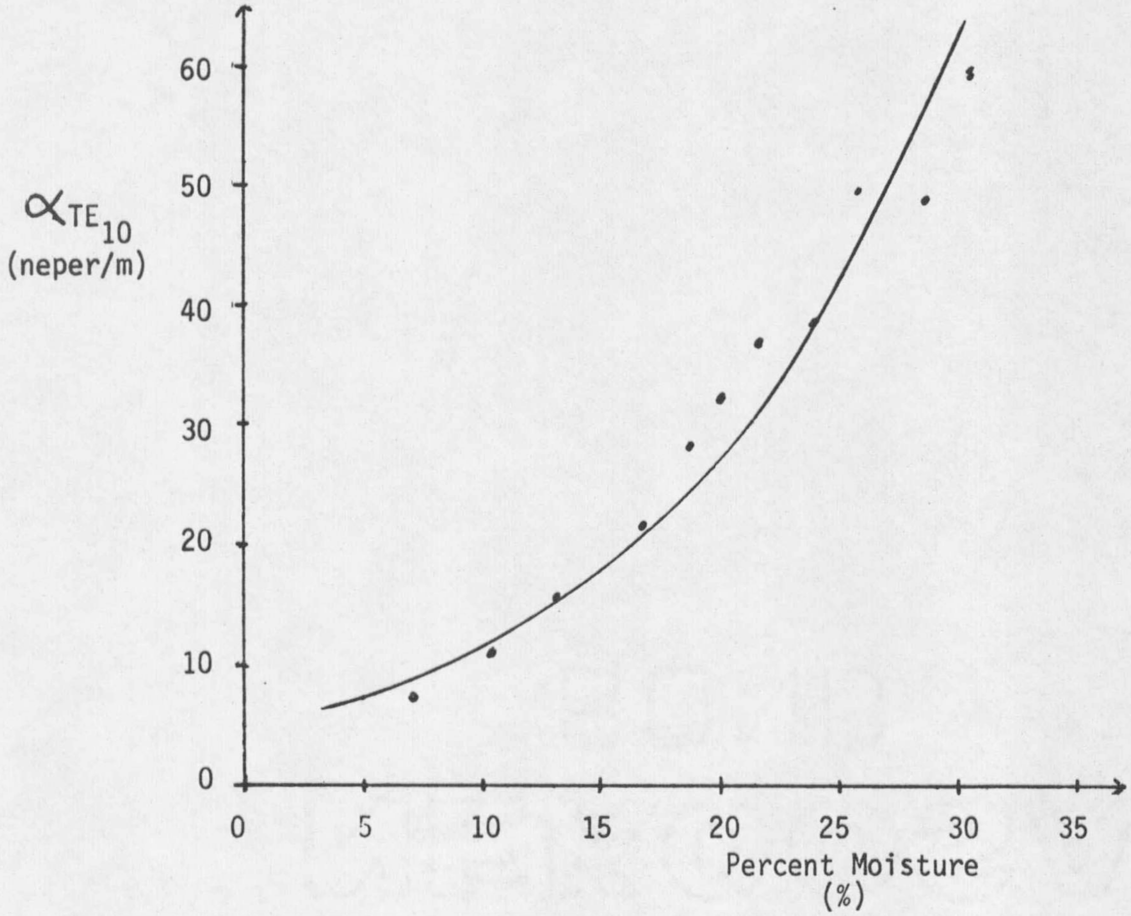

Figure 5 Attenuation versus Percent Moisture for Barley

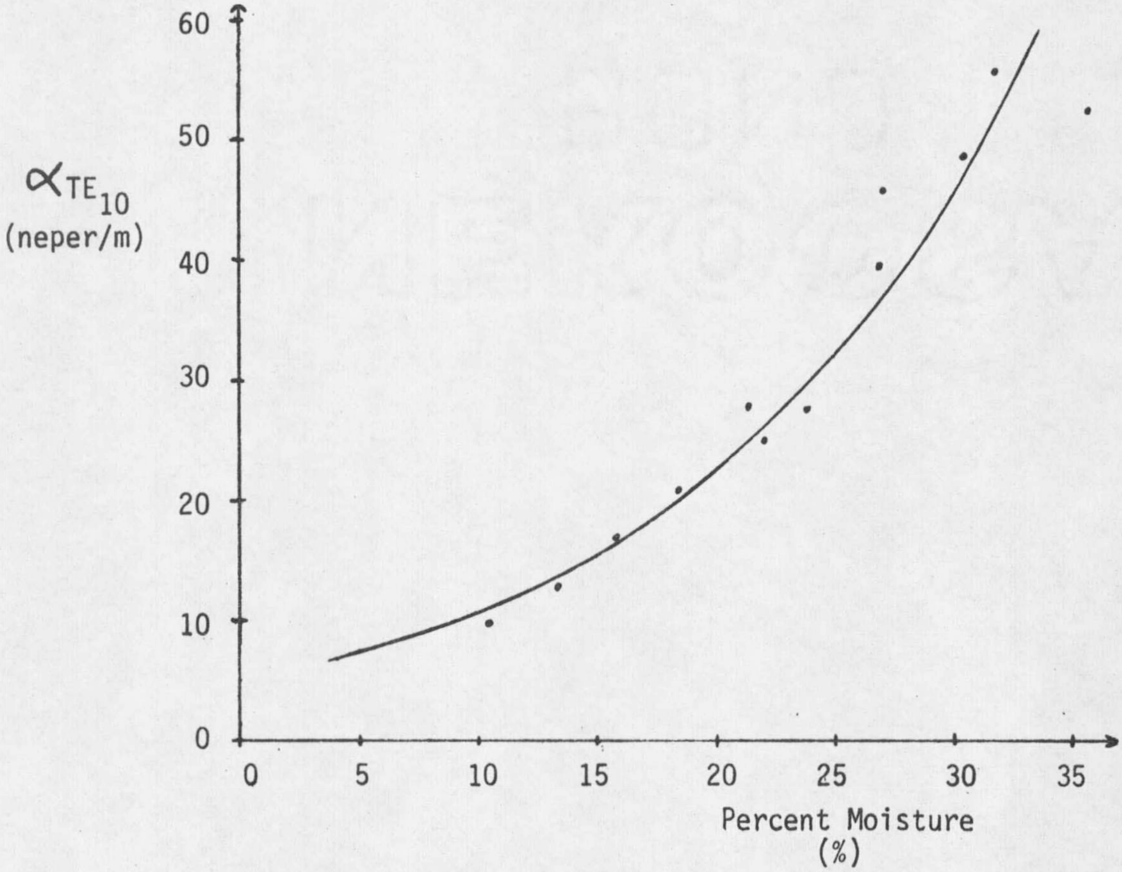

Figure 6 Attenuation versus Percent Moisture for Oats

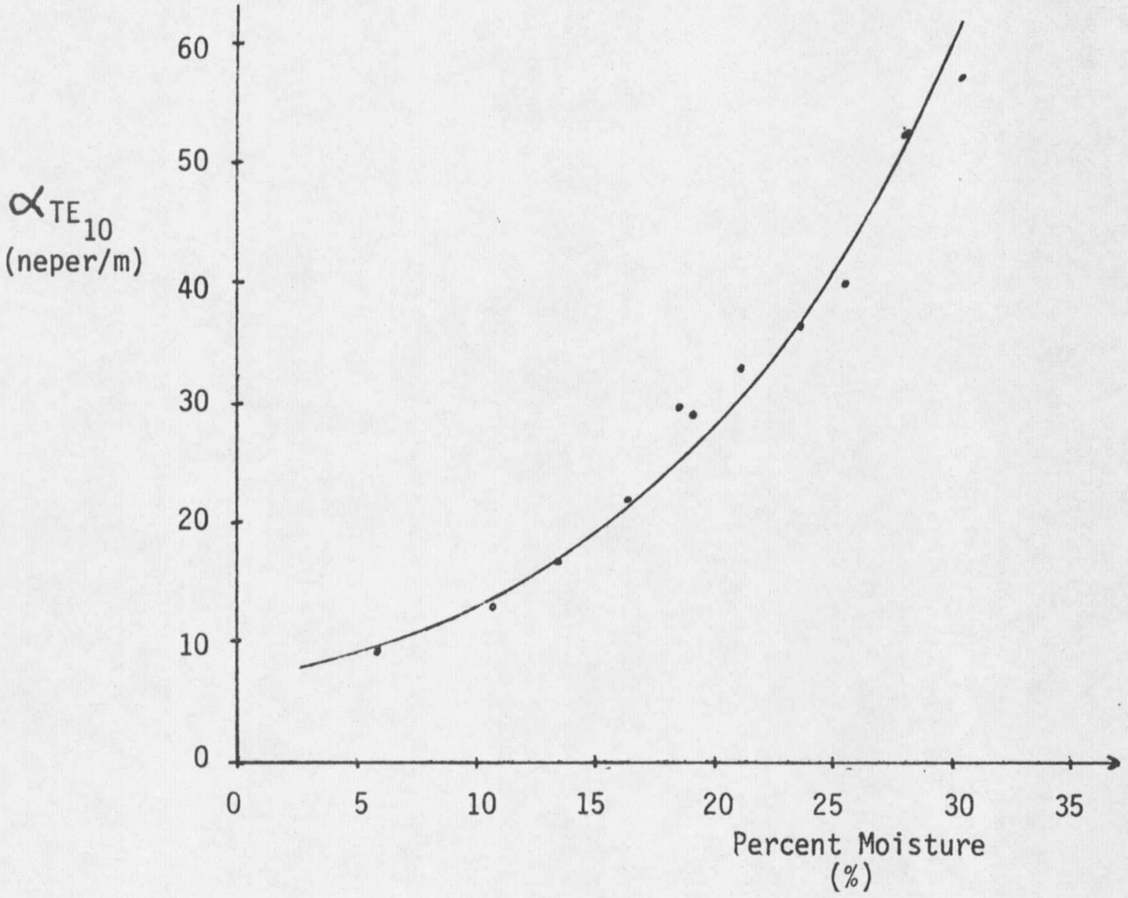

Figure 7 Attenuation versus Percent Moisture for Spring Wheat (run 1)

