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Insect-Control Studies with Microwaves and Other Radiofrequency Energy[1,2,3]

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Recent advances in practical application of microwave power and current interest in physical methods for insect control have given rise to hope that microwave energy might be useful for controlling insects. This is not a new concept. While available information may not be sufficient for detailed evaluation of such potential applications, considerable data are available in the literature concerning the effects on insects of energy in the radiofrequency (RF) region of the electromagnetic spectrum.

The RF region is often considered that portion of the electromagnetic spectrum which lies between the audiofrequencies and the infrared region. For practical radio transmission, it is generally the region between about 10 kHz (10×10^3 cycles/sec) and 100 GHz (100×10^9 cycles/sec). The corresponding wavelengths are 30,000 m and 3 mm. "Microwave" is a term used rather loosely for electromagnetic waves in the RF region with frequencies higher than about 1 GHz (wavelengths shorter than about 30 cm). The term "radiofrequency" therefore applies to a very wide range of frequencies or wavelengths of electromagnetic energy, and the term "microwave" applies to the higher frequency end of the RF spectrum.

Experiments to evaluate the possible use of RF energy for controlling insects were begun in the late 1920's by Thomas J. Headlee and his co-workers at the New Jersey Agricultural Experiment Station (Headlee and Burdette 1929, Headlee 1934). Ark and Parry (1940) reviewed this and other early work. Later reviews of the literature relating to insect control using RF energy were published by Webber et al. 1946, Proctor and Goldblith 1951, Frings 1952, Thomas 1952, Peredel'skii 1956, and van den Bruel et al. 1960a. The critical résumé by Thomas (1952) is singularly excellent in its depth and comprehensive treatment. More recent reviews also include material on studies relating to insect control using RF electromagnetic energy (Nelson 1962, 1966, 1967, 1972; Watters 1962, Nelson and Seubert 1966).

Insects exposed to RF electric fields of sufficiently high frequency and intensity experience a rapid rise in temperature as they absorb energy from the field. Lethal effects of such exposures are generally attributed to lethal temperatures arising from dielectric heating. In the past, researchers have often expected that lethal action of RF electric fields might be due to some "specific effect" of the field rather than to purely thermal causes. While a few "nonthermal effects" have been described for biological systems, the subject of thermal and nonthermal RF effects remains somewhat controversial. Some reported observations of RF effects on insects have not been completely or satisfactorily explained on the basis of heating effects alone (Mickey 1963, Nelson 1967, Kadoum 1969a, Carpenter and Livstone 1971). However, heating effects and any nonthermal effects are difficult to separate. Because of the nature of the dielectric mixture in biological materials, localized heating of tissues, which is not detected by feasible temperature measurements, may occur. In any case, lethal "nonthermal effects" useful for insect-control purposes have not been conclusively demonstrated.

Control of insects infesting grain, wood, food, and other stored products can be achieved through dielectric heating. Microwave heating is RF dielectric heating using microwave frequencies. Dielectric heating offers an advantage over more conventional types if the insects can be heated selectively, i.e., if the insects absorb energy at a higher rate than their host material and can thus be raised rapidly to lethal temperature levels without damaging the host material. It is the purpose of this paper to review briefly the general principles and findings relating to insect control using RF electric energy and to offer some comments regarding the potential practical application of the method.

GENERAL PRINCIPLES

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

$$P = 55.63\, f\, E^2\, \epsilon_r'' \times 10^{-12} \text{ watts/m}^3, \qquad [1]$$

where f represents the frequency of the applied field in Hz (cycles/sec), E represents the electric field intensity in volts/m, and ϵ_r'' is the relative dielectric loss factor, or loss index, of the dielectric material. The loss factor, ϵ_r'', is also the imaginary part of the complex relative permittivity or complex dielectric constant, $\epsilon_r = \epsilon_r' - j\epsilon_r''$, and the real part, ϵ_r', is called the dielectric constant of the material.

