Frequency Dependence of Energy Absorption by Insects and Grain in Electric Fields

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THE possibility of controlling insects through application of high-frequency electric fields has been explored by many investigators during the past five decades. This work has been reviewed and cited in previous publications (Nelson, 1966, 1967). The principles involved in applying RF electric fields for the control of stored-grain insects have also been considered (Nelson and Whitney, 1960; Nelson et al, 1966), and the influences of various physical and entomological factors have been summarized as well (Nelson, 1967, 1972b).

Control of insects infesting grain can be achieved by dielectric heating. There are reasons to expect that insects should absorb energy from an RF electric field at a higher rate than their host material, and experimental evidence has been obtained supporting this contention (Nelson and Whitney, 1960). This selective absorption of energy, or differential heating, offers an advantage for RF dielectric heating in contrast to other more conventional types of heating for controlling stored-grain and certain other stored-product insects.

BASIC RELATIONSHIPS

The power absorption in a dielectric material subjected to an RF electric field is given by the following relationship:

$$P = E^2\sigma = E^2\omega\epsilon'' = E^2\omega\epsilon_o\epsilon_r'' = 55.63\ fE^2\epsilon_r'' \times 10^{-12}\ \text{watts/m}^3, \quad \ldots[1]$$

where P is the power density per unit volume, E the electric field intensity in V/m, f the frequency in hertz, ω the angular frequency ($2\pi f$), ϵ_o the permittivity of free space (8.854×10^{-12} farad per m), and σ, ϵ'', and ϵ_r'' are, respectively, the a-c conductivity, the dielectric loss factor, and the relative dielectric loss factor of the material. The loss factor, ϵ'', is the imaginary part of the complex permittivity or complex dielectric constant, $\epsilon = \epsilon' - j\,\epsilon''$, whereas ϵ_r'' is the imaginary part of the complex relative permittivity $\epsilon_r = \epsilon/\epsilon_o = \epsilon_r' - j\epsilon_r'' = \epsilon_r'\,(1 - j\tan\delta)$. Hereafter, as is conventional in practical applications, the relative quantities ϵ_r' and ϵ_r'' are simply referred to as the dielectric constant and dielectric loss factor, respectively. The quantity $\tan\delta = \epsilon_r''/\epsilon_r'$ is usually called the loss tangent or dissipation factor. In this context, σ, ϵ'', and ϵ_r'' include all energy-dissipating mechanisms observed in the dielectric as a result of its subjection to the forces of the alternating electric field.

From equation [1] it is apparent that the dielectric properties of insects and grain influence the degree of differential heating which can be expected. Also, the values of the dielectric properties are frequency dependent. Therefore, a study was conducted to determine the frequency dependence and its influence on the energy absorption by insects and grain subjected to RF fields (Nelson, 1972b).

MATERIALS AND METHODS

Materials chosen for measurement of dielectric properties were a seed lot of Scout 66 hard red winter wheat, *Triticum aestivum,* harvested in 1970 and adults of the rice weevil, *Sitophilus oryzae (L.),* described further elsewhere (Nelson, 1972b). Bulk samples of 1- to 3-week-old adult rice weevils and bulk samples of wheat at 10.6- and 12.4-percent moisture (wet basis) were used for measurements at 22 different frequencies in the range from 250 Hz to 12.2 GHz. Moisture content of wheat samples was determined by approved oven methods (AOAC, 1970). That of rice weevils was determined by drying triplicate samples of approximately 1 ml each in a forced-air oven for 16 hrs at 105 C.

Eight different measurement systems were employed to span the frequency range. For measurements in the 250-Hz to 20-kHz range, the method was that described by Corcoran et al (1970). The Q-Meter method (Nelson et al, 1953) was used for the frequency range between 50 kHz and 50 MHz. Between 50 MHz and 200 MHz, the RX-Meter and methods reported by Jorgensen et al (1970) were employed. The Admittance Meter and methods reported by Stetson and Nelson (1970) were used for the 200- to 500-MHz range. The short-circuited coaxial-line and waveguide method originally reported by Roberts and von Hippel (1946), with refinements described by Westphal (1954) and Nelson (1972b), was employed with four additional systems for the measurements at higher frequencies.

One of these systems, used between 1 and 2 GHz, consisted of a Rohde and Schwarz* Type SLRD Power Signal Generator, LMD Slotted Line, UBK Indicator, and Short-Circuit Specimen Container. Another system, used between 2.3 and 6 GHz, employed a Rohde and Schwarz Type SLRC Power Signal Generator, LMC Non-Slotted Line, UBK Indicator, and Short-Circuit Specimen Container. A Central Research Laboratories Model 2 Microwave Dielectrometer was also used for measurements at 1, 3, and 8.5 GHz. Measurements in the range from 8.2 to 12.4 GHz were obtained with an X-band microwave measurement system described elsewhere (Nelson, 1973). A computer program for calculating dielectric properties of materials from measurements data taken on these four systems has also been described in detail elsewhere (Nelson, 1972b; Nelson et al, 1972).