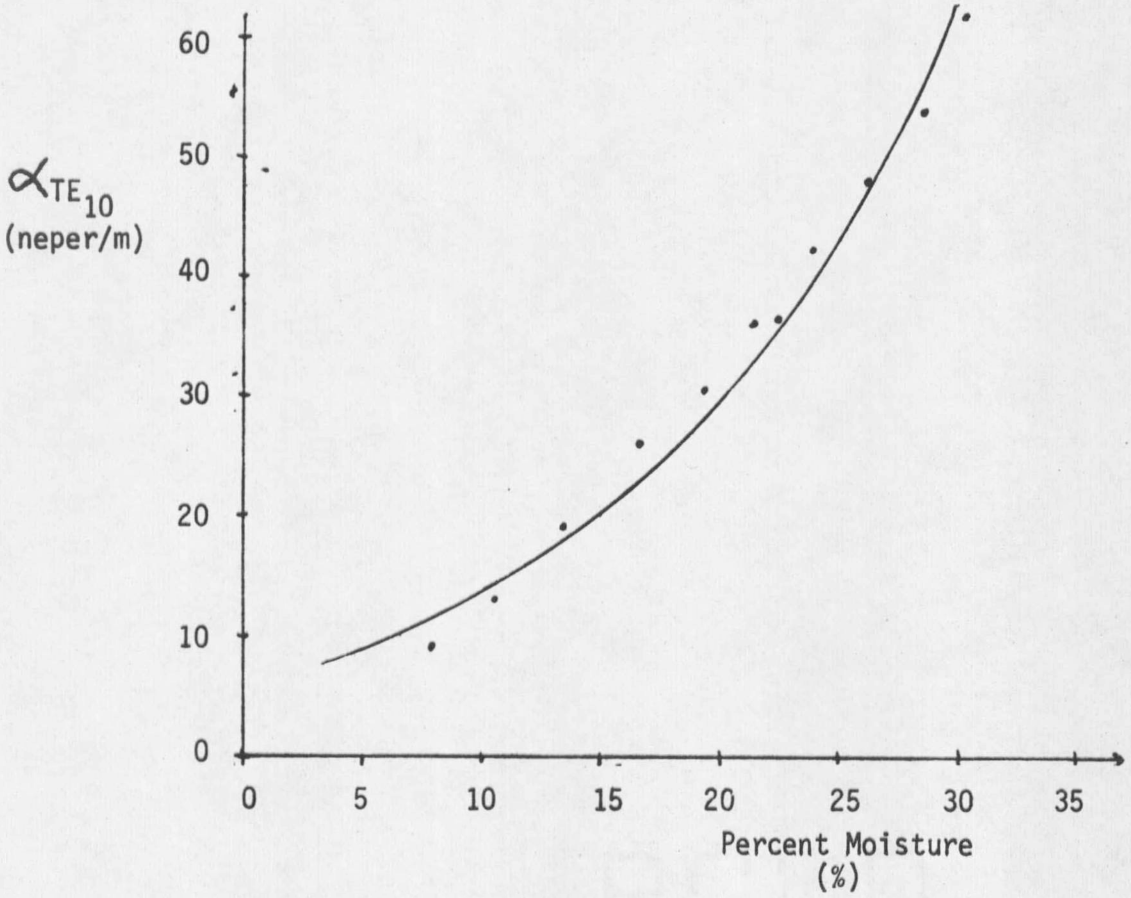

Figure 8 Attenuation versus Percent Moisture for Spring Wheat (run 2)

different grains are nearly identical. This was expected because the physical dimensions as well as the cellular structure of wheat, oats and barley are very similar (6). With similar seed characteristics, the microwave interacts approximately the same for the different seeds.

After determining how much energy was absorbed by the seeds, the next procedure was to determine how much energy was reflected from the seeds as a function of percent moisture. In this test, the standard method of measuring the VSWR (voltage standing wave ratio) was used. See Appendix C for the equipment setup and the procedures for measuring the VSWR. Once the VSWR was measured, the reflected energy was calculated in terms of the transmitted or incoming energy to the seeds by the following relationship:

$$\frac{\text{Energy reflected}}{\text{Energy incoming}} = \left[\frac{(\text{vswr}-1)}{(\text{vswr}+1)}\right]^2$$

The results for the VSWR tests are shown on Figures 11, 12, 13 and 14 on the next two pages. Also, on the figures are the least squares fit of the data points. As can be observed, the reflected energy varies fairly slowly over the range of percent moisture. As an example, data from Figure 12 (spring wheat) will be considered.

$$\frac{E_r}{E_i}\ (0\%\text{m}) = 7.4\% \quad \text{and} \quad \frac{E_r}{E_i}\ (30\%\text{m}) = 17.6\%$$

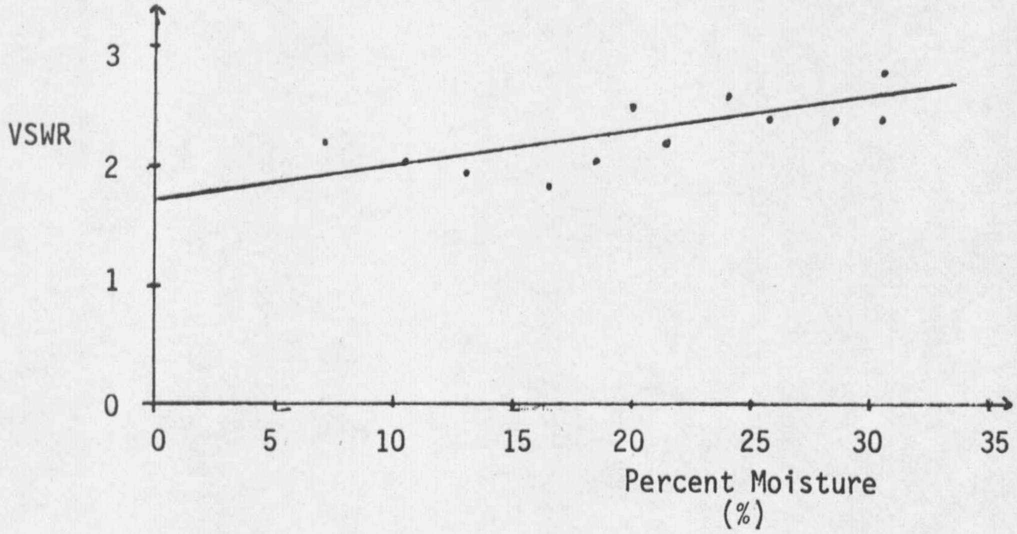

Figure 9 VSWR versus Percent Moisture for Barley

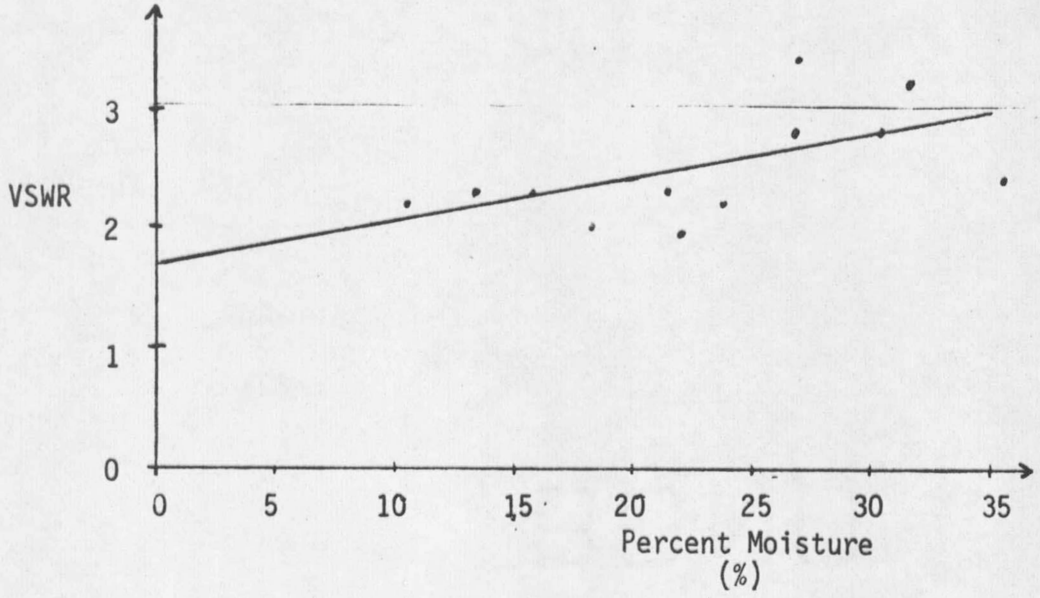

Figure 10 VSWR versus Percent Moisture for Oats

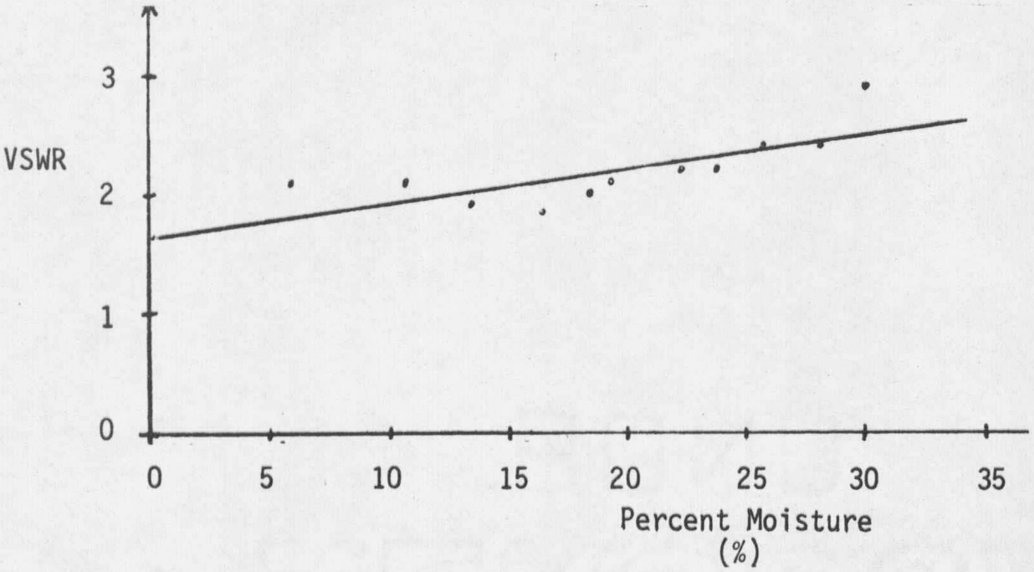

Figure 11 VSWR versus Percent Moisture for Spring Wheat (run 1)

