Possibilities for Controlling Insects with Microwaves and Lower Frequency RF Energy

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Abstract—**Principles applicable to the control of stored-product insects with radio-frequency (RF) electric energy and general research findings on this topic are reviewed. Data are presented on the frequency dependence of the dielectric constant and dielectric-loss factor of insects and grain, and use of such information is discussed in relation to RF treatment of infested products to control insects. Experimental data that confirm the usefulness of information on dielectric properties are presented. These data show that RF treatment at 39 MHz is much more effective for controlling adult rice weevils in wheat than is treatment at 2450 MHz. Some aspects of practical application are also considered.**

INTRODUCTION

Successful control of various economically important insect species with chemical insecticides has contributed substantially to the ability of modern American agriculture to provide abundant supplies of high-quality food. Chemical control methods are essential for efficient production and preservation of food products. However, for the past several years concerted efforts have been devoted to the study of possible supplemental or alternative insect-control methods that might be helpful in minimizing the environmental hazards associated with chemical insecticides. Among the many possibilities considered is the use of radio-frequency (RF) electric energy to control certain stored-product insects.

Since the 1920's it has been known that insects can be killed by high-frequency electric fields. Since then, many researchers have explored possibilities for controlling various insect species with RF energy, and their findings have been reviewed in several publications [1]–[7].

Insects that infest grain, cereal products, wood, seed, and other stored products can be controlled through dielectric heating by microwave or lower frequency RF energy. Some studies have been conducted with insects in soils and in fruits and other food products. Raising the temperatures of infested materials by any means can be used to control insects if the infested product can tolerate the temperature levels that are necessary to kill the insects. Dielectric heating offers an advantage over more conventional types of heating if the insects can be heated selectively. If the insects will absorb energy at a higher rate than the host material, their temperatures may be raised rapidly to a lethal level without excessively heating the host product.

In many of these studies, a question has arisen concerning the lethal mechanism responsible for the injury or death of the insects exposed to RF electric fields. Most investigators believe that deleterious effects can be accounted for on the basis of RF dielectric heating. Often, "specific effects" attributed to the electric field have been explained by differential or localized heating of insect body tissues. However, some observations may or may not be explained satisfactorily on this basis [6], [8], and further research is needed to resolve the question.

Recent advances in the application of microwave power and interest in nonchemical methods of controlling insects have stirred new interest in the potential use of RF energy to control insects. The purpose here is to summarize the general findings and to review briefly some of the fundamental principles relating to the use of RF electric energy for controlling insects.

FUNDAMENTAL PRINCIPLES

Because principles that are known to be useful for insect control depend upon thermal effects, the concepts of RF dielectric heating of substances will be considered briefly.

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The average power dissipated per unit volume in a dielectric under the influence of an alternating electric field may be expressed as

$$P = |E|^2 \sigma = |E|^2 \omega\epsilon_0\epsilon_r'' = 2\pi f |E|^2 \epsilon_0\epsilon_r'' = 55.63 f |E|^2 \epsilon_r'' \times 10^{-12} \text{ W/m}^3 \quad (1)$$

where E is the rms value of the electric-field intensity in the dielectric (volts/meter), f is the frequency of the alternating field (hertz), ω is the angular frequency ($2\pi f$), ϵ_0 is the permittivity of free space (8.854×10^{-12} F/m), and σ and ϵ_r'' are, respectively, the ac conductivity and the relative dielectric loss factor or loss index of the material at the particular frequency considered. The loss factor ϵ_r'' is the imaginary part of the complex relative permittivity $\epsilon_r = \epsilon_r' - j\epsilon_r''$ and the real part ϵ_r' is the dielectric constant.

The time rate of temperature increase (degrees Celsius/second) in the dielectric, as a result of energy absorption from the RF field, may be expressed as

$$dT/dt = 0.239 \times 10^{-6} P/c\rho \quad (2)$$

where P is the power density in watts/cubic meter, and c and ρ are, respectively, the specific heat and specific gravity of the dielectric. This expression neglects heat losses from the dielectric during exposure and is not valid if energy is used for the volatilization of water or other materials in the dielectric.

Although (1) and (2) are applicable to homogeneous dielectrics under specified conditions, they are difficult to apply to heterogeneous dielectrics or mixtures of materials. In these instances, the relationships should be valid for individual constituents of the mixture, but reliable values for the field intensity E, the loss factor ϵ_r'', and even the specific heat and specific gravity may be somewhat difficult to obtain.

