RADIOFREQUENCY, INFRARED, AND ULTRAVIOLET RADIATION FOR CONTROL OF STORED-PRODUCT INSECTS: PROSPECTS AND LIMITATIONS

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INTRODUCTION: It has long been recognized that electromagnetic energy might offer possible methods for controlling insects. More than 40 years ago Headlee[1] initiated a series of explorations on the effects of electromagnetic waves on insects. Since then numerous researchers have studied the use of various types of electromagnetic radiation to control insects, and interest has intensified with the realization of the health hazards and environmental contamination problems associated with many effective chemical insect-control methods.

The findings from research on insect control with electromagnetic energy have been discussed in previous reviews[2,3,4,5,6,7]. Therefore, this paper will include only an updated summary of this material as it relates to stored-product insect control, and the scope is limited to the radiofrequency, infrared, and ultraviolet portions of the electromagnetic spectrum.

A chart of the electromagnetic spectrum is shown in Fig. 1. With reference to the quantum energy of electromagnetic radiation, the radiofrequency (RF) region is near the lower end of the spectrum. The infrared region lies just above the radio-wave region, and "light," the visible portion of the spectrum, occupies the region between the infrared and the ultraviolet regions. Above the ultraviolet region are the high-energy ionizing X and gamma radiations.

Associated with any kind of electromagnetic wave are a quantum energy, E, a wavelength, λ, and a frequency of oscillation of the electromagnetic fields, ν. They are interrelated as $E = h\nu$ and $\lambda\nu = c$, where h and c are universal constants, respectively, Planck's constant (6.625×10^{-27} erg-sec) and the velocity of light or velocity of propagation in vacuum (2.9979×10^{8} m/sec).

All types of electromagnetic radiation have some potential applications for insect control. We shall now consider those applications that have been explored for radiofrequency, infrared, and ultraviolet radiation.

RADIOFREQUENCY ENERGY: General Principles - The interest in possible application of RF energy to control stored-product insects stems from the nature of its propagation and absorption in matter. Because it is electromagnetic energy, it can be radiated and directed where it is wanted. The nature of its absorption, however, is the unique character that makes it interesting for insect control.

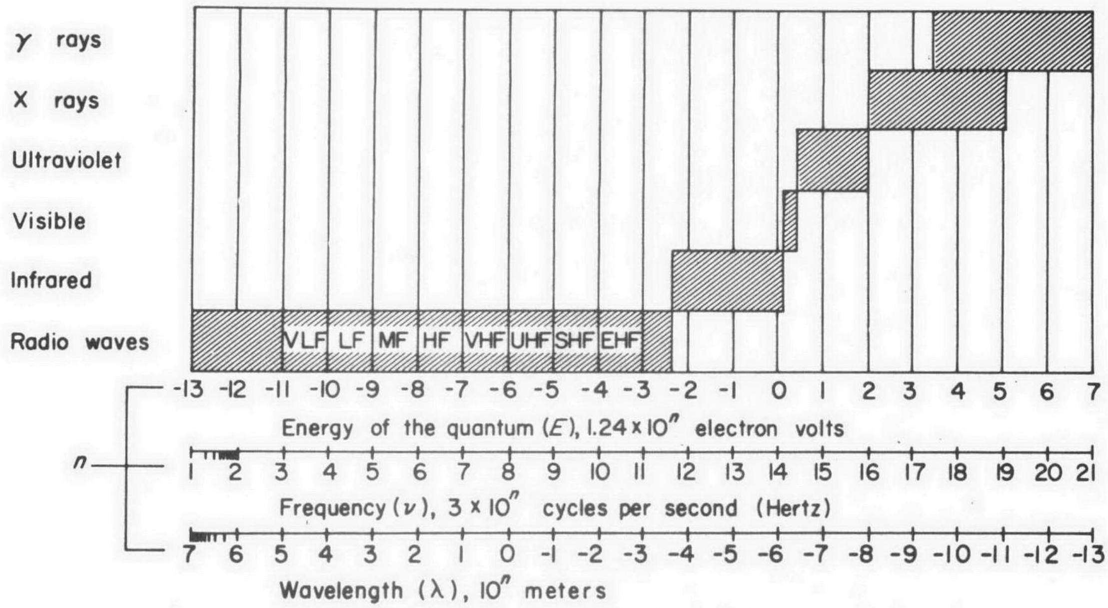

FIGURE 1. Chart of the electromagnetic spectrum showing approximate ranges of the radiation and corresponding wavelengths, frequencies, and quantum energies.

Materials subjected to RF electric fields absorb energy in different degrees, depending upon their chemical composition and molecular structure. Energy absorbed from RF electric fields is converted to heat, and this process is known as dielectric heating. At microwave frequencies, it is also termed microwave heating.

The properties of materials that determine their behavior in electric fields are called dielectric properties. The dielectric loss factor, ε_r'', is an index of the power absorption that occurs when a material is exposed to RF electric fields. This power dissipation per unit volume is expressed as

$$P = 55.63\ \nu\ E^2\ \varepsilon_r'' \times 10^{-12}\ \text{w/m}^3 \qquad (1)$$

when ν is the frequency of the applied field in Hz (cycles/sec) and E is the rms electric field intensity within the material in v/m.