The degree of heating which occurs in a material exposed to RF electric fields depends not only upon the power density in the material, P, but also upon the specific heat and specific gravity of the material. The rate of temperature increase is expressed as $dT/dt = 0.239 \times 10^{-6}\ P/c\rho$, where P is the power density in watts/m^3, and c and ρ represent specific heat and specific gravity, respectively. This equation does not take into account any energy loss from the material by conduction, radiation, or convection, or any energy used to vaporize water or other substances.

PHYSICAL FACTORS

Eq. 1 provides a basis for considering some of the physical factors that will influence effectiveness of RF electric fields in controlling insects. From Eq. 1 it is apparent that the power or rate of energy absorption depends upon the frequency, electric field intensity, and dielectric loss factor of the material.

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Differential Heating.—When infested products such as grain or wood are subjected to an RF electric field, both the host medium and the insects are subjected to the same frequency, but the electric field intensity, E, and the dielectric loss factor, ϵ_r'', may be different for the host medium and the insects. The loss factor is an intrinsic property of the material, but its value may be dependent upon frequency and temperature. Dielectric properties of hygroscopic materials also depend upon their moisture content. The dielectric properties can be determined by appropriate measurement techniques. Determination of the relative electric field intensities in the insect and the host medium is more difficult. Some insight concerning the relative field intensities in the insect and the host medium can be obtained by considering the case for a spherical inclusion of one material in a medium of another material. If one is willing to consider this model for the relationship between the insect and its host medium, the field intensity ratio may be expressed mathematically as

$$E_i/E_h = 3/(2 + \epsilon_{ri}/\epsilon_{rh}), \qquad [2]$$

where the subscript i represents the insect and h the surrounding host medium, and ϵ_{ri} and ϵ_{rh} are the respective complex relative permittivities or, for all practical purposes, the dielectric constants (Nelson and Charity 1972). If the dielectric properties, i.e., ϵ_r and ϵ_r'', of the insect and its host medium are sufficiently different and bear the proper relationship to one another, selective absorption of energy by the insect, or differential heating of the insect and its host, may be achieved. The desired relationships are a high value for the insect-to-host dielectric loss factor ratio, $\epsilon_{ri}''/\epsilon_{rh}''$, and a low value for the insect-to-host complex relative dielectric constant ratio, $\epsilon_{ri}/\epsilon_{rh}$. A lower value for $\epsilon_{ri}/\epsilon_{rh}$ will provide a higher E_i/E_h ratio (Eq. 2), which will favor a higher rate of energy absorption in the insect compared with the host medium (Eq. 1). Consideration of the equation for rate of temperature increase indicates that low insect-to-host ratios would be desirable for the specific heat and specific gravity also.

Using similar theoretical considerations, Thomas (1952) concluded that selective heating of insects in grain should be possible in high-frequency electric fields. Differences in temperature of host media necessary for control of the rice weevil, *Sitophilus oryzae* (L.), and the confused flour beetle, *Tribolium confusum* Jacquelin duVal, using 39-MHz electric fields, were explained using this type of analysis (Nelson and Whitney 1960). For adult rice weevils and confused flour beetles in wheat, the theory predicted selective heating of the insects, but, for confused flour beetles in wheat shorts, it did not. When insects were treated in wheat, grain temperatures below lethal temperatures for rice weevils and confused flour beetles achieved complete mortality. When confused flour beetles were treated in wheat shorts, however, lethal temperatures in the host medium were required for comparable insect mortality.

Host Medium.—The field intensity to which infesting insects are subjected depends upon geometric and spatial factors as well as the dielectric properties of the insects and their host medium. Therefore, particle size and shape of the granular host material might be expected to influence lethal exposure levels. Experiments with adult granary weevils, *Sitophilus granarius* (L.), in wheat and in corn of the same moisture content showed that insects suffered lower mortalities in wheat than in corn at comparable grain temperatures (Nelson and Kantack 1966). Rice weevil adults exposed to RF electric fields in host media of glass beads of different sizes survived better in smaller than in larger glass particles (Nelson et al. 1966).