Reliability of all measurement systems was verified by measurements on samples of materials of known dielectric properties (Nelson, 1972b). Results presented for measurements on wheat represent mean values for three separate sets of measurements. Six sets of measurements were obtained on the adult

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*Mention of specific items of equipment is made for purposes of description only and does not imply endorsement by the USDA or cooperating State agencies.

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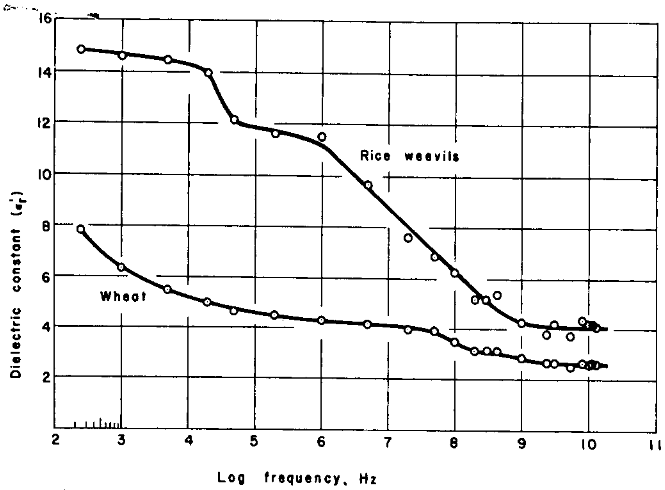

FIG. 1 Comparison of the frequency dependence of the dielectric constant of bulk samples of 1970 Scout 66 hard red winter wheat (10.6-percent moisture, 24 C., and 0.79-g per ml density) and 1- to 3-week-old adult rice weevils (49-percent moisture, 24 C , and 0.49-g per ml density).

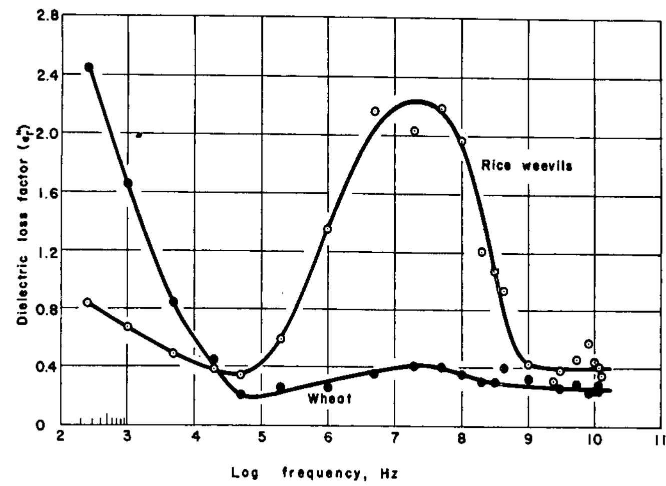

FIG. 2 Comparison of the frequency dependence of the dielectric loss factor of bulk samples of 1970 Scout 66 hard red winter wheat (10.6-percent moisture, 24 C, and 0.79-g per ml density and 1- to 3-week-old adult rice weevils (49-percent moisture, 24 C and 0.49-g per ml density).

rice weevils. Anesthetization of the insects with carbon dioxide was necessary in handling the large numbers of insects required and to hold them inactive in the sample holders.

Variation in densities of both bulk grain and bulk insect samples among different-sized holders was taken into account. Values for resulting dielectric properties were adjusted to a common density for all measurements by linear interpolation between measurements at different sample densities. All measurements were obtained at a temperature of 24 C. Further details on methods and equipment used are presented elsewhere (Nelson, 1972b).

RESULTS AND DISCUSSION

Resulting values for the dielectric constant, ϵ_r', and the dielectric loss factor, ϵ_r'', for both the adult rice weevils and the wheat are plotted in Figs. 1 and 2. Examination of the ϵ_r' and ϵ_r'' vs. frequency curves reveals a prominent, broad dispersion and absorption region between about 10^5 and 10^9 Hz (100 kHz to 1 GHz) for the rice weevils. The shapes of the dispersion (ϵ_r' vs. log f) and absorption (ϵ_r'' vs. log f) curves in this frequency range resemble quite closely the Debye-type dispersion curves characteristic of the behavior of polar molecules. While the exact nature of the dispersion noted here has not been investigated, it seems likely to be attributable to bound forms of water in the insects. The high values measured for ϵ_r'' at the low end of the frequency range (Fig. 2) are most likely accounted for by the contribution of the ionic conductivity.