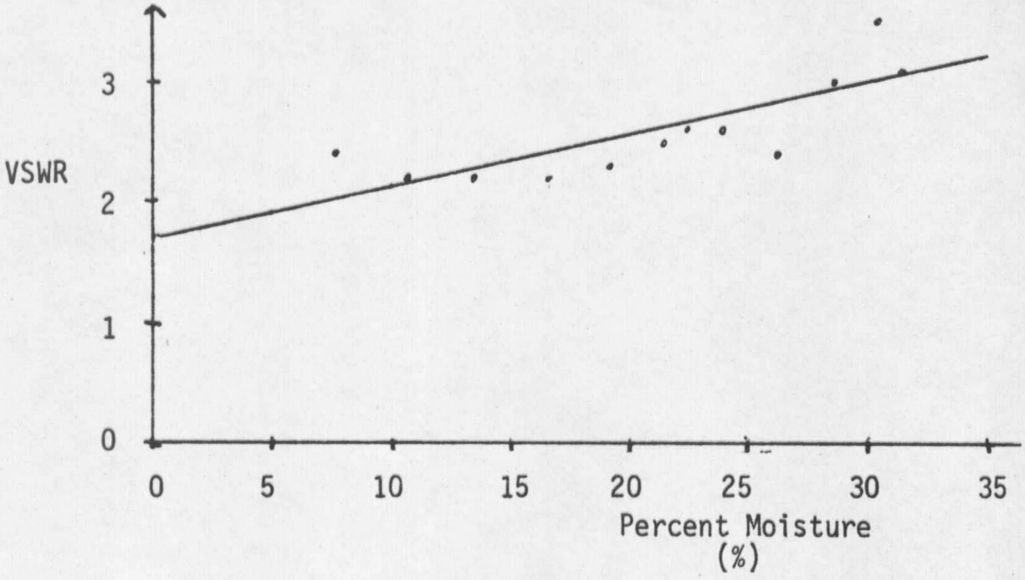

Figure 12 VSWR versus Percent Moisture for Spring Wheat (run 2)

Thus only a 10.2% difference in energy reflected per energy incident occurs from a 0 to 30 percent moisture content change of the seeds. The corresponding least squares linear function along with the correlation coefficient are available in Table 3.

Seed Type	Mathematical Function	Correlation Coefficient
Spring Wheat (run 1)	$y = .028x + 1.65$	.72
Barley	$y = .025x + 1.75$	.69
Spring Wheat (run 2)	$y = .042x + 1.69$	.79
Oats	$y = .034x + 1.71$	.56

where: y = VSWR
x = percent moisture

Table 3 Mathematical VSWR Functions

Again, the similarities between the behavior of the reflected energy from the three types of seeds can be related to the similar cellular structures and compositions of the seeds.

Due to the boundary conditions of the waveguide, the attenuation constant ($\alpha_{TE_{10}}$) measured in the waveguide is not the same as the attenuation constant (α_{TEM}) in free space. Since α_{TEM} is required in the pulse high power test since no boundries will be present, then a connecting relationship must be sought. The relationship is as follows and the derivation of the equation is in Appendix D.

$$\alpha_{TEM} = \alpha_{TE_{10}}(1-(\lambda a/\lambda c)^2)^{1/2}$$

where: λc = .04572 meters

$\lambda a = \lambda o/(\text{relative dielectric constant})^{\frac{1}{2}}$

In order to complete this relationship the relative dielectric constant must be found. Of the many techniques available, the shorted guide method first introduced by Von Hippel (7) was used to determine "ε_r" and "tan δ" as a function of percent moisture. In using this method a transcendental complex equation of the form (tanh x)/x must be solved to determine the relative dielectric constant and loss tangent. The Newton's Rule Method (8) for solving transcendental equations was used in a computer program on a Texas Instruments model 59 calculator to determine the relative dielectric constant and the loss tangent of the seeds as a function of percent moisture. Figures 13 and 14 on the next page shows the results of the shorted guide method to determine "ε_r" and "tan δ". In Figures 13 and 14 the loss due to the waveguide walls was not taken into account. With reference to Figure 13, the increased concentration of H_2O caused an increase in polarization (dielectric constant increased) of the seeds. This effect was expected because the high dielectric constant of water influences the polarization of the seeds more as the percent moisture of the seeds increases. To check

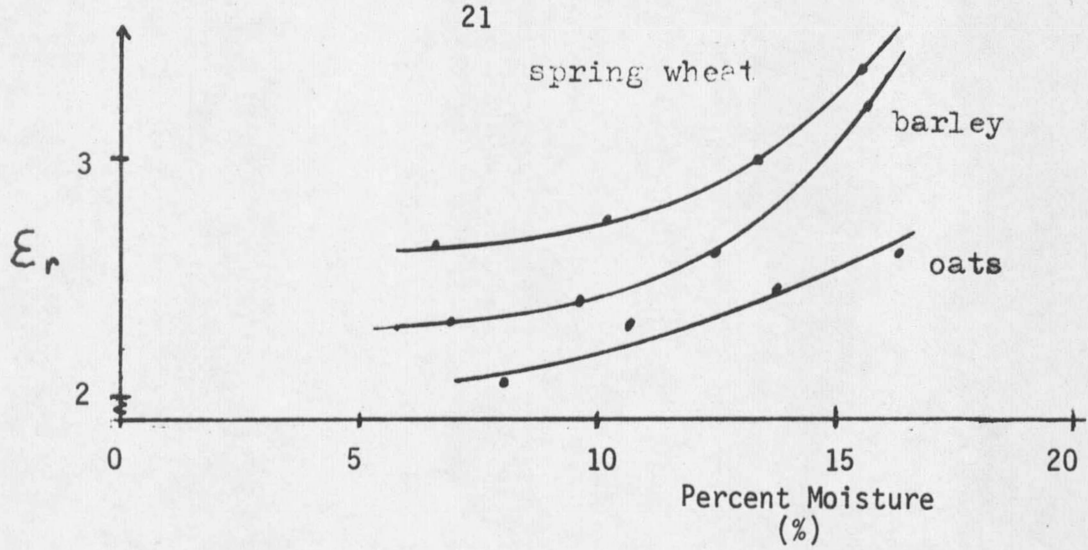

Figure 13 Relative Dielectric Constant versus Percent Moisture for Spring Wheat, Oats and Barley

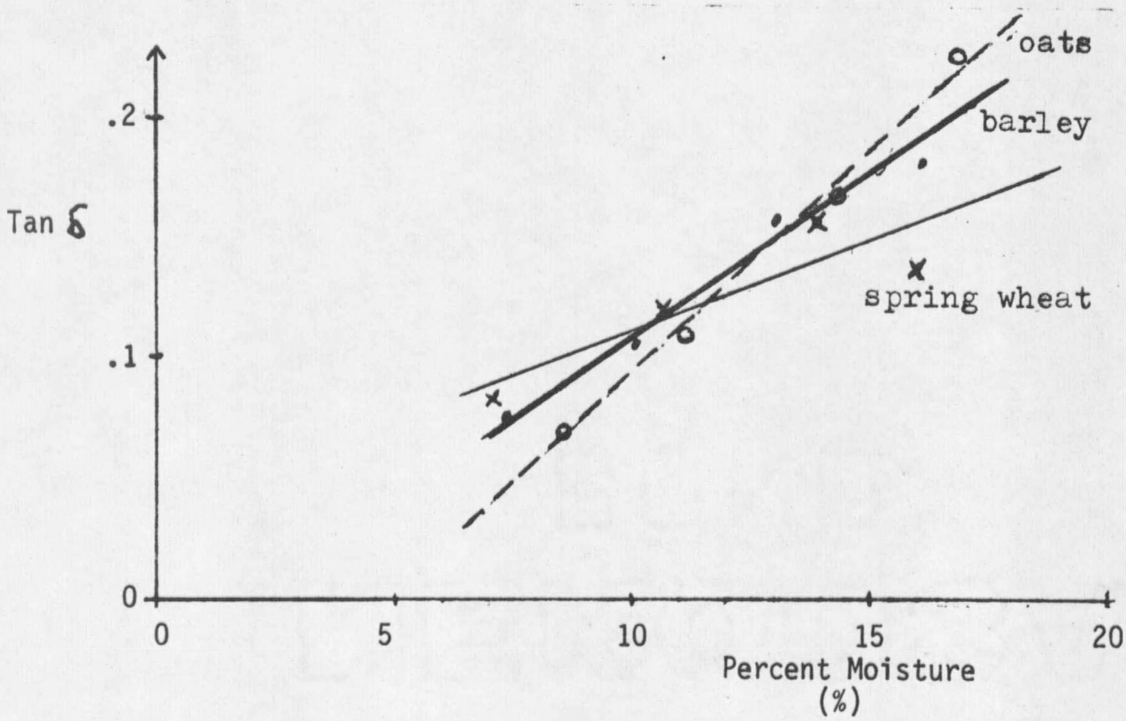

Figure 14 Loss Tangent versus Percent Moisture for Spring Wheat, Oats and Barley

these results, a comparison was made between the values obtained by S. O. Nelson (9) and the values shown in Figures 13 and 14. Because only one value of percent moisture for wheat was presented by Nelson, only a check of one moisture level is available.

	S.O. Nelson results	preceeding test results
frequency	8.388 GHz.	8.682 GHz.
ε_r	2.624	2.74
tan δ	.092	.1195
% moisture	10.5%	10.7%
wheat type	Scout 66 HRW	spring wheat

Table 4 Comparison of Results

As can be observed from the above table, the two values agree well within experimental limitations.