For the simple case of a sphere of one material (medium 1) embedded in an infinite medium of another material (medium 2), the relationship between field intensities in the two media may be expressed as

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

Thus the relative magnitude of the dielectric constants of materials in the mixture and their geometric shapes and relationships will influence the electric-field-intensity distribution in a mixture of materials.

At microwave frequencies, the attenuation of the energy as it penetrates large objects is another factor to be considered. The degree of attenuation depends mainly upon the dielectric loss factor of the materials.

Although an accurate analytical approach to the action of microwaves (and lower frequency RF energy as well) on a complex mixture such as insects and their host materials may appear futile, basic principles can provide useful insight in understanding observed phenomena.

GENERAL FINDINGS

Many early findings from insect-control studies can be substantiated by considering the basic principles. The heating rate of materials exposed to RF electric fields increases with increasing field intensity and with increasing frequency [(1) and (2)]. Since the loss factor of hygroscopic materials generally increases with moisture content, their heating rates also are higher when moisture contents are greater.

Studies have shown that many insects that infest grain, cereal products, and wood products can be controlled by short exposures to RF fields that do not damage the host material. Generally, for successful RF insect-control treatments, resulting temperatures in the host material range between about 40 and 70°C, depending upon the host, the insect species, and the nature of the RF treatment. So far as is known, however, RF methods have not been practical, because they are more costly than conventional chemical methods.

Entomological Factors

Differences among various insect species in their susceptibility to control have been noted when they were treated in common host media under comparable conditions [7], [9]–[11]. Some differences are no doubt attributable to interspecific characteristics of a biological or physiological nature, but some may be explained by variations in size and in geometric relationships.

Differences have also been found in the susceptibility of different developmental stages within the same species [2], [7], [9]–[13]. In general, the adults are more susceptible to control by RF fields than are the immature forms, i.e., the egg, larval, and pupal stages. Some of the stored-grain insect species have been found more susceptible to control when they are outside the grain kernels than when they are concealed within the kernels [11].

Various injuries to the legs and other appendages of insects subjected to sublethal RF exposures have been observed [2], [14]–[16]. These injuries have usually been attributed to high *E*-field concentrations and consequent localized heating during RF exposure. Interspecific differences have been found in the degree of delayed mortality observed during the weeks following RF treatment [7], [11], [14].

Reproductive sterilization of the type produced by ionizing radiations has not been observed in RF-treated insects. Reproductive capacity, however, has been reduced in surviving adults by treatments that achieve a relatively high mortality of the population. Studies have revealed the nature of some of the damage to insect testicular and ovarian tissues—such damage probably resulting from thermal effects of RF energy [17].

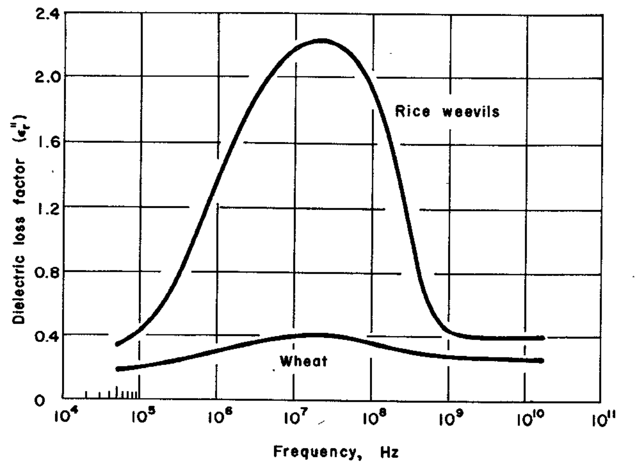

Fig. 2. Dielectric absorption of bulk samples of adult rice weevils and of hard red winter wheat (10.6-percent moisture) at 24°C.

Physical Factors

The influence of various physical factors, such as frequency, electric-field intensity, pulse modulation, heating rate, and characteristics of host materials, have also been studied [7], [11]. General conclusions are difficult to draw concerning some of these factors. High field intensities are more effective than are low field intensities in some instances. High heating rates are to be preferred, generally, to minimize thermal loss from the insect to the host medium. Although pulse modulation permits the use of higher field intensities, definite advantages in using modulation to control insects have not been confirmed.

