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Comparative Effectiveness of 39- and 2450-MHz Electric Fields for Control of Rice Weevils[1] in Wheat[2,3,4]

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ABSTRACT

A comparison of 39-MHz and 2450-MHz radiofrequency (RF) electrical treatments to control adult *Sitophilus oryzae* (L.) in hard red winter wheat revealed that the 39-MHz treatment was much more effective than treatment at 2450 MHz. Complete insect mortality was achieved by 39-MHz treatments that raised grain temperatures to 40°C; whereas, grain temperatures of ca. 80°C were required for complete mortality in 2450-MHz treatments. Insect mortalities from 39-MHz exposures were much greater 1 day after treatment than were those from 2450-MHz exposures producing comparable grain temperatures. The degree of injury and delayed mortality resulting from 39-MHz exposures also was much more severe than that resulting from 2450-MHz exposures. The results confirmed predictions, based on measurements of dielectric properties of adult rice weevils and wheat, that 39-MHz treatments should provide a much better opportunity for selectively heating the insects than would treatments at 2450 MHz.

The use of radiofrequency (RF) electric fields has been considered for controlling stored-product insects that infest grain, cereal products, and other commodities. The influence of various physical and entomological factors has been discussed in detail by Nelson (1967, 1973a).

Biological materials exposed to electric fields of sufficiently high frequency and intensity are rapidly heated as they absorb energy from the electric field. The process is known as dielectric heating. Since the rate of energy absorption by any substance depends upon its electrical characteristics, an opportunity exists for selectively heating one type of substance in a mixture of different substances. Thus, insects in grain can be heated to lethal temperatures by the process of RF dielectric heating without raising the grain temperature to the same level as that of the insects.

The electrical properties of interest here are the relative dielectric constant, ϵ'_r, and the relative dielectric loss factor, ϵ''_r, which are, respectively, the real and imaginary parts of the relative complex permittivity, $\epsilon^*_r = \epsilon'_r - j\epsilon''_r$.

The power dissipated per unit volume in a dielectric exposed to an RF electric field is given by

$$P = 0.556fE^2\epsilon''_r\,, \qquad (1)$$

where P is in W/cm^3 when f is expressed in MHz (10^6 cycle/sec), and the rms electric field intensity, E, is in kV/cm. In a mixture of different materials, the power dissipation in each depends upon the electric field intensity in each material and the dielectric loss factor of that material. An analysis of these factors for insects and grain was reported by Nelson and Charity (1972). Although the field-intensity distribution in a mixture depends upon the ϵ'_r values of the components of the mixture and their geometric relationships, the loss factor was shown to be the dominant factor influencing the ratio of the power dissipation in the insects to that in the grain.

Because the dielectric properties are frequency-dependent, their variation with frequency was determined for bulk samples of adult rice weevils, *Sitophilus oryzae* (L.), and hard red winter wheat (Nelson and Charity 1972). Fig. 1 shows the relationship between the dielectric loss factor of these materials and frequency. Consideration of these data and additional factors revealed that control of adult rice weevils in wheat should be accomplished more efficiently at frequencies between ca. 5–100 MHz than at microwave frequencies above ca. 1 GHz (10^9 cycle/sec). Information on experimental treatment of stored-grain insects in the frequency ranges of interest (5–100 MHz and the microwave range) supports this supposition (Nelson 1973a).

Reported here are results of an experiment designed to provide a direct comparison of the effectiveness of RF treatment on rice weevils in wheat at frequencies of 39 and 2450 MHz.

Materials and Methods.—Five- to 6-week-old adult rice weevils were removed from cultures[6] by aspiration and placed in 1970 Nebraska-origin 'Scout 66' hard red winter wheat with a moisture content of 13.3%. Moisture content was determined by drying ground samples in a forced-air oven for 1 h at 130° C in accordance with standard methods (Horwitz 1970). Dielectric properties of the wheat were measured as $\epsilon'_r = 4.13$ and $\epsilon''_r = 0.55$ at 39 MHz, and as $\epsilon'_r = 2.77$ and $\epsilon''_r = 0.30$ at 2450 MHz. The methods of measurement were described by Nelson et al. (1953) and Nelson (1973b). Samples were prepared for exposure by filling Bradley No. 3 polystyrene boxes (ca. 4.7 × 4.7 × 1.9 cm outside dimensions) with thoroughly mixed wheat (ca. 25 g) and placing 10 insects in each box. Sample boxes were then exposed to RF electric fields at frequencies of 39 or 2450 MHz for a series of exposure times at each frequency. Ten replicates were employed for each exposure time at each frequency, and 10 boxes were held as untreated checks, thus providing 100 insects for observation at each treatment level.