With the dielectric constants determined, the connecting relationship between "α_{TEM}" and "$\alpha_{TE_{10}}$" is complete. In order to verify this connecting relationship, the following test was done to experimentally measure "α_{TEM}". The substitution method was again used and the equipment set up is shown in Figure 15 page 23. Because the electromagnetic wave coming from the horn antenna (as shown in Figure 15) is not a true TEM wave due to the multimode conditions set up by the boundary conditions, the attenuation constant versus distance separating the horn antennas was plotted. By using this data, a region can be located where the separation of the horn antennas will just begin to cause a loss in

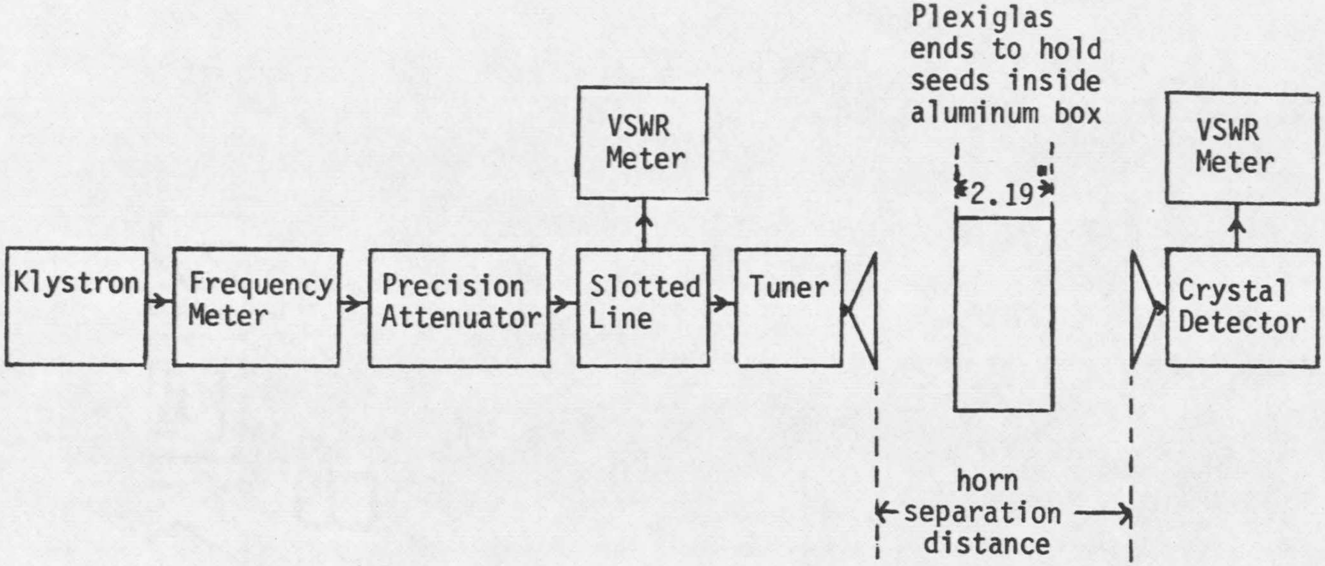

Figure 15 Equipment Setup for Measuring α_{TEM}

measurement accuracy in the attenuation reading due to the loss of scattered waves and just after the multimode components die out. Figure 16 on the next page shows the attenuation constant (α_{TEM}) versus horn separation for spring wheat. No attempt was made to connect the data points to a curve in Figure 16 because only enough data was taken to find out where the multimodes died out and not the exact behavior of the attenuation constant under multimode conditions. Also on Figure 16 is the calculated value of "α_{TEM}". This calculated value was obtained from the data taken from Figures 7 and 13 and the connecting equation shown on page 20. The test was done at a frequency of 8.682 GHz and at a moisture content of 7.8%. With reference to Figure 16, when the two horns were two wavelengths (horn separation of 7.63 inches) away from the sample then the calculated value of "α_{TEM}" agrees very well with the experimental results.

Since straw is coming off of the combine along with the grain, it becomes necessary to determine if the straw will absorb and/or reflect energy along with the seeds. Using the substitution method of measuring attenuation and using the VSWR test to determine the reflections, the energy absorbed and reflected for straw at 8.2 percent moisture was obtained. In Table 5 on page 26 a comparsion is done between straw and spring wheat at 8.2 percent moisture and a frequency of 8.682 GHz. With reference to Table 5, the energy absorbed for the seeds is

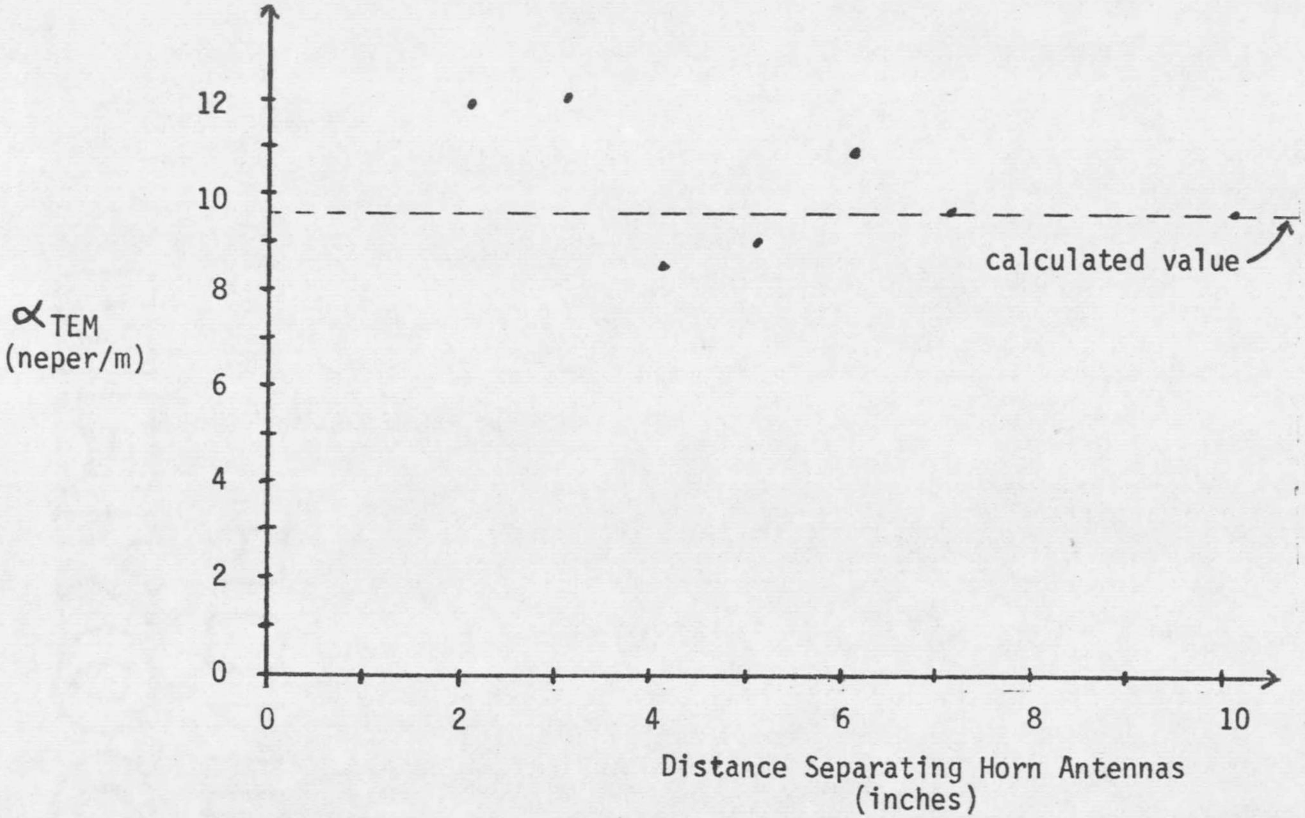

Figure 16 Attenuation versus Horn Antenna Separation

	Straw	Spring Wheat
percent moisture	8.2%	8.2%
VSWR	1.16	1.92
power reflected	.55%	18.1%
$\alpha_{TE_{10}}$	.91	11.5

Table 5 Comparison between Straw and Spring Wheat

on the order of twelve times the energy absorbed for the straw. Also, the energy reflected from the straw is negligible compared to the seeds. From these results, the straw can be ignored in relationship to the seeds as far as microwave interaction is concerned.

CHAPTER III

HIGH POWER MEASUREMENTS

From earlier tests performed on spring wheat and barley by use of a microwave oven (10), it was determined that germination decreased to 74% for spring wheat and 52% for barley after 30 seconds of exposure time. These tests were completed using a continous wave Litton (model 970) microwave oven whose power rating is 650 watts and frequency is 2.45 GHz. For optimum performance a instantaneous kill rate of 100% is required.

From Jolly and Tate (11), is was suggested that "short time exposures at a high amplitude of power is much less favorable than the converse" for enhancement of germination for Douglas-fir seeds. Jolly and Tate used exposure times down to 4 seconds with a 2.45 GHz multimode cavity (Varian model TCS-2.5A). Also, they suggested from their results the following unproven postulate. "The germination enhancement rate may be primarily dependent upon the amplitude of the electromagnetic field and therefore may be more than a simple thermal phenomenon".

Using these previous tests and assumptions, the high power tests were initiated using a pulsed magnetron (Varian model VMX-1025) at a frequency of 9.375 GHz and a Epsco model PFN-1 modulator. By use of this system, the pulse width was varible from 1 to 3 microseconds, the duty cycle from 0 to .001 and an output power of 18.1 kilowatts peak was available. The object now was to find an optimum kill point for the seeds.

In performing the high power tests, the equipment was setup as shown in Figure 17 on the next page. The power output delivered to the seeds was controlled by the modulator driving current. This current was monitored by the oscilloscope. The duty cycle and pulse width were also varied and controlled by the modulator, and monitored by the oscilloscope. The horn antenna used had the following base dimensions and from Gandhi (12) the following 3db beam widths.

H-plane dimension = .073 meters
E-plane dimension = .054 meters

H-plane beamwidth = 31.4 degrees
E-plane beamwidth = 35.0 degrees

In order to insure the seeds are in maximum field strength, the dimensions of the styrofoam test box as shown in Figure 17 must be within the above beamwidths; therefore, the styrofoam test box was made to have the same dimensions as the horn antenna.