Contrasting differences in the effectiveness of RF insect-control treatments have been noted when widely differing frequencies have been used. In particular, comparisons of stored-grain insect-control treatments at frequencies of 11–90 MHz with treatments at 2450 MHz have shown the lower frequency range to be much more efficient in controlling the insects [7], [18]. Resulting temperatures in the host media were considerably higher at 2450 MHz than at the lower frequencies for exposures required to control the different insect species and developmental stages of those species.

The importance of frequency has been further illustrated in studies of the frequency dependence of the dielectric properties of insects and the host medium. Values for the dielectric constant and dielectric loss factor of adult rice weevils, *Sitophilus oryzae* (L.), and wheat, *Triticum aestivum* (L.), have been measured over a wide range of frequencies [18]. Frequency dependence of the dielectric constant ϵ_r' and the loss factor ϵ_r'' for these two kinds of materials are illustrated in Figs. 1 and 2. An analysis of the differential dielectric heating to be expected at different frequencies, based on (1) and (3) and values of ϵ_r' and ϵ_r'', revealed that the dielectric loss factor is the dominant factor to be considered [18]. Therefore, it is obvious from the data of Fig. 2 that better selective heating of the insects should be expected in the frequency range between about 5 and 100 MHz than can be expected at frequencies above 1 GHz.

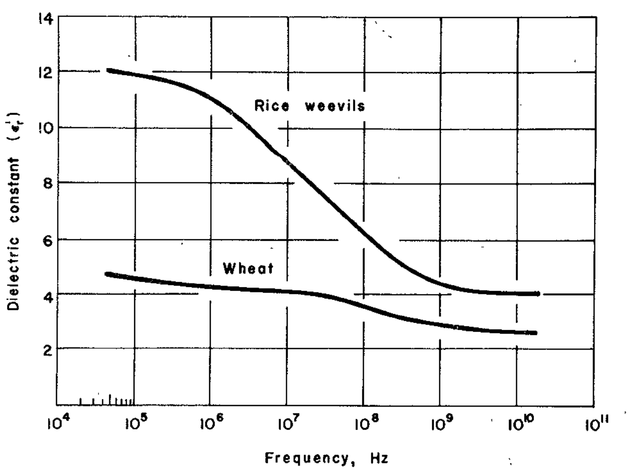

Fig. 1. Dielectric dispersion of bulk samples of adult rice weevils and of hard red winter wheat (10.6-percent moisture) at 24°C.

These predictions have been confirmed by experimental results obtained when exposing hard red winter wheat infested with adult rice weevils to RF fields at frequencies of 39 and 2450 MHz for sequences of time exposures ranging from 1 to several seconds [19]. Observed relationships between insect mortalities and resulting temperatures in the wheat are illustrated in Fig. 3. Complete insect mortality was obtained with much lower grain temperatures when infested grain was treated at 39 MHz than when it was treated at 2450 MHz. This result indicates that a much higher degree of differential heating was obtained in the lower frequency range than was obtained at microwave frequencies. The delayed mortality of the insects was also much more severe when they were treated at 39 MHz than it was when they were treated at 2450 MHz.

DISCUSSION

Since the curves for ϵ_r' and ϵ_r'' of rice weevils and wheat, as illustrated in Figs. 1 and 2, are characteristic of some dielectric dispersion and absorption phenomenon (Fig. 4), it is probable that the relaxation frequencies (frequencies of maximum loss) will shift to higher frequencies as the temperatures of the materials increase. Shifts in relaxation frequencies of one or two orders of magnitude may be possible in the range through which the temperature of the insects must be elevated to achieve complete mortality. If these shifts should occur during RF treatment at a fixed frequency of 40 MHz, for example, it means that the insect-to-grain loss-factor ratio will decrease during the exposure, and the relatively large selective heating advantage possible at the beginning of the exposure may be reduced during later stages of the exposure. Therefore, it may be possible to materially improve the efficiency of RF treatment for insect-control purposes by increasing the frequency during exposure to more nearly follow the maximum insect-to-grain loss-factor ratio as the treatment progresses.

Because the energy absorption in different tissues of the insect body depends upon the relative dielectric properties of the different tissues, frequency- and temperature-dependence information concerning the dielectric properties of the different kinds of body tissue might also reveal ways of improving the effectiveness of RF insect-control methods and thus improve chances for practical application.