For 39-MHz exposures, samples were treated in a General Electric Model 4HD3B2 Electronic Dielectric Heater as described by Nelson and Whitney (1960), but it was equipped with a filtered power supply for the power oscillator (Nelson et al. 1966) so that the continuous-wave oscillator output was not modulated. For exposures at 2450 MHz, samples were supported at the center of a Raytheon Model 1162 Mark III Radarange® microwave oven with 1 magnetron opera-

[1] Coleoptera: Curculionidae.

[2] Published as Paper No. 3756, Journal Series, Nebraska Agric. Exp. Stn. Received for publication May 1, 1974.

[3] Dr. H. J. Ball endorses and communicates.

[4] Mention of trade names is for purposes of identification only and does not imply endorsement by the USDA.

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[6] Rice weevil cultures furnished by the USDA, ARS, Stored-Product Insects Res. and Devel. Lab., Savannah, Ga.

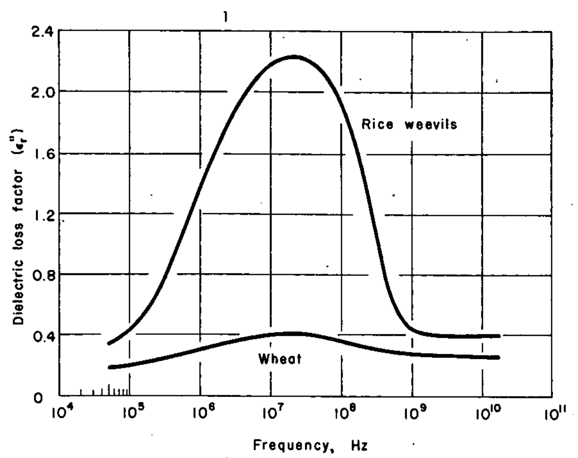
Reprinted from the
JOURNAL OF ECONOMIC ENTOMOLOGY

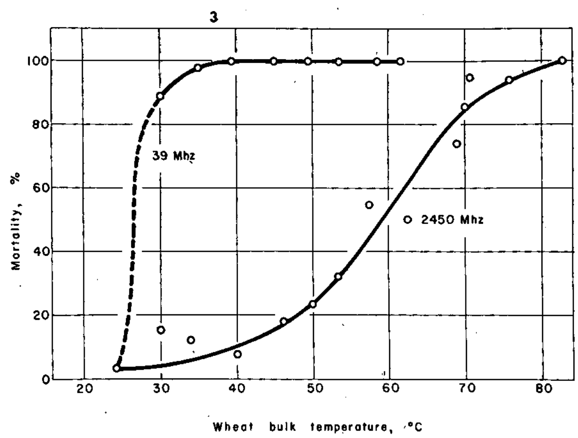
ting (800-W output rating) and with a 250-ml water load placed in a standard location in the oven for all of the exposures (Stetson and Nelson 1972).

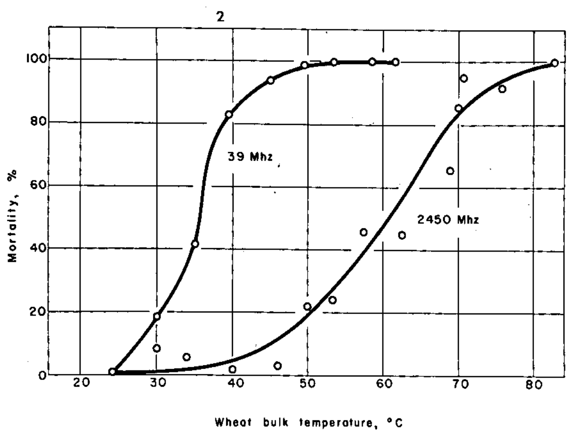
Exposures ranged from 1–8 s at 39 MHz and from 1–13 s at 2450 MHz and were incremented in 1-s intervals at both frequencies. The electric field intensity for the 39-MHz treatments (1.4 kV/cm) was selected to provide the same heating rate for the wheat as that obtained with the 2450-MHz microwave oven. The grain-mass temperatures in the sample boxes were recorded immediately after exposure by inserting No. 36 gauge, nylon-insulated, duplex, copper-constantan thermocouples through a small hole (No. 60 wire-size drill) in the side of each box. Temperatures in the boxes at the instant RF exposures ended were then determined using extrapolation techniques described by Nelson and Whitney (1960). Sample boxes were then permitted to cool at room temperature (24° C) before being placed in a controlled storage chamber at 27° C and 65–70% RH to be held for observation.