Because it is known that the power received from an antenna is inversely proportional to the square of the distance between the transmitting and receiving antenna (Friss' transmission formula) then it is necessary to measure the power delivered to the seeds as a function of distance from the transmitting antenna. Of the various methods to measure power, making a simple calorimeter out of the styrofoam test box seemed to be the most practical in terms of reasonable cost and

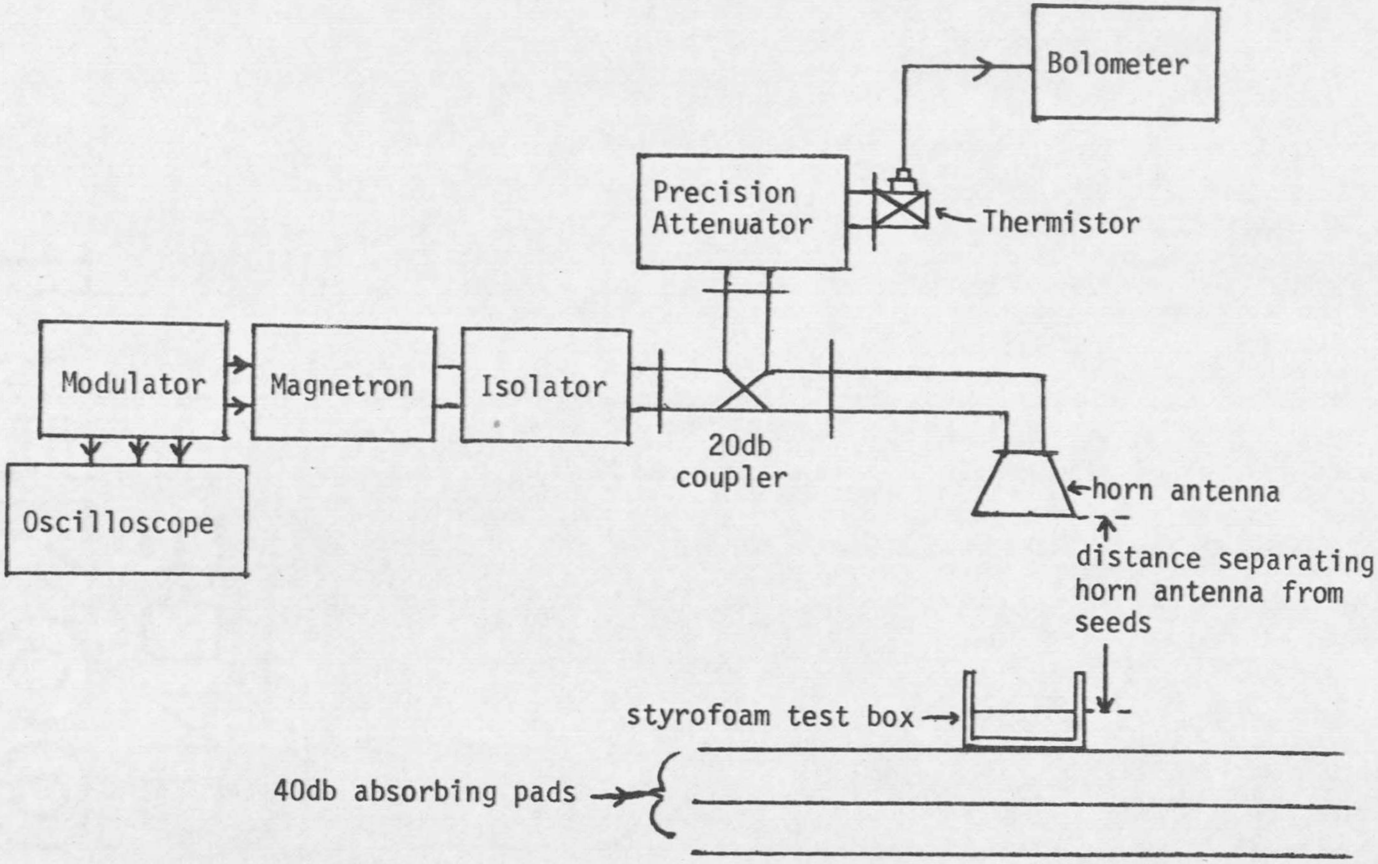

Figure 17 Equipment Setup for High Power Pulse Tests

minimum distortion of the field pattern.

By using the calorimeter and the following equation, the amount of power delivered to the seeds as a function of distance from the horn antenna can be determined.

$$P_{\text{delivered}}\ (\text{kilowatts}) = \frac{\Delta Q(10.74\text{x}10^{-3})}{\text{time of exposure (seconds)}}$$

where: ΔQ = change in heat in calories of the water

Appendix E contains the description of the calorimeter and Appendix F contains the derivation of the above formula.

Figure 18 on the next page shows the power delivered to the seeds as a function of distance from the horn antenna. The graph is normalized to the reading taken from the bolometer. As can be observed, the power delivered to the seeds falls off very quickly with distance from the horn antenna, but it did not go as the inverse square of the separation distance. The reason being secondary effects caused by the horn antenna at the measured distance nullifies the far field assumption (Isotropic antenna) used in deriving the Friss transmission formula.

Because the magnetron is limited to a load mismatch of VSWR=1.5 (13), then the following test was done to find VSWR versus distance separating the horn antenna from the seeds. By measuring the VSWR

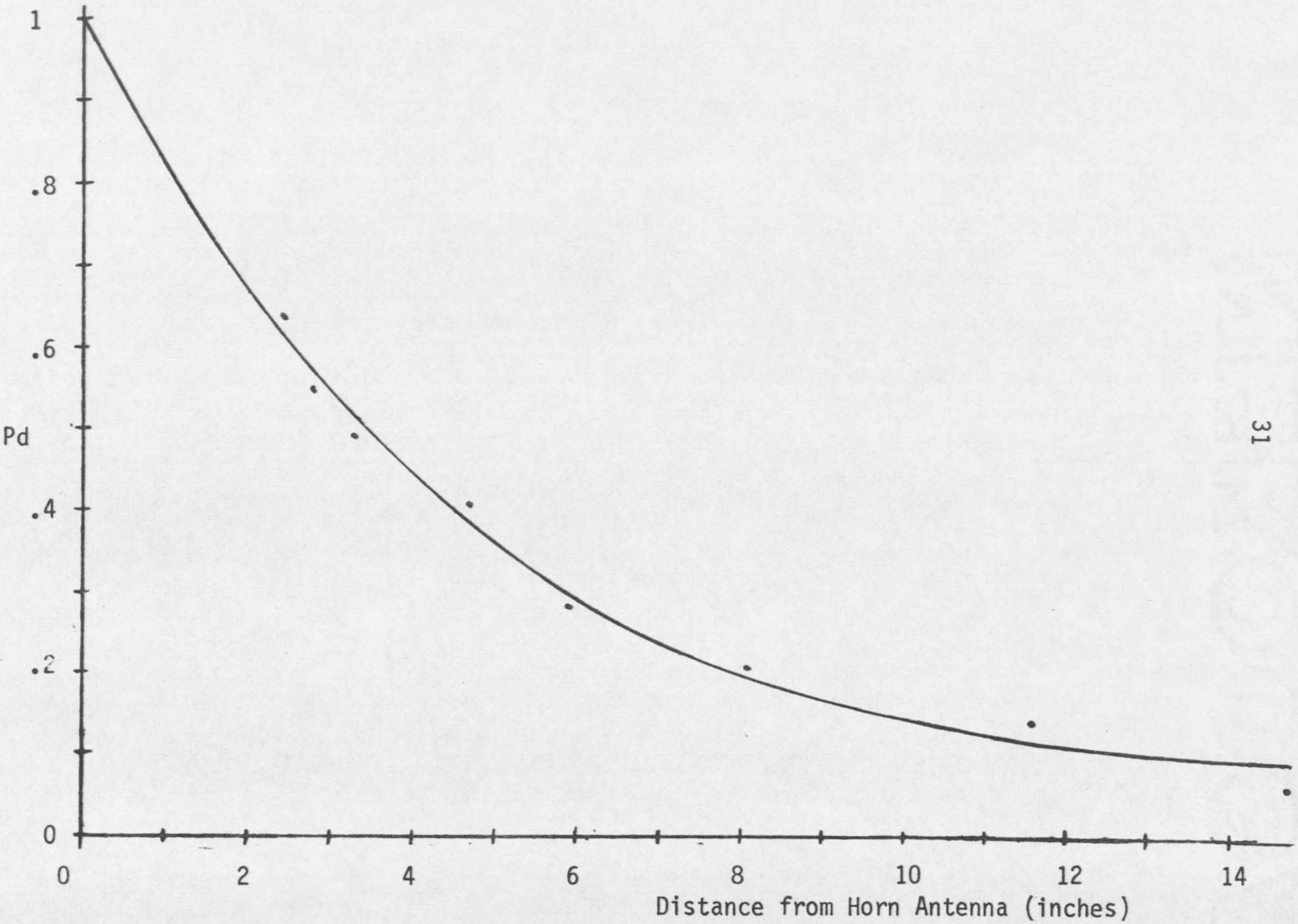

Figure 18 Normalized Power Delivered to the Seeds as a Function of Distance

with the setup shown in Figure 22 in Appendix E, the results shown in Table 6 were obtained. A rather interesting result is shown in Table 6, namely that the VSWR increases at integer multiples of half wavelength from the end of the horn antenna. Similar results appeared during four separate trials.

"d" (inches)	VSWR	Frequency (GHz)	Wavelength (inches)
0.0	1.5	9.375	1.26
.375	1.28	"	"
.625	1.7	"	"
1.0	1.32	"	"
1.1875	1.32	"	"
1.625	1.4	"	"
1.75	1.6	"	"
2.0	1.32	"	"
2.5	1.55	"	"
3.0	1.36	"	"
3.25	1.38	"	"
3.375	1.16	"	"
3.75	1.3	"	"
4.0	1.26	"	"
4.375	1.28	"	"

Table 6 VSWR versus Horn Separation for Spring Wheat

In a low loss transmission medium the VSWR should remain fairly constant and in a high loss medium the VSWR should decrease at an exponential rate. In the above situation an oscillation type of effect is observed. From this observation the following postulate is made:

Resonant modes are setup between the surface of the seeds and the horn antenna. When the seeds approach multi-half wavelengthes from the horn a cavity is setup between the horn antenna and the seeds. The cavity causes an increase in the driving point impedance of the horn antenna. This increase of impedance corresponds to an increase in the VSWR.

Using the same test equipment this effect was not noted when H_2O was used as the load instead of the seeds.(See Figure 23 in Appendix E). The reason this oscillation effect was not observed is because the water is very lossy thus the cavity setup between the water and the horn antenna had a very low Q. To further test this postulate, a brass plate was used as a load instead of the seeds. Using the brass plate as the load, the oscillation effect was even more pronounced then when the seeds were the load.

To determine the kill point of the seeds, a seed sample between 2 to 3 seeds in depth was placed in the styrofoam test box and exposed to the microwave pulses produced by the magnetron. The reason this depth was chosen was because under worst case conditions the seed depth on the seives would be less than 3/16" thick. See Appendix G for explanation.