Early studies by Pyenson (1933) showed that certain materials surrounding insects tend to shield them when exposed to high-frequency fields. Some evidence has been obtained also that insects inside kernels of grain may be partially shielded. The kernels have too low an electrical conductivity to provide an effective shield, but they may alter the electric field distribution in a way that is favorable to insect survival. Experiments with rice weevil adults and with adults of the lesser grain borer, *Rhyzopertha dominica* (F.), treated inside and outside wheat kernels, indicated that insects treated outside the kernels suffered somewhat higher mortalities than insects of the same age that were exposed while inside the kernels (Nelson et al. 1966).

Moisture content of the host medium also may influence the effectiveness of RF treatment. Mortalities of adult rice weevils treated at 39 MHz in wheat of 11.4% and 12.8% moisture were indistinguishable (Whitney et al. 1961), but more recent work showed that, within the range from 12% to 16% moisture, RF treatment may be slightly more effective as the moisture content of the wheat increases (Nelson and Kantack 1966). Moisture content of the host medium can influence insect survival of sublethal exposures. Mortalities of insects transferred to higher moisture wheat following exposure to RF electric fields were lower than those of insects transferred to wheat of lower moisture contents, even though the moisture content of the wheat was high enough to maintain normal insect activity (Nelson et al. 1966). Insects treated at lethal exposures lose moisture which amounts to a small percentage of their weight. Therefore, it seems reasonable to expect that insects subjected to sublethal exposures should survive better in media of higher moisture content where they are able to regain lost moisture more rapidly.

Another factor to be considered is heat loss from the insect to the surrounding host medium. An insect in close contact with the host medium may survive brief exposures to higher temperatures if the heat developing in the insect body can be transferred more rapidly to its surroundings. Thomas (1960), discussed this point with regard to long times of exposure. He studied control possibilities for wood-infesting insects at frequencies of 37.5 and 76 MHz. Disinfestation of wood using microwaves has been studied also at 2.425 GHz (van den Bruel et al. 1960b).

Field Intensity.—Because the electric field intensity, E in Eq. 1, is an important factor influencing the heating rate, its effects on insect mortality have received attention. Webber et al. (1946) used field intensities in the 1.2- to 1.8-kV/cm range in treating the Mediterranean flour moth, *Anagasta kuehniella* (Zeller), and the confused flour beetle in flour at a frequency of 11 MHz. No differences were apparent in the mortality data which might be attributed to field intensity. Effects of field intensity and frequency on insect mortality are difficult to distinguish, because both influence the heating rate. The three factors—frequency, field intensity, and heating rate—must, therefore, be considered in relation to one another. Several experiments at 10 and 39 MHz, involving exposure times ranging from a few seconds to a minute or more, with different combinations of field intensities and heating rates, indicated that there are subtle frequency effects which depend upon the species and developmental stages of the insects (Nelson et al. 1966).

In comparing 10- and 39-MHz treatments with similar heating rates, the 10-MHz treatment was consistently better for some species and stages, whereas the 39-MHz treatment was consistently better for others. For still others, the 2 frequencies produced similar mortalities.

High field intensities were much more efficient than low intensities in killing adult rice weevils in wheat at both 10 and 39 MHz, but with immature stages of the same species, high and low intensities produced the same results (Nelson and Whitney 1960, Whitney et al. 1961). Generally, differences in insect mortality attributable to field intensity diminished at intensities greater than 1.2 kV/cm. For a given frequency, an increase in field intensity increases the heating rate. The more rapid elevation of temperature that accompanies high-field-intensity treatments appears to offer a possible explanation for the greater effectiveness of high-field-intensity treatments which might produce a higher degree of thermal shock. Loss of heat energy to surroundings during treatment can also be a factor when exposure times are long. Heating rate alone, however, does not appear to determine the effectiveness of treatment at different frequencies (Nelson et al. 1966).