Insect mortality counts were taken at 1 and 8 days and 3 weeks after treatment. None of the insects, dead or alive, were discarded until the final mortality count. The criterion for death in adult insects was complete immobility, as determined by visual examination, with stimulation by prodding, air currents, and radiant heat from the incandescent lamp used for illumination. At the time of the final mortality count, adult rice weevils were removed from the sample boxes, and wheat samples were held in the controlled storage chamber for 4 more weeks to observe any rice weevil emergence resulting from reproductive activity of the test insects.

RESULTS AND DISCUSSION.—Fig. 2 and 3 summarize resulting mortality counts; adult rice weevil mortalities are shown as a function of the grain-bulk temperatures resulting from 1- to 8-s RF exposures at 39 MHz and 1- to 13-s exposures at 2450 MHz. Mortality in untreated checks was 1% at 1 day and 3% at 8 days. Both 1-day and 8-day counts revealed that the 39-MHz exposures were much more effective than were 2450-MHz exposures in killing the insects. Comparison of the 8-day mortality curves shows a particularly striking







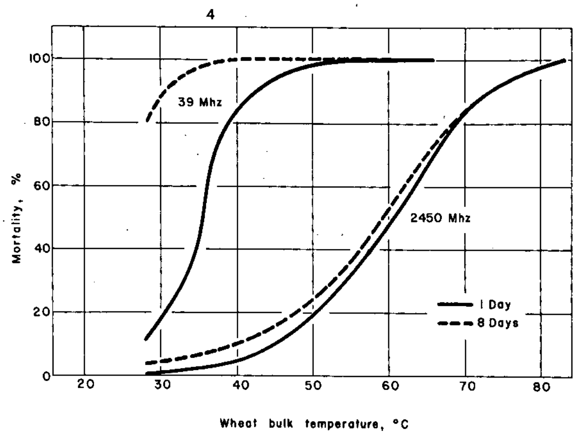


FIG. 1.—Frequency dependence of the dielectric loss factor of bulk samples of adult rice weevils and hard red winter wheat at 24°C.

FIG. 2.—Mortality curves for adult rice weevils 1 day after exposure, in hard red winter wheat, to 39- and 2450-MHz electric fields. Untreated checks at 24°C.

FIG. 3.—Mortality curves for adult rice weevils 8 days after exposure, in hard red winter wheat, to 39- and 2450-MHz electric fields. Untreated checks at 24°C.

FIG. 4.—Comparison of 1-day and 8-day mortality curves for adult rice weevils exposed to 39- and 2450-MHz electric fields.

difference. Complete mortality was achieved at 39 MHz by exposures that produced grain temperatures of ca. 40° C, whereas much more severe treatments that produced grain temperatures of ca. 80° C were necessary for complete mortality when the insects and wheat were treated at 2450 MHz. Eight-day and 3-week mortality counts were essentially the same.

More variation is noted in the mortality-temperature points plotted in Fig. 2 and 3 for 2450-MHz data than for the 39-MHz data. Because of the shorter wavelength of 2450-MHz waves in the grain, greater variation in energy absorption in different portions of the sample can occur in these treatments than might be expected at 39 MHz.

An interesting contrast also is evident in the delayed mortality observed in samples treated at 39 and 2450 MHz (Fig. 4). At all mortality levels below 100%, the additional insect mortality observed between 1 and 8 days posttreatment was much greater in samples exposed at 39 MHz than in samples exposed at 2450 MHz. This indicates some difference in the degree of injury produced by treatments at the 2 frequencies. Differences in the insects exposed to the 2 frequencies were obvious by visual examination. Most insects in the samples treated at 2450 MHz that were not dead at the time of the 1-day count moved around normally. Most of the insects in the 39-MHz samples that were not dead at the time of the 1-day count appeared badly injured. Very few were able to walk at all, and even these exhibited leg injury as noted by Whitney et al. (1961). Most of those that were not dead were lying on their backs and were capable of moving only the head or legs. Movement in some insects was so slight that it was difficult to distinguish them from dead insects.