By varying the power level, duty cycle, pulse width and time of exposure for various moisture content of the seeds, the results shown in Table 7 on the next two pages were obtained. In Table 7, the power delivered to the seeds (Pd) was determined by reading the value of power from the bolometer and recording the separation distance between the horn antenna and the seeds. With these two parameters

%moisture	%germination	Pd(average)	Duty	Pulse Width	Exposure Time
11.1	98	9.6 watts	.0008	2 microsec.	30 min.
14.2	98	"	"	"	"
16.8	96	"	"	"	"
19.4	94	"	"	"	"
21.8	96	"	"	"	"
7.6	98	8.8 watts	"	"	45 min.
7.6	96	9.5 watts	"	"	15 min.
11.8	98	"	"	"	"
14.1	98	"	"	"	"
16.9	98	"	"	"	"
19.7	88	"	"	"	"
20.1	92	"	"	"	"
7.6	96	11.2 watts	"	"	"
10.7	100	"	"	"	"
14.1	100	"	"	"	"
16.6	96	"	"	"	"
18.9	90	"	"	"	"
21.3	88	"	"	"	"
7.3	100	"	"	"	30 min.
11.5	100	"	"	"	"
14.0	96	"	"	"	"
16.9	94	"	"	"	"
19.7	90	"	"	"	"
22.4	84	"	"	"	"
7.8	94	13.6 watts	.001	"	15 min.
11.2	98	"	"	"	"
14.2	88	"	"	"	"
16.8	96	"	"	"	"
19.7	78	"	"	"	"
21.6	78	"	"	"	"

Table 7 Results of Spring Wheat Exposed to High Pulse Power

%moisture	%germination	Pd(average)	Duty	Pulse Width	Exposure Time
7.4	98	11.6 watts	.0008	3 microsec.	15 min.
12.5	96	"	"	"	"
13.7	96	"	"	"	"
16.1	100	"	"	"	"
19.8	96	"	"	"	"
22.5	88	"	"	"	"
7.4	98	"	.001	"	"
11.9	90	"	"	"	"
15.0	92	"	"	"	"
17.2	92	"	"	"	"
19.7	98	"	"	"	"
21.8	96	"	"	"	"
7.9	96	7.8 watts	.0008	1 microsec.	"
11.6	98	"	"	"	"
14.5	94	"	"	"	"
17.8	96	"	"	"	"
19.2	98	"	"	"	"
22.5	84	"	"	"	"
7.8	98	10.1 watts	.001	"	"
10.9	92	"	"	"	"
13.5	90	"	"	"	"
16.1	96	"	"	"	"
19.3	73	"	"	"	"
23.3	86	"	"	"	"

Table 7(cont.) Results of Spring Wheat Exposed to High Pulse Power the power delivered to the seeds was determined from Figure 18. The peak power then can be determined by the following equation.

$$P_{peak} = Pd/\text{duty cycle}$$

Again with reference to Table 7, the percent germination was determined by counting the abnormal and non-germinated seeds on the seventh day of germination. The procedure for germination of the seeds consisted of placing a fifty seed sample in between four paper towels which were saturated in water and then placed into two styrofoam trays (9.25"x 11.25"x .5") at room temperature. The paper towels were checked periodically over the course of seven days to insure they remained damp.

As can be observed from Table 7, the power level available was not enough to kill the seeds. Other information obtained from Table 7 shows that in almost all the runs a steady decrease in germination was noted for an increasing percent moisture. This result was expected because the seeds absorb more energy as the percent moisture increases as was shown in the low power measurements. Also, the decrease in germination seemed to be dependent mainly on the average power level and percent moisture and not the peak power, duty cycle or pulse width for the equipment used.

Since the original assumption of applying a high power pulse to kill the seeds did not work for the available peak power level and since the results tend to focus on raising the average power level, then it was necessary to determine how much average power was needed to kill the seeds. Since Dr. Jim Sims had not previously determined the exact kill point of spring wheat by use of a microwave oven (1), it was decided to continue in this direction to find the kill point.

The final test in the high power tests consisted of using a Frigidare Model PGM-6 microwave oven which has a power output of 675 watts and a frequency of 2.45 GHz. Because the microwave oven is a microwave cavity, all the output power will be absorbed by the seeds except for the small loss in the walls of the oven. By placing the seeds that are in the styrofoam test box into the oven and by varying the time of exposure and percent moisture Figure 19 on the next page was obtained. With reference to the 12% moisture content curve in Figure 19, an exposure time of 60 seconds killed over 90% of the spring wheat. This exposure time multiplied by the amount of output power of the oven gives the amount of energy needed to kill the seeds. Therefore, the amount of energy needed to kill over 90% of the spring wheat of 12% moisture content was 40.5 kilowatt-seconds. To check the above kill energy, a calculation was performed to determine the amount of heat needed to vaporize the amount of water that would be contained in the above 12% moisture content sample. By assuming standard temperature and pressure, the heat needed to raise

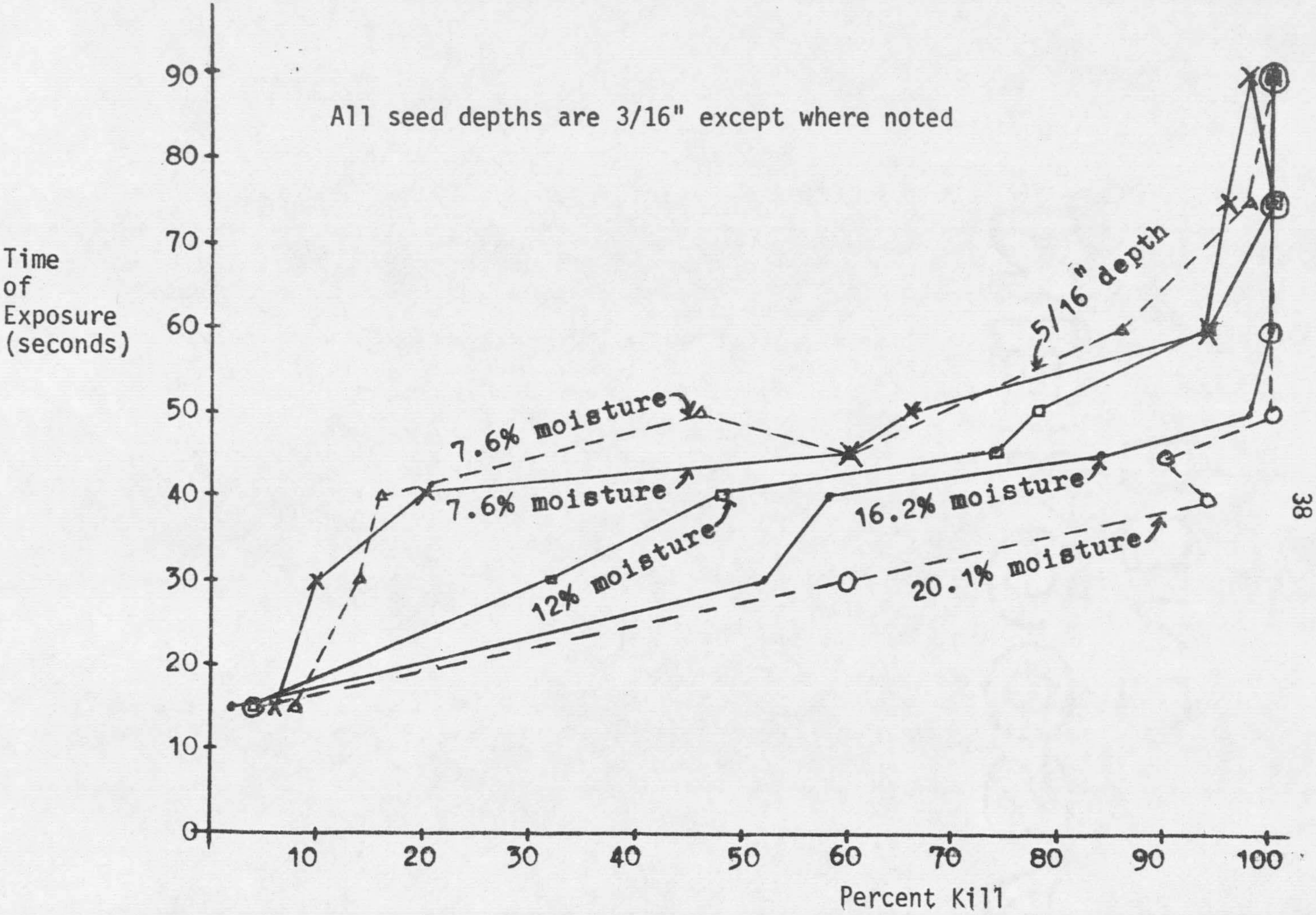

Figure 19 Kill Rate for Spring Wheat

the temperature of the water from 25^{o}C to 100^{o}C plus the heat of vaporization would be 7.1 kilowatt-seconds. It seems reasonable and indeed the case that the amount of energy needed to kill the seeds would be above the 7.1 kilowatt-seconds for the sample weight of 23 grams at 12% moisture content.

CHAPTER IV

CONCLUSION

From the information gathered in the Low Power Measurements, the energy absorbed and reflected are functions of percent moisture. These results were expected due to the high dielectric constant and loss tangent of water. In addition, random orientation of the seeds at the lower percent moisture content does not change the energy absorbed appreciably. Finally, straw can be ignored in relationship to the seeds when considering microwave absorption or reflection.

In the High Power Measurements the possible use of a pulse system to kill the seeds was tested. By using a pulse magnetron that produced a peak output power of 18.1 kilowatts and delivered 14.5 kilowatts (11.6 average watts) to the seeds, the desired effect of killing the seeds did not work for the system used. These results indicate that an even higher power pulse system with relatively low average power would still not be an effective way to kill the seeds.

Also in the high power tests a continuous wave cavity microwave oven (frequency = 2.45 GHz) was used to determine the kill point for spring wheat. By use of the 675 watt oven it was determined that the kill point was a function of percent moisture. This result was expected due to the increase of energy absorbed by the seeds as percent moisture increases. In addition, the energy level needed to kill over 90 percent of the spring wheat for a percent moisture of 12 percent was calculated to be 40.5 kilowatt-seconds.

From the information contained within this thesis, it can be concluded that a system designed to kill the seeds coming off the sieves of a combine would be impractical due to the high power levels needed to kill the seeds.

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APPENDICES

APPENDIX A

ATTENUATION MEASUREMENT BY THE SUBSTITUTION METHOD

ATTENUATION MEASUREMENT BY THE SUBSTITUTION METHOD

The block diagram of equipment setup is shown on the next page and the list of procedures was as follows:

(1) Set klystron to 8.682 GHz. (X-band range)

(2) Insert waveguide without sample but with two styrofoam (polystyrene) ends.

(3) Adjust slide-screw tuner to obtain match condition.

(4) Remove slotted line probe

(5) Set precision attenuator and VSWR meter to a convenient reference level.

(6) Insert sample into waveguide.

(7) Insert probe back into slotted line and obtain match condition.

(8) Remove slotted line probe.