Modulation.—Thomas (1952) suggested possible advantages in controlling insects by using pulse-modulated RF electric fields, though no theoretical basis for any particular optimism was evident. Experiments with pulse-modulated 39-MHz fields ranging from 5 to 40 ms in pulse width and from 10 to 40 pulses/sec (pps) in pulse repetition rate did not show improved efficiency for control of adult rice weevils and confused flour beetles in wheat (Nelson et al. 1966). Limited subsequent work with pulses as short as 50 μs at field intensities of 4 kV/cm did not indicate better results than unmodulated treatments in controlling adult rice weevils and granary weevils in wheat. Some improvement in treatment efficiency was noted for controlling lesser grain borer adults using 10-ms pulses at a repetition rate of 10 pps at a field intensity of 3.5 kV/cm, compared with unmodulated treatment at 1.4 kV/cm (Nelson et al. 1966). Much higher field intensities can be used with pulse modulation, even with relatively long pulse durations. For clean wheat at 13–14% moisture content, field intensities for unmodulated RF treatment at a frequency of 40 MHz are limited to about 1.6 kV/cm because of the tendency for arcing to occur between kernels, thus charring the grain. Maximum permissible intensities increase with decreasing grain moisture content. The length of exposure also influences arcing, and moisture escaping from the grain kernels during dielectric heating increases the tendency for arcing. The maximum field intensity which may be used with pulse modulation appears to increase as the pulse width and pulse repetition frequency are decreased. Microwave treatments can produce equivalent heating rates for materials at much lower field intensities because of the higher frequency (Eq. 1). Therefore, arcing problems are usually less likely to be encountered in microwave heating than in dielectric heating at lower frequencies.

Frequency.—Most studies on insect control with RF electric fields have been conducted in the frequency range from about 1 to 50 MHz. Some differences in insect control attributed to differences in frequency in this range have been mentioned in connection with the discussion of field intensity. As Thomas (1952) explained, early implications that certain frequencies were more effective for heating insect tissues than plant tissues were based on faulty assumptions. Also, the idea that certain highly selective frequencies might exist for certain insects has not been demonstrated through either experimental or theoretical work.

Studies in which confused flour beetles in flour and granary weevils in wheat were exposed to 2.45-GHz microwave energy indicated that selective heating of the insects was not obtained (Baker et al. 1956). Temperatures in the host media in excess of 82 and 72°C, respectively, were required for control of immature stages. Corresponding control of granary weevils, rice weevils, and lesser grain borers in wheat at 39 MHz was achieved when grain temperatures were momentarily raised to the 60–66°C range (Whitney et al. 1961). 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 are able to survive for many hours at these temperatures in a hot-air oven. Holding infested cereal products at 60°C for 10 min effectively controls stored-grain insects (Cotton 1963).

RF treatment of confused flour beetle adults in wheat at 39 MHz required grain temperatures of 47°C for complete mortality (Nelson and Whitney 1960). In other studies at the same frequency, complete control of granary weevil adults was achieved at wheat temperatures of 41°C (Nelson and Kantack 1966). When adults of the same species were treated in wheat at 2.45 GHz, grain temperatures above 57°C were required for complete insect mortality (Baker et al. 1956). Table 1 summarizes for comparison these findings and others by Webber et al. (1946) at 11 MHz and by van den Bruel et al. (1960a), working at a frequency of 90 MHz. Examination of data in Table 1 shows that, in each case (with the possible exception of adult confused flour beetles treated at 11 MHz), considerably higher temperatures in the host medium are required for 100% mortality of the insects when treated at 2.45 GHz than when treated at lower frequencies in the 10- to 100-MHz range. It seems likely, therefore, that the degree of selective heating of the insects obtained in the lower frequency range is much better than that obtained in the microwave range at 2.45 GHz.