PRACTICAL ASPECTS AND CONCLUSIONS

If the anticipated shifts in relaxation frequencies occur, as explained in the foregoing example, the optimum frequency for finishing the treatment may well approach the microwave range. The most practical design for a high-power RF system might include two or more fixed-frequency power oscillators. The infested product could be conveyed continuously through the system, with the exposure starting at the lower frequency and finishing at the higher frequency.

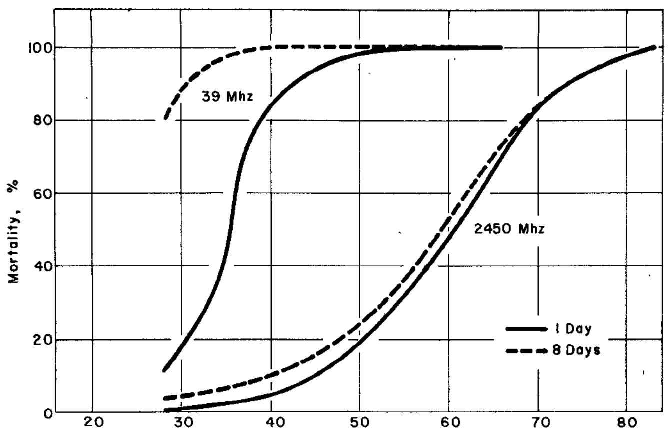

Fig. 3. Comparison of mortalities of adult rice weevils treated in hard red winter wheat at frequencies of 39 and 2450 MHz. (Mortalities observed 1 and 8 days after treatment.)

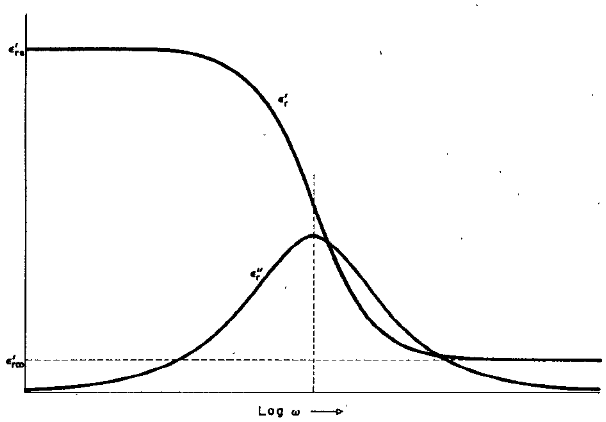

Fig. 4. Dispersion and absorption curves representing the Debye relaxation process for polar molecules.

Cost estimates for RF insect control in grain, based on fixed-frequency equipment operating at one frequency, indicate that RF methods might be three to five times more expensive than chemical controls currently in use. Various other factors that influence practical application have also been considered [7]. A major improvement in the efficiency of RF treatment could materially change the economic picture. Therefore, a survey of the frequency and temperature dependence of the dielectric properties of insects and host materials for any particular application may provide important information on which to assess the practicability of an RF insect-control application.

Continually increasing concern about environmental aspects of chemical control methods is another factor that should be considered. RF insect-control methods offer two unique advantages—speed of treatment and a lack of potentially harmful chemical residues. Establishment of any nonthermal effects, which might be exploited for insect-control purposes, should substantially improve chances for practical application. On the basis of differential dielectric heating alone, however, it may be possible, with improvements in effectiveness and with developing technology, to apply RF insect-control methods for certain applications for which the techniques may be especially well suited.

REFERENCES

[1] A. M. Thomas, "Pest control by high-frequency electric fields—Critical resume," British Electrical and Allied Industries Research Association, Thorncroft Manor, Dorking Road, Leatherhead, Surrey, England, Tech. Rep. W/T23, 1952.

[2] H. Frings, "Factors determining the effects of radio-frequency electromagnetic fields on insects and materials they infest," *J. Econ. Entomol.*, vol. 45, pp. 396–408, 1952.

[3] A. A. Peredel'skii, "The problem of electrotechnical measures for combatting harmful insects" (in Russian), *Usp. Sovrem. Biol.*, vol. 41, pp. 228–245, 1956.

[4] F. L. Watters, "Control of insects in foodstuffs by high-frequency electric fields," *Proc. Entomol. Soc. Ontario*, vol. 92, pp. 26–32, 1962.