Progeny counts on the wheat samples 7 weeks posttreatment revealed that as many as 200 adults had emerged from many of the 25-g samples infested by the 10 initial test insects. This high level of infestation was noted in the untreated controls and also in lower level 2450-MHz treatments. In treated sample boxes, oviposition could have taken place before the RF exposures because the adult test insects were placed in the boxes a few hours before treatment. Of course, oviposition also could have taken place after treatment if the insects were not too badly injured or killed. Earlier studies showed that rice weevil eggs in wheat kernels survive RF treatment better than adult insects (Nelson and Whitney 1960, Whitney et al. 1961, Nelson and Kantack 1966, Nelson et al. 1966). Emergence of progeny was noted in all 2450-MHz sample groups except those that received the most severe exposure (13 s, 83° C) although the number of emerging insects declined steadily with increasing exposure in samples that reached temperatures above ca. 50° C. In comparison, the number of insects emerging from samples treated at 39 MHz was small, averaging ca. two/25-g sample for the mildest exposure (1 s, 30° C). No emergence was observed in 39-MHz samples that reached temperatures of 50° C or higher.

Since the insect mortality is attributed to lethal temperatures resulting from dielectric heating within the insects, the degree of differential heating obtained at 39 MHz is obviously much greater than that obtained at 2450 MHz. Consideration of the dielectric loss-factor values for bulk samples of adult rice weevils and wheat (Fig. 1) and reference to Equation 1 show that this contrast in differential heating at 39 and 2450 MHz is to be expected. The time rate of temperature increase in a material depends directly upon the power dissipated per unit volume, $dT/dt = 0.239\ P/c\rho = 0.1329 fE^2\epsilon''_r/c\rho$, where T represents the temperature in ° C, t is time in seconds, c and ρ are the specific heat and specific gravity of the material, respectively, and the other factors are as defined for Equation 1. Therefore, the heating rates of the insects and the grain depend directly, though not exclusively, upon their respective dielectric loss factor, ϵ''_r, values. Comparison of ϵ''_r values for the insects and grain (Fig. 1) at 2450 MHz reveals that little differential heating of the insects should be expected because of the difference in their values for ϵ''_r. However, at a frequency of 39 MHz, the ϵ''_r value for the insects is more than 5 times greater than that for the wheat, and marked differences in their heating rates should therefore be expected, with the insects heating much more rapidly than the wheat.

The dielectric properties of biological materials are temperature-dependent as well as frequency-dependent. Data shown for ϵ''_r in Fig. 1 were taken at 24° C. As the insects and grain increase in temperature, their relative loss factors may change. From basic theory of dielectrics, one would expect the peak in the curves (Fig. 1) to shift to higher frequencies. If this shift should occur, the ratio of the loss factor for the insects to that for the grain may change during the RF treatment. It might then be advisable to change the treatment frequency as the treatment progresses to follow the maximum difference between the loss factors of the insects and grain to optimize selective heating of the insects. Both the temperature and frequency dependence of the dielectric properties of insects and grain should be determined to learn whether selective heating of the insects can be further improved, thus making the treatment more efficient and more economically competitive.

CONCLUSIONS.—A direct comparison of 39-MHz and 2450-MHz RF electric fields to kill adult rice weevils in hard red winter wheat confirmed predictions, based on measurements of the dielectric properties of the insects and grain, that the 39-MHz treatment should provide much better differential heating of the insects than would treatment at 2450 MHz in the microwave frequency range.

Complete mortality of adult rice weevils in wheat was achieved by 39-MHz electrical treatments that produced grain temperatures of 40° C; whereas treatments at 2450 MHz did not achieve complete mortality until grain temperatures reached about 80° C.

Treatments at 39 MHz that did not produce complete mortality of the rice weevils were much more injurious to insects surviving the exposures 1 day after treatment than were treatments at 2450 MHz that produced corresponding 1-day mortalities. Consequently, delayed mortality in 39-MHz treatments was severe; whereas very little additional mortality was observed in 2450-MHz treatments after the 1-day mortality counts.

Further study of the temperature- and frequency-dependent characteristics of the dielectric properties of insects and grain is necessary to learn whether additional improvements in the efficiency of RF insect-control methods may be achieved.

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