Boulanger et al. (1969) compared a microwave grain-treating system, operating at 2.45 GHz, and a 13-MHz dielectric heating system, but, unfortunately, they did not report a clear comparison of the relative effectiveness of the 2 different frequencies for controlling stored-grain insects. Complete control of the confused flour beetle was reported with 65°C grain temperatures following treatment at 2.45 GHz in a waveguide applicator; however, it was not stated whether the tests included the more resistant immature forms. Experimental treatment of 3 stored-grain insect species at 2.45 GHz in a microwave oven was reported by Kirkpatrick and Roberts (1971), but data given are of little value for comparison with other work, because grain temperatures were not reported. Jolly and Tate (1971) suggested possible advantages of microwaves for controlling chalcids in seed of Douglas fir trees. Dielectric-properties values selected for their argument are very questionable, however, and their conclusion is in direct opposition to that suggested by data of Fig. 1 and 2 to be discussed in the next section.

Frequency Dependence of Dielectric Properties.—To assess the degree of differential heating to be expected at different frequencies in the RF spectrum, dielectric properties of wheat and rice weevils were measured

Table 1.—Reported host-media temperatures following radiofrequency exposures necessary for 100% insect mortality.

Species	Stage	Frequency	Medium	Temperature	Reference
		MHz		°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	>72	Baker et al. (1956)
Confused flour beetle	adult	11	flour	75	Webber et al. (1946)
	larval	11	flour	65	Webber et al. (1946)
	adult	90	flour	59	van den Bruel et al. (1960a)
	larval	90	flour	53	van den Bruel et al. (1960a)
	adult	2450	flour	>68	Baker et al. (1956)
	larval	2450	flour	>82	Baker et al. (1956)

throughout the frequency range from 250 Hz to 12 GHz (Nelson and Charity 1972). Fig. 1 and 2 show resulting values for the dielectric constant, ϵ_r', and loss factor, ϵ_r'', for bulk samples of a hard red winter wheat and of adult rice weevils for the range from 50 kHz to 12 GHz. An analysis of the data, based on relationships of Eq. 1 and 2, revealed that ϵ_r'' is the dominant factor influencing differential energy absorption from the RF field. Therefore, the best selective heating of the adult rice weevil in wheat is expected to be obtained in the frequency range between ca. 5 and 100 MHz. On the basis of these data, little differential heating can be expected at frequencies between 1 and 12 GHz. It appears that predictions from these measurements are consistent with experimental data available on exposure of insects to RF electric fields at the different frequencies (Table 1).

The similarity of the curves of Fig. 1 and 2 and those of Fig. 3, based on the classical theory of dielectric dispersion and energy absorption of polar molecules originally proposed by Debye (1929), is indeed interesting. In Fig. 3, ϵ_{rs}' represents a low frequency value for the dielectric constant, $\epsilon_{r\infty}'$ a high-frequency value, and $\omega = 2\pi f$ is the angular frequency. The curves show the frequency dependence of ϵ_r' and ϵ_r'' in the dispersion and absorption region for a material with polar molecules which follow the Debye relaxation process (Nelson 1973). The relaxation frequencies (peak of the ϵ_r'' curves) for rice weevils and wheat lie in the range where bound forms of water are expected to contribute to this type of frequency-dependent behavior (de Loor 1968).

Since the dielectric properties of insects and their host media are temperature dependent, and since the temperatures of these materials change during RF exposure, the temperature dependence of the dielectric properties also requires study. It is likely that the dielectric relaxation frequency for insects and grain may increase with temperature. Upon determining the degree of change in ϵ_r'' with temperature for insects and their host media, it may well be possible to improve effectiveness of an RF treatment by changing the frequency during exposure to take advantage of the maximum differences in the loss factor, ϵ_r'', for the 2 different materials.

ENTOMOLOGICAL FACTORS

Several entomological factors have been explored as to their influence on insect control by RF electrical exposures. Nelson (1967) published a review of the literature on these aspects.