Consider now the relative power dissipation to be expected in a mixture of insects and grain exposed to an alternating electric field. Applying equation [1] to the insects and grain separately, it is apparent that the frequency will be the same for both the insects and the grain. The dielectric loss factor, ϵ_r'', for the two may be quite different. The electric field intensity, E, may also be different for the two materials. It is probably impossible to calculate accurately the field intensities in the grain and in the insects, but some insight can be obtained by considering mathematically amenable models. The case for a homogeneous sphere of one material embedded in an infinite homogeneous medium of another material represents such a model. The field intensity in the sphere is related to that in the infinite medium by the following equation:

$$E_1 = E_2 \left(1 - \frac{\epsilon_{r1} - \epsilon_{r2}}{2\epsilon_{r2} + \epsilon_{r1}}\right) = E_2 \left(\frac{3\epsilon_{r2}}{2\epsilon_{r2} + \epsilon_{r1}}\right), \quad \ldots\ldots [2]$$

where the subscript 1 refers to the sphere and 2 to the medium in which it is embedded. The electric field intensity in the sphere, of course, depends upon the relative values of the complex permittivities of the two materials.

Neither the insects nor the bulk grain are homogeneous dielectrics, but, if one can envision the insect and its share of the surrounding air space as a sphere embedded in a dielectric with the effective dielectric properties of the bulk grain sample, equation [2] may be written

$$E_i/E_g = 3/(2 + \epsilon_{ri}/\epsilon_{rg}), \quad \ldots\ldots [3]$$

where subscripts 1 and 2 have been replaced by i and g for reference to the insects and the grain. For selectively heating the insects, a high E_i/E_g ratio is needed, so it is obvious from equation [3] that a low $\epsilon_{ri}/\epsilon_{rg}$ ratio is desirable. (It may also be shown from other approaches that a low insect-to-grain ratio for the dielectric constant is desirable for obtaining higher field intensities in the insect.) Since the magnitude of $\epsilon_r = \epsilon_r' - j\epsilon_r''$ is within about 5 percent of the value of ϵ_r', even for the insects in the region of highest loss, the dielectric constants, ϵ_r', may be used in place of the complex relative permittivities in equation [3] for purposes of the following discussion.

Based on assumptions already outlined, the influence of frequency on the selective or differential heating of rice weevils in wheat can now be evaluated using equations [1] and [3] and values of ϵ_r' and ϵ_r'' from the curves of Figs. 1 and 2. A ratio of power dissipation in the insects to that in the grain can be calculated as $R_p = (E_i/E_g)^2 (\epsilon_{ri}''/\epsilon_{rg}'')$, and its calculation at several selected frequencies is summarized in Table 1. Examination of values in the table shows that the loss factor is the dominant factor influencing the power dissipation ratio in this case. The dielectric-constant ratio changes less with frequency, and its influence on R_p through its effect on the field-intensity ratio is minor compared to that of the loss-factor ratio.

R_p values in Table 1 show that the frequency range between about 10 and 100 MHz should offer the best opportunity for selectively heating the rice

TABLE 1. CALCULATION OF THE POWER DISSIPATION RATIO, R_p, FOR ADULT RICE WEEVILS IN WHEAT AT SELECTED FREQUENCIES

Frequency, Hz	$\epsilon'_{ri}/\epsilon'_{rg}$	E_i/E_g	$(E_i/E_g)^2$	$\epsilon''_{ri}/\epsilon''_{rg}$	R_p
10^3	2.32	0.69	0.48	0.41	0.20
10^4	2.75	0.63	0.40	0.70	0.28
10^5	2.57	0.66	0.43	2.10	0.91
10^6	2.63	0.65	0.42	4.53	1.90
10^7	2.15	0.72	0.52	5.59	2.93
10^8	1.77	0.80	0.63	5.60	3.54
10^9	1.50	0.86	0.73	1.56	1.15
10^{10}	1.60	0.83	0.69	1.60	1.11

weevils. In fact, for the case of rice weevils in wheat at 24 C, the plot of loss factors vs. frequency can be used to identify the most promising frequency range for differential heating. The peak of the loss-factor curve for rice weevils (Fig. 2) falls in the range between 5 and 100 MHz.

Measurements throughout the 250-Hz to 12.2-GHz range on wheat conditioned to 12.4-percent moisture gave somewhat higher values for the loss factor at frequencies below 1 MHz than those observed for the wheat at 10.6-percent moisture. At frequencies above 1 MHz, however, loss-factor values were very nearly the same for the two moisture contents. This difference at high and low frequencies in the dependence of the loss factor on moisture content of wheat in this moisture range was also revealed in earlier work (Nelson, 1965; Stetson and Nelson, 1972). Therefore, the conditions for selective heating of rice weevils in wheat are not appreciably changed in the frequency range of interest by an increase in wheat moisture from 10.6 percent to 12.4 percent.