(9) Vary precision attenuator until VSWR meter is in same position as in step 5 above.

(10) Record difference in attenuation between steps 9 and 5.

Because the crystal detector had a measured VSWR=1.25, a second tuner to match the load to the crystal detector was not required because 98.8 percent of the power was absorbed in the crystal.

Since polystyrene has a loss tangent and relative dielectric constant nearly that of air (14), then the assumption of a matched condition between the polystyrene and the air in the waveguide can be

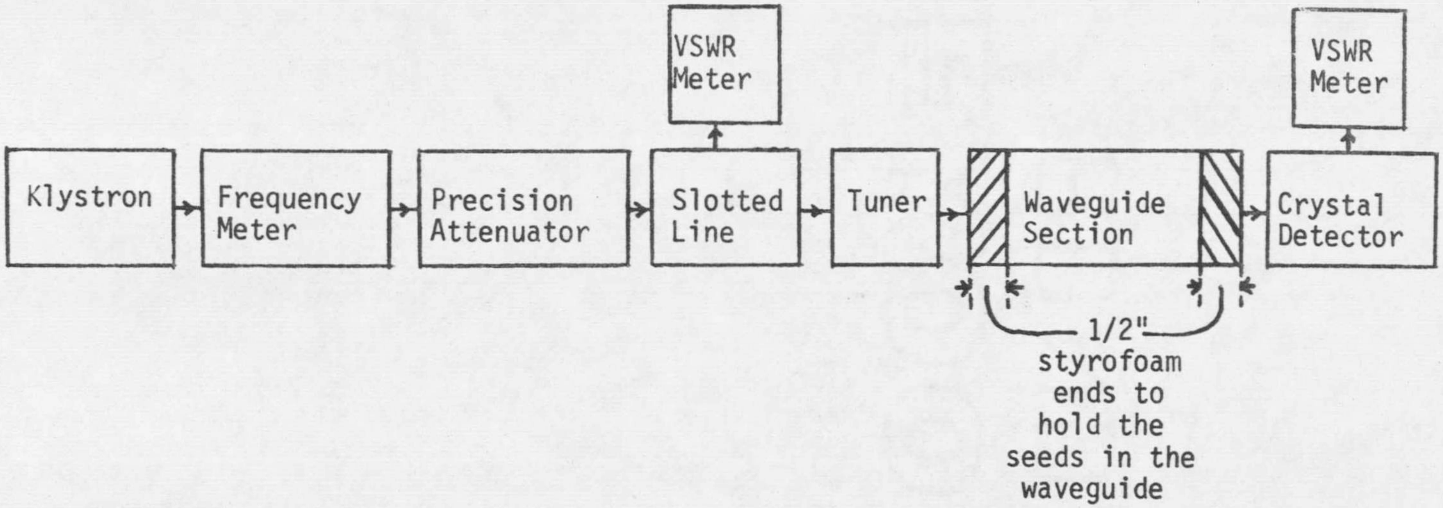

Figure 20 Block Diagram of Equipment Setup for the Attenuation Tests

made. Therefore, the use of the polystyrene ends to hold the seeds in the waveguide does not affect the data.

APPENDIX B

DERIVATION OF THE ATTENUATION CONSTANT

DERIVATION OF THE ATTENUATION CONSTANT

Starting with the wave equation, the following derivation was done to determine the attenuation constant from the change in "db" as measured from the substitution method which was described in Appendix A.

$$\nabla^2 E + \gamma^2 E = 0$$

$$E = E_+ e^{\gamma z} + E_- e^{-\gamma z}$$

$$(1) \qquad E = E_+ e^{\alpha z} e^{j\beta z} + E_- e^{-\alpha z} e^{-j\beta z}$$

Since the interest is only in the attenuation and not the phase shift (1) reduces to the following.

$$E = E_+ e^{\alpha z} + E_- e^{-\alpha z}$$

$$E/E_+ = e^{\alpha z} + \Gamma e^{-\alpha z}$$

where: Γ = reflection coefficient = E_-/E_+

Since the slide screw tuner was adjusted to have a VSWR = 1 as explained in Appendix A then the following is true.

$$|\Gamma| = (\mathrm{VSWR}-1)/(\mathrm{VSWR}+1) = 0$$

$$(2) \qquad E/E_+ = e^{\alpha z}$$

Because "z" was measured to be "m" meters long then equation (2) becomes the following:

$$\Delta db = 20\log(E/E_+) = 20\log e^{-\alpha m}$$

This equation then reduces to the following:

$$\alpha = \Delta db/(8.686 \times m)$$

APPENDIX C

VOLTAGE STANDING WAVE RATIO MEASUREMENT

VOLTAGE STANDING WAVE RATIO MEASUREMENT

The block diagram of equipment setup is shown in Figure 1C below.

The list of procedures for the test are as follows:

(1) Set klystron to 8.682 GHz.

(2) Move slotted line until minimum condition is observed on the VSWR meter.

(3) Adjust VSWR meter until movement is set on 1.

(4) Rotate slotted line probe along the line until maximum condition is observed on the VSWR meter.

(5) Record the value of VSWR as read from the VSWR meter.

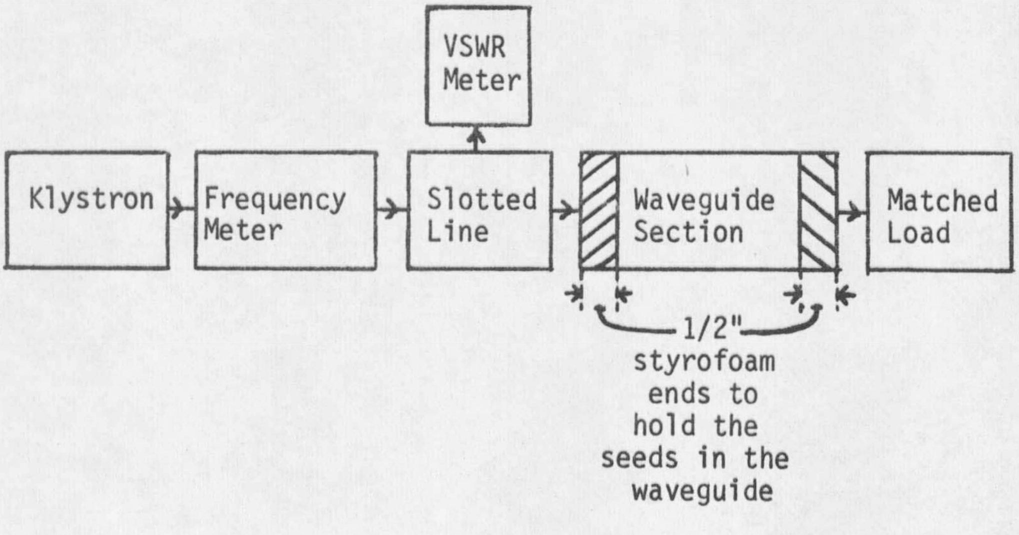

Figure 21 Block Diagram of Equipment Setup for the VSWR Test

APPENDIX D

DERIVATION OF α_{TEM} FROM $\alpha_{TE_{10}}$

DERIVATION OF α_{TEM} FROM $\alpha_{TE_{10}}$

From Ramo, Whinnery and Van Duzer (15) the following equation was derived by retaining the first two terms of a binomial expansion.

$$\alpha_{TE_{10}} = \frac{\omega(\mu\varepsilon)^{1/2}\varepsilon''}{2\varepsilon'(1-(\omega_c/\omega)^2)^{1/2}} \qquad (1)$$

ω = driving frequency (rad./sec.)
ω_c = waveguide cutoff frequency (rad./sec.)
μ = permeability (henry/m)
ε'' = imaginary part of the dielectric constant (farad/m)
ε' = real part of the dielectric constant (farad/m)
$\varepsilon = \varepsilon_o\varepsilon'$

Equation (1) becomes valid when the following assumption is made.

$$\omega\mu\sigma \ll \left|(\pi/a)^2 - \omega^2\mu\varepsilon\right| \qquad (2)$$

a = length of the wide end of the waveguide (m)

To check the validity of equation (1) by use of equation (2), data from Figures 13 and 14 for spring wheat at 14 percent moisture content will be substituted into equation (2). From this substitution the retention of only the first two terms of the binomial expansion used to derive equation (1) would result in an error introduction of less than 4.3%. Also from Ramo, Whinnery and Van Duzer (16) the attenuation constant for the TEM mode was derived and is as follows.

$$\alpha_{TEM} = \frac{\omega(\mu\varepsilon)^{1/2}\varepsilon''}{2\varepsilon'} \qquad (3)$$

This equation was also derived by retaining only the first two terms of a binomial expansion and the following equation is the bases for a valid assumption.

$$\omega\varepsilon >> \sigma \qquad (4)$$

By again substituting data from Figures 13 and 14 into equation (4) the retention of just the first two terms of the binomial expansion used to derive equation (3) will result in an error introduction of less than 3.3%. Because error introduction caused by use of equation (1) and (3) are within experimental limitations of $\alpha_{TE_{10}}$, then equations (1) and (3) will be considered valid for use in the remaining derivation.

By moving the radical in the denominator of equation (1) to the left side of the equation and then substituting the resultant equation into equation (3), the following relationship is formed.

$$\alpha_{TEM} = \alpha_{TE_{10}}(1-(\omega_c/\omega)^2)^{1/2}$$

This relationship then reduces to the following equation.

$$\alpha_{TEM} = \alpha_{TE_{10}}(1-(\lambda_0/\sqrt{\varepsilon'}\lambda_c)^2)^{1/2} \qquad (5)$$

λ_c = cutoff wavelength of the waveguide (m)
λ_0 = free space wavelength (m)

Equation (5) is the connecting relationship between the attenuation constant measured without boundries and the attenuation constant bounded by a rectangular waveguide.

APPENDIX E

DESCRIPTION OF THE CALORIMETER

DESCRIPTION OF CALORIMETER

Because the amount of power delivered to the seeds in the styrofoam test box was a concern, a simple calorimeter built out of the styrofoam test box was used to measure power. A ISA type J Iron-Constant Thermocouple and a type 2809 Omega Digital Thermometer were used to determine the change in temperature of the water in the styrofoam test box at various distances from the horn antenna.

Because water has a high relative dielectric constant with respect to air a large mismatch occurs at the boundries of the water and air. Since a maximum mismatch of the magnetron (VSWR = 1.5) is specified (13) care must be taken not to put the calorimeter to close to the antenna or else the specification will be exceeded. By filling the styrofoam container with water and measuring the VSWR of water through the horn antenna as shown in Figure 1E on the next page, a distance was determined were the maximum mismatch occurs. Figure 2E on the following page shows the VSWR versus distance from the water to the horn antenna. As can be observed, the calorimeter was used to measure the power delivered to the water for distances greater than 1.5 inches.