Developmental Stage.—In general, the adult insects are more susceptible to control by RF exposure than are the immature stages. In the case of the rice weevil, granary weevil, and lesser grain borer, the immature forms develop inside the kernel. The adults are more susceptible to control in each case (Whitney et al. 1961, Nelson et al. 1966), and partial shielding of the immature forms, as already discussed, might account for some of the difference in susceptibility. Differences in larval and adult susceptibility, however, seem to vary among species.

Little difference was noted in mortalities of the adult and larval stages of the confused flour beetle when treated at 39 MHz and 1.4 kV/cm in wheat shorts (Whitney et al. 1961). However, Webber et al. (1946) found in work at 11 MHz that larvae of the same species treated in flour were somewhat more susceptible than the adult. Baker et al. (1956) found that, when treated in whole wheat flour at 2.45 GHz, the adult confused flour beetle was more susceptible than either the larval or egg stages.

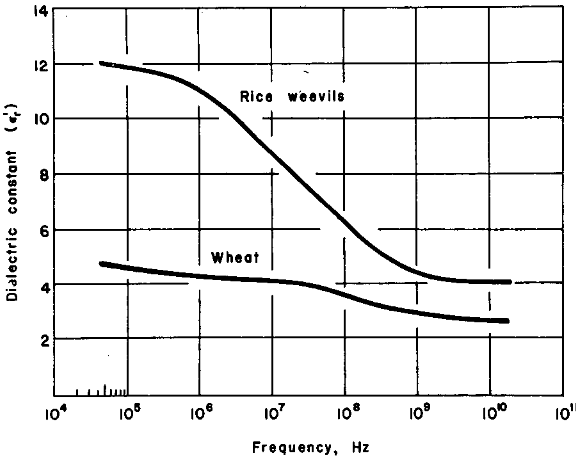

FIG. 1.—Frequency dependence of the dielectric constant of bulk samples of adult rice weevils and hard red winter wheat (10.6% moisture) at 24°C.

The adult granary weevil was also shown to be more susceptible than the egg in these studies. Larvae of the cadelle, *Tenebroides mauritanicus* (L.), are more susceptible than the adult (Nelson and Kantack 1966). With the cadelle, however, the larva is much larger, and it feeds outside the kernels; thus, physical factors such as size and geometric relationships may well account for the difference in susceptibility. Frings (1952) noted that differences in adult and larval susceptibility might well be explained by morphological differences, particularly the presence of legs in the adult stage. The age of larvae of the yellow mealworm, *Tenebrio molitor* L., at the time of sublethal exposure, influences the degree of resulting morphological abnormality which is observed in adults developing from these larvae (Kadoum et al. 1967a, Rai et al. 1971). It has been found also that 1-day-old eggs of the yellow mealworm are more susceptible to RF exposures at 39 MHz than 3-day-old eggs (Rai et al. 1972).

Species.—Species, too, vary in their susceptibility to control by RF exposure. Based on adult mortality, comparison of several stored-grain-insect species, treated in wheat at a frequency of 39 MHz and at an electric field intensity of 1.2 kV/cm, showed the following rank in order of decreasing susceptibility: rice and granary weevil; sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.); confused flour beetle, and red flour beetle, *Tribolium castaneum* (Herbst); the dermestid *Trogoderma variabile* Ballion (formerly *parabile* Beal); cadelle; and lesser grain borer (Whitney et al. 1961, Nelson and Kantack 1966).

Another interspecific difference noted was the degree of delayed mortality following treatment. A substantial increase in mortality was obtained with rice and granary weevils between 1 day and 1 week after treatment, whereas practically no change in mortality attributable to the RF treatment occurred thereafter. The lesser grain borer also exhibited a substantial amount of delayed mortality, but such mortality occurred mostly during the 2nd week after treatment rather than during the 1st week. Confused and red flour beetles exhibited less delayed mortality, most of which occurred during the 2nd and 3rd week after treatment (Whitney et al. 1961, Nelson et al. 1966). In other studies, mortality of yellow mealworm larvae continued to increase during a 2-week period following treatment at 39 MHz (Kadoum et al. 1967c).