[5] S. O. Nelson, "Electromagnetic and sonic energy for insect control," *Trans. ASAE*, vol. 9, pp. 398–403 and 405, 1966.

[6] ——, "Electromagnetic energy," in *Pest Control—Biological, Physical, and Selected Chemical Methods*, W. W. Kilgore and R. L. Doutt, Ed. New York: Academic, 1967, pp. 89–145.

[7] ——, "Insect-control studies with microwaves and other radiofrequency energy," *Bull. Entomol. Soc. Amer.*, vol. 19, pp. 157–163, 1973.

[8] R. L. Carpenter and E. M. Livstone, "Evidence for nonthermal effects of microwave radiation: Abnormal development of irradiated insect pupae," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Biological Effects of Microwaves*), vol. MTT-19, pp. 173–178, Feb. 1971.

[9] S. O. Nelson and W. K. Whitney, "Radio-frequency electric fields for stored-grain insect control," *Trans. ASAE*, vol. 3, pp. 133–137 and 144, 1960.

[10] S. O. Nelson and B. H. Kantack, "Stored-grain insect control studies with radio-frequency energy," *J. Econ. Entomol.*, vol. 59, pp. 588–594, 1966.

[11] S. O. Nelson, L. E. Stetson, and J. J. Rhine, "Factors influencing effectiveness of radiofrequency electric fields for stored-grain insect control," *Trans. ASAE*, vol. 9, pp. 809–815 and 817, 1966.

[12] H. H. Webber, R. P. Wagner, and A. G. Pearson, "High-frequency electric fields as lethal agents for insects," *J. Econ. Entomol.*, vol. 39, pp. 487–498, 1946.

[13] V. H. Baker, D. E. Wiant, and O. Taboada, "Some effects of microwaves on certain insects which infest wheat and flour," *J. Econ. Entomol.*, vol. 49, pp. 33–37, 1956.

[14] W. K. Whitney, S. O. Nelson, and H. H. Walkden, "Effects of high-frequency electric fields on certain species of stored-grain insects," Market Quality Research Division, AMS, U. S. Department of Agriculture, Marketing Res. Rep. 455, 1961.

[15] A. M. Kadoum, H. J. Ball, and S. O. Nelson, "Morphological abnormalities resulting from radiofrequency treatment of larvae of *Tenebrio molitor*," *Ann. Entomol. Soc. Amer.*, vol. 60, pp. 889–892, 1967.

[16] P. S. Rai, H. J. Ball, S. O. Nelson, and L. E. Stetson, "Morphological changes in adult *Tenebrio molitor* (Coleoptera: Tenebrionidae) resulting from radiofrequency or heat treatment of larvae or pupae," *Ann. Entomol. Soc. Amer.*, vol. 64, pp. 1116–1121, 1971.

[17] ——, Cytopathological effects of radiofrequency electric fields on reproductive tissue of adult *Tenebrio molitor* (Coleoptera: Tenebrionidae)," *Ann. Entomol. Soc. Amer.*, vol. 67, pp. 687–690, 1974.

[18] S. O. Nelson and L. F. Charity, "Frequency dependence of energy absorption by insects and grain in electric fields," *Trans. ASAE*, vol. 15, pp. 1099–1102, 1972.

[19] S. O. Nelson and L. E. Stetson, "Comparative effectiveness of 39- and 2450-MHz electric fields for control of rice weevils in wheat," *J. Econ. Entomol.*, vol. 67, pp. 592–595, 1974.

A More Than 4-Percent-Efficiency Solid-State Transmitter for a 4-GHz Radio Relay

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***Abstract*—An FM transmitter having 220-mW output power and 5-W total dc input power and operating in the 4-GHz band has been developed. This transmitter provides a dc-to-RF signal-conversion efficiency of more than 4 percent. Featuring low power consumption and high reliability, this transmitter is suitable for use as a transmitter or an exciter for radio relay of a maximum of 1380 channels.**

INTRODUCTION

This transmitter has been developed with consideration for the use of batteries and elimination of maintenance servicing. In order to achieve low power consumption and high-reliability transmitter performance it may be inevitable that one must reduce the number of active devices and improve the efficiencies of these devices. For this purpose, it may be most desirable to use a high-gain transistor injection-locked amplifier in combination with a low-level up converter driven by a low-power local oscillator.

A transistor injection-locked amplifier which employs a transistor

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