Some experimental evidence is available which tends to support predictions based on the foregoing analysis concerning selective heating of insects when exposed in grain to high-frequency electric fields (Table 2). Adult rice weevils in hard red winter wheat were all killed by 39-MHz dielectric heating treatments of a few seconds that raised the grain temperature to 39 C (Nelson and Whitney, 1960), whereas these insects could survive many hours at these temperatures in a hot-air oven. Mortality of the insects was explained on the basis of selective heating of the insects by the RF field. Similar treatment of granary weevil, Sitophilus granarius (L.), adults in wheat resulted in complete mortality of adults when grain temperatures were momentarily raised to 41 C by 39-MHz exposures (Nelson and Kantack, 1966). In experiments in which the same species were treated in a microwave oven operating at a frequency of 2.45 GHz, exposures resulting in grain temperatures above 57 C were required to kill all of the adults (Baker et al, 1956). At 2.45 GHz, grain temperatures of 78 C were necessary to prevent hatching of granary weevil eggs. Work at 39 MHz indicated that all developmental stages of rice and granary weevils could be controlled by exposures which raised the grain temperature momentarily to the 60 to 66 C range. Thus, the expectation that better selective heating of the insects should be achieved at 40 MHz than at 2,450 MHz, on the basis of measured dielectric properties, appears to be supported by the experimental work cited. Similar comparisons are presented in Table 2 for experiments conducted at 90 and 2,450 MHz with the confused flour beetle, *Tribolium confusum* Jaquelin duVal.

The dielectric properties of the insects and grain are also temperature dependent. Therefore, the power dissipation ratio may change during RF treatment. Information on the temperature dependence as well as frequency dependence of the dielectric properties of insects and grain would be useful in formulating a more complete picture of the relative power dissipation in the two materials during the dielectric heating process.

CONCLUSIONS

1 The dielectric constants of bulk samples of wheat and of adult rice weevils decrease continuously with increasing frequency throughout the range from 250 Hz to 12.2 GHz. Dielectric constants for rice weevils are considerably higher than those for wheat, and the ϵ'_r - vs. - log f curve for rice weevils exhibits a broad Debye-type dispersion in the region between 100 kHz and 1 GHz.

2 Values for the dielectric loss factors of wheat and rice weevils decrease with increasing frequency from 250 Hz to a minimum in the region of 50 kHz, then increase to a peak in the region between 5 and 100 MHz, and decline to minimum values again at frequencies above 1 GHz. The ϵ''_r-vs.-log f curve for rice weevils exhibits a prominent absorption peak between 5 and 100 MHz accompanying the Debye-type dispersion noted in the frequency range between 100 kHz and 1 GHz. The highest insect-to-grain loss-factor ratios were noted in this absorption region.

3 Differential radiofrequency power dissipation in insects and grain depends mainly upon differences in the loss factors of the two materials, but, also, to a lesser extent, upon differences in their dielectric constants, because the dielectric constants, or permittivities, influence the electric field intensities in the materials.

4 Insect-to-grain power dissipation ratios, calculated from insect-to-grain loss-factor and dielectric-constant ratios, reveal the 10- to 100-MHz frequency range as the most promising region for selectively heating the insects. Limited experimental data tend to support this prediction.

TABLE 2. REPORTED TEMPERATURES IN HOST MEDIA PRODUCED BY RF FIELDS NECESSARY FOR 100-PERCENT MORTALITY OF INSECTS

Species	Stage	Frequency	Medium and temperature		Reference
		MHz		deg C	
Rice weevil	adult	39	wheat	39	Nelson and Whitney, 1960
	mixed immature	39	wheat	61	Nelson and Whitney, 1960
Granary weevil	adult	39	wheat	41	Nelson and Kantack, 1966
	adult	2450	wheat	>57	Baker et al., 1956
	larval	2450	wheat	>82	Baker et al., 1956
	egg	2450	wheat	78	Baker et al., 1956
Confused flour beetle	adult	90	flour	59	van den Bruel et al., 1960
	larval	90	flour	53	van den Bruel et al., 1960
	adult	2450	flour	>68	Baker et al., 1956
	larval	2450	flour	>82	Baker et al., 1956

SUMMARY

Selective energy absorption from radiofrequency (RF) electric fields offers a possible means for controlling stored-grain insects. The degree of differential or selective dielectric heating which can be accomplished in treating a mixture of materials depends upon the relative values of their respective dielectric properties. The dielectric properties of wheat and adult rice weevils were measured throughout the frequency range from 250 Hz to 12.2 GHz. Subsequent analysis of the new information obtained reveals that the most promising frequencies for selectively heating the insects lie in the range between 10 and 100 MHz.

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