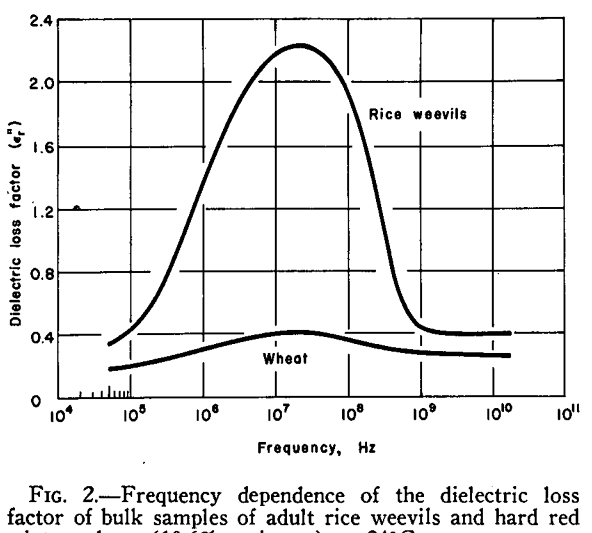

FIG. 2.—Frequency dependence of the dielectric loss factor of bulk samples of adult rice weevils and hard red winter wheat (10.6% moisture) at 24°C.

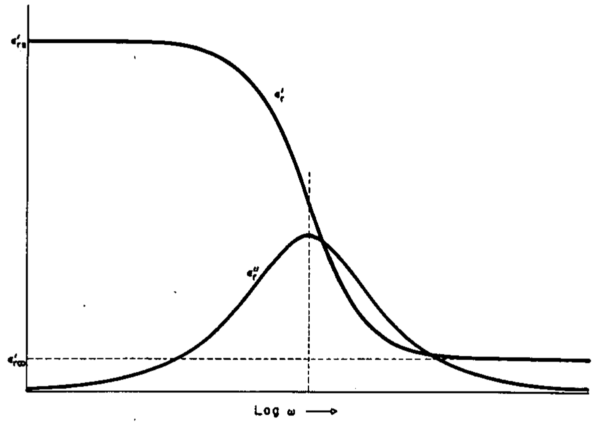

FIG. 3.—Dispersion and absorption curves representing the Debye relaxation process for polar molecules.

Physiological Injury.—As pointed out in the introduction, the lethal action of RF electric fields on insects is believed to be principally thermal in nature. Frings (1952) noted and studied in some detail the "knockdown" of insects when exposed to RF electric fields, and he concluded that rapid heating in the legs could explain the knockdown effect. Injuries noted by Whitney et al. (1961) in stored-grain insects, after RF treatment in wheat, lend support to this theory. The injuries were noted in the appendages, particularly in the joints of the legs. Injury to the histoblasts was suspected in RF-treated larvae of the yellow mealworm that developed into adults with badly deformed or missing legs (Kadoum et al. 1967a). Rai et al. (1971) described abnormal development in both cephalic and thoracic appendages of the same species, after RF treatment in the larval and pupal stages. Other types of abnormal development, characterized by incomplete metamorphosis, were reported by Carpenter and Livstone (1971), who exposed pupae of the same species to 10-GHz microwave energy at levels so low that little total body heating was observed.

In work at 39 MHz, internal body heating of yellow mealworm larvae accounted for observed mortality of the insects (Kadoum et al. 1967c). Kocian (1936) observed marked increases in the respiration rate of larvae of this species after exposure to 2-MHz electric fields. Kadoum et al. (1967b) observed losses in body weight and increased oxygen uptake rates in yellow mealworm larvae following RF exposure at 39 MHz. The increased oxygen uptake rates were similar to those of surgically injured larvae. Kadoum (1969a, b) also observed an accompanying increase in the rate of protein synthesis. He suggested that the changes in protein synthesis may be comparable to those caused by direct mechanical damage.