The next step was to determine the depth and the amount of water so that no energy will be transmitted through the water with minimum

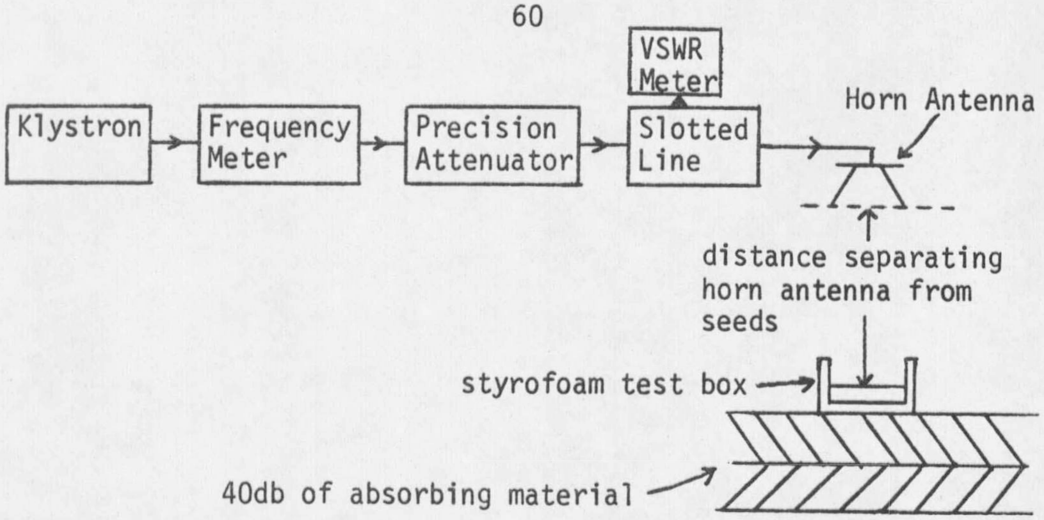

Figure 22 Block Diagram of Equipment Setup for the VSWR Test

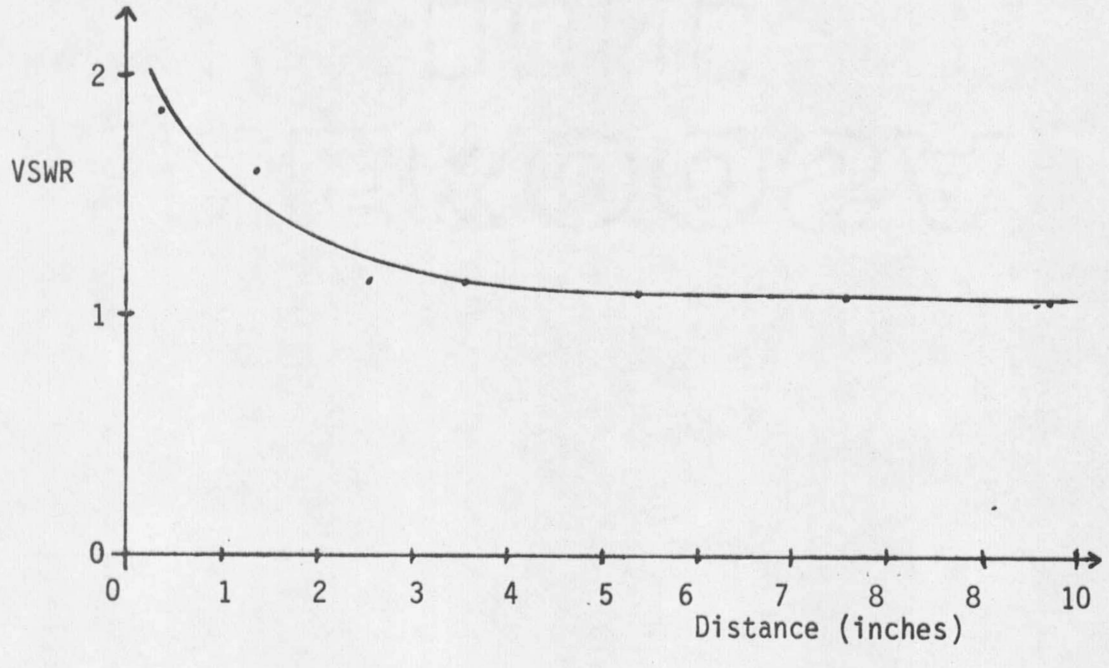

Figure 23 VSWR versus Distance from Horn Antenna to Water

temperature gradient in the water. By using this calorimeter with a thermocouple, it was experimentally determined that 50 grams of water be a good operating load. With 50 grams of water in the styrofoam test box the water depth in the box was .022 meters. With this water depth the following calculation was done to determine the amount of power transmitted through the water compared to the input power to the water. The transmitted E field through the water will have the following form:

$$E = E_{+}e^{-\alpha m} \qquad (1)$$

If both sides of equation (1) are squared and are divided by the characteristic impedance of the water then equation (2) is formed.

$$E^2/Z_0 = (E_{+}^2/Z_0)e^{-2\alpha m} \qquad (2)$$

Equation (2) then reduces to equation (3) below.

$$P_{in} = P_{transmitted}e^{-2\alpha m} \qquad (3)$$

Since "m" was given to be .022 meters then "α" must be found to solve equation (3). Since "ε'" is 55 and "tan δ" is .54 for water at 10 GHz and at 25^{o}C (2), then "α" was found by taking the real part of the propagation constant as shown below.

$$\gamma = j\omega(\mu\hat{\varepsilon})^{1/2} = \alpha + j\beta \qquad (4)$$
$$\hat{\varepsilon} = \varepsilon' - \varepsilon' \tan\delta$$

Substituting the values for "ε'" and "$\tan\delta$" into equation (4), "α" was determined to be 380.4 nepers/meter. By substituting this value back into equation (3), the power transmitted through the water would be equal to 5.38x10^{-8} of the input power. From this calculation it was concluded that all the power entering the water in the styrofoam test box will be absorbed by the water.

APPENDIX F

DERIVATION OF POWER DELIVERED TO THE WATER

DERVIATION OF POWER DELIVERED TO THE WATER

By measuring the change in temperature of the water in the calorimeter the amount of heat absorbed by the water was determined by the following equation.

$$\Delta Q = mC\Delta T$$

where: ΔQ = change in heat in calories
m = mass of water in grams
C = specific heat (for water it is 1 calorie/gram-^{o}C)
ΔT = change in temperature in ^{o}C

Knowing the time of exposure and the change in heat of the water the average power absorbed by the water was determined by the following equation.

Since: 1 calorie = 1.163×10^{-6} kilowatt-hour
1 calorie = 4.19×10^{-3} kilowatt-sec.

Then: $$P_{absorbed}(\text{kilowatts}) = \frac{\Delta Q \times 4.19 \times 10^{-3}\text{kilowatt-sec.}}{\text{time of exposure(sec.)}} \qquad (1)$$

To determine the power delivered to the water the magnitude of the reflection coefficient was found by assuming the following:

$$Z_o = 377 \text{ ohms for air}$$

$$Z_1 = (\mu_o/\varepsilon_o\hat{\varepsilon})^{1/2} = 377/(\hat{\varepsilon})^{1/2} = 46.24 + j11.7 \text{ ohms for water}$$

Since: $|\Gamma| = |(Z_1 - Z_o)/(Z_1 + Z_o)| = |.781|$

Then: $P_{reflected}/P_{delivered} = |\Gamma|^2 = .61$

Since:

$$P_{absorbed}/P_{delivered} + P_{reflected}/P_{delivered} = 1$$

by the conservation of energy then the following is true.

$$P_{absorbed}/P_{delivered} = 1 - .61 = .39 \qquad (2)$$

Substituting equation (1) into equation (2) the desired equation was formed as follows.

$$P_{delivered} = P_{absorbed}/.39$$

$$P_{delivered} = \frac{\Delta Q(4.19 \times 10^{-3})\text{kilowatt-sec.}}{\text{time of exposure(sec.)} \times .39}$$

$$P_{delivered} = \frac{\Delta Q(10.74 \times 10^{-3})}{\text{time of exposure(sec.)}} \text{ kilowatts}$$

APPENDIX G

DETERMINATION OF DEPTH OF SEEDS LOST FROM THE SIEVES

DETERMINATION OF DEPTH OF SEEDS LOST FROM THE SIEVES

For worst case situation 1.5 to 2 bushels of grain are lost off of the combine per acre. Since one acre equals 43,536 square feet then the square of 208.7 feet would constitute an acre. Using John Deer combines as an example, cutter head widths of 26, 24 and 22 feet are available. Using a harvest unit of 26 feet for worst case situation and using the above information the amount of bushels per cut strip was calculated to be:

2 bushels/(208.7feet/26feet) = .25 bushels/strip

Since a cut strip is 208.7 feet long, then the amount of grain loss per foot was calculated to be:

.25 bushels/208.7 feet = .0012 bushels/foot

Because the weight of harvest grain is on the order of 60 pounds per bushel, then the weight of the seeds loss per foot was as follows:

.0012 bushels/ft. x 60 lbs./bushel = .072 lbs/ft.

since the sieve width is 4.39 feet (17) and the depth of the seeds is "y" feet which is unknown, then the weight loss per unit volume was calculated to be:

(.072 lbs./ft.)/(4.39 ft. x "y" ft.) = .0164 lbs/ "y" ft.^3

From the experiments it was determined that 32 grams of spring wheat at 13.4 percent moisture would occupy .0014 cubic feet or 22,531 grams per cubic foot. Converting grams per cubic foot to pounds per cubic foot it was determined that 13.4 percent moisture spring wheat would weight 49.68 pounds per cubic foot. By knowing this information, the depth of the seed on the sieves was calculated as follows:

$$.0164 \text{ lbs}/\text{"}y\text{"}\text{ft.}^3 = 49.68 \text{ lbs/ft.}^3$$

$$y = 3.3\text{x}10^{-4} \text{ ft.}$$

This calculated depth is an average depth of the seeds on the sieves. Since this value is less than the actual size of the seeds, it was decided to run the high power tests on a seed depth of 3/16" which is between 2 to 3 seeds in depth. This standard would give approximately a factor of 50 higher than the above calculated average depth.