Experiments have shown that rice weevils and confused flour beetles that survived sublethal exposures at 39 MHz were capable of reproduction (Whitney et al. 1961). However, the more severe treatments greatly reduced the number of progeny of a given number of surviving adults. Studies with lesser grain borers showed that the reproduction rate was lowered when adults exposed to RF treatment suffered greater than about 50%

mortality (Nelson et al. 1966). Earlier, Webber et al. (1946) reported reproductive capability of confused flour beetles that survived exposures in flour at 11 MHz. Observations by Rai (1970) indicated that lowered reproductive capacity in *T. molitor* results from probable heat damage to sperm cells and ovarian tissues.

PRACTICAL ASPECTS

While considerable optimism has been expressed in the past concerning application of RF energy for insect control, its use has never become practical for economic reasons. Cost estimates, based on conditions in England 20 years ago, indicated that RF treatment for grain or some other commodities might be competitive with conventional fumigation methods (Thomas 1952). Similar comparisons, based on prevailing conditions in the United States in 1958, indicated that total costs for RF treatment of grain would range between about 3 and 4 cents/bu—several times the cost for chemical fumigation at that time (Nelson and Whitney 1960, Whitney et al. 1961). Boulanger et al. (1969) estimated figures in the same range for high-frequency and microwave systems based on prices in Canada in 1969.

Total costs for fumigation are difficult to obtain, but, for large-scale applications, they are no doubt considerably less than the 3–4 cents/bu estimated for the RF treatment. Watters (1962) gave costs of 1.5–2 cents/bu for fumigating large grain bulks in Canada.

Costs of chemical fumigants vary considerably, depending upon the type and volume purchased, but they probably range between 0.3 and 1 cent/bu of grain treated. The energy required to raise the temperature of grain to 60°C, which is probably a minimum that can be considered at this time, is ca. 0.5 kWh/bu. The energy requirement depends upon the initial temperature, and, since an RF installation is not 100% efficient, the actual energy requirement may be closer to 1 kWh/bu. Thus, the necessary cost for energy alone will generally exceed cost for chemical fumigation materials alone.

Cost comparisons of a general nature are difficult to make and may be misleading. Accurate comparisons can be worked out only for specific situations. Much larger investments in equipment would generally be required for RF-treating systems than are needed for chemical fumigant application. Cost figures for RF power sources often range between 0.5 and 1 dollar/W of output rating. Moving the grain through the treating equipment would certainly be necessary for RF processing, but this is sometimes necessary also for chemical treatment. Labor and maintenance requirements must also be compared.

The principal advantage for RF processing is lack of any harmful residues. This factor could become increasingly significant if the trend of tightening regulations on pesticides should continue.

Another factor which might be taken into account is the possibility of dual-purpose applications for the RF equipment. RF treatments have been successful in laboratory work to improve seed germination, and some work has shown that such equipment might be useful in accelerating grain-drying processes.

At present, immediate application of RF processing methods for insect control appears questionable from an economic standpoint; however, cost factors change with time and developing technology. Advantages of RF processing methods could become more important in the future, and further evaluation of such methods for particular applications would seem advisable. Troublesome insect-control problems in high-value products might yield to RF control techniques.

To best exploit selective heating advantages, data on the frequency dependence and temperature dependence of the dielectric properties of insects and their host materials are needed. For any particular application, data of the sort presented in Fig. 1 and 2 for different temperature ranges would seem to be valuable. The possibility of varying frequency to follow shifts in the maximum $\epsilon_{ri}''/\epsilon_{rh}''$ ratio, if it does shift with temperature, could result in more efficient and, therefore, less costly RF treatment for insect-control purposes.

Unless a rapid rate of heating is important for a particular application, obviously the RF heating must provide some other unique advantage to be considered in preference to less costly heat energy sources. Selective heating of the insect can sometimes be such an advantage. Establishment of any nonthermal effects, which might be exploited for insect-control purposes, could be an even more important advantage which could materially improve the chances for practical application.

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