The dielectric loss factors of insects found in grain, wood, and some other products may be much larger than those of the host product. When exposed to RF electric fields, the insects in such products can be expected to absorb energy at a higher rate than the host material, and, although there are other factors to be considered, selective heating of the insects may be possible. If the insects can be heated to a lethal level without damaging the host product, RF energy may provide an advantageous method of insect control.

RF energy also has the advantage of penetrating deeply into infested material so that internal infestations can be treated. At frequencies between about 1 and 100 MHz, infested materials can be exposed by placing or passing them between electrodes that confine the RF electric fields to a given region. At microwave frequencies (above about 1 GHz), the radiation may be directed into the infested material, or the material may be placed in or passed through a chamber or cavity where it is exposed to the microwave energy.

There are other factors that influence the heating of materials by RF electric fields. In a mixture of materials, the dielectric constant, ε_r', may be different for the different constituents of the mixture. The relative relationships of the dielectric constants of insects and host materials and their geometric relationships influencing the value of the field intensity, E, that exists in the materials, thus affecting the power dissipation (Eq. 1). The heat capacity or specific heat, c, and the specific gravity, ρ, of the insects and host materials also influence their heating rates, since the time rate of temperature increase may be expressed as $dT/dt = 0.239 \times 10^{-6}\, P/c\rho$ °C/sec. The thermal conductivities of the insect and host are also important factors that help to determine how heat will be conducted away from the insect during and following a dielectric heating exposure.

Research 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. Because the loss factor of hygroscopic materials generally increases with moisture content, the heating rates of these materials are higher when moisture contents are greater.

Studies have shown that many insects that infest grain, cereal products, and wood products can be controlled, without damaging the host material, by exposures to RF fields for only a few seconds. For successful RF insect-control treatments, resulting temperatures in the host material generally range between about 40° and 70° C, depending upon the host material, insect species, and nature of the RF treatment.

Entomological Factors - Differences in the susceptibility of various insect species to control have been noted when treated in common host media under comparable conditions [7,8,9,10]. 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 geometric relationships.

Differences have also been found in the susceptibility to control of different developmental stages within the same species [7,8,9,10,11,12,13]. In general, adults are more susceptible to control by exposure to RF fields than are immature forms, i.e., the egg, larval, and pupal stages. Some 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 [10].

Injuries to the legs and other appendages of insects subjected to sublethal RF exposures have been observed [13,14,15, 16]. Such injuries usually have been attributed to high electric-field concentrations and consequent localized heating during RF exposure. Interspecific differences have been found in the degree of delayed mortality observed during the period of a few weeks after RF treatment[7,10,14].

Reproductive sterilization of the type produced by ionizing radiations has not been observed in RF-treated insects[10,14]. 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].

Physical Factors - The influence of various physical factors, such as frequency, electric field intensity, pulse modulation, heating rate, and characteristics of host materials, also has been studied [7,10]. General conclusions concerning some of these factors are difficult to draw. 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 the use of such 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 to 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 is illustrated in Figs. 2 and 3. An analysis of the differential dielectric heating to be expected at different frequencies revealed that the dielectric loss factor is the dominant factor to be considered[18]. Therefore, it is obvious from the data of Fig. 3 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.

These predictions were confirmed by experimental results obtained when hard red winter wheat infested with adult rice weevils was exposed 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. 4. When infested

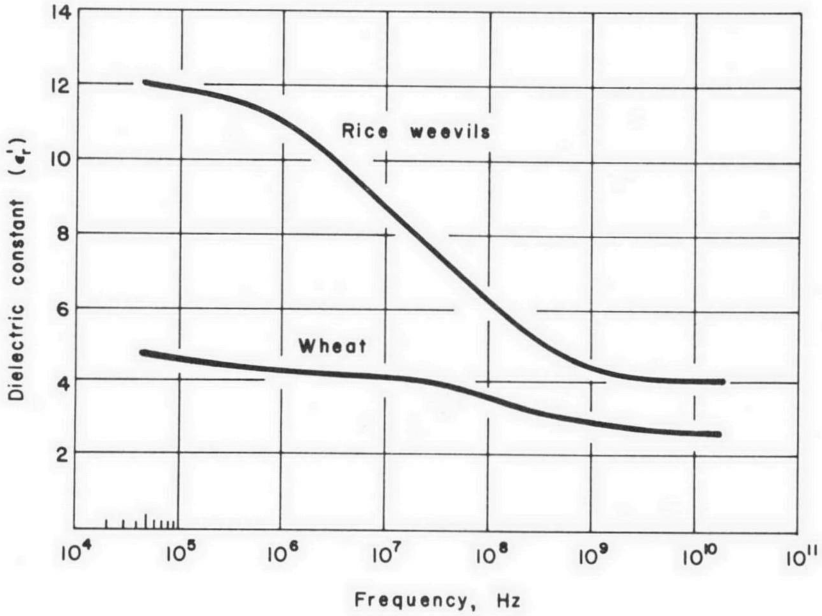

FIGURE 2. Frequency dependence of the dielectric constant of adult rice weevils and of 10.6%-moisture wheat, at 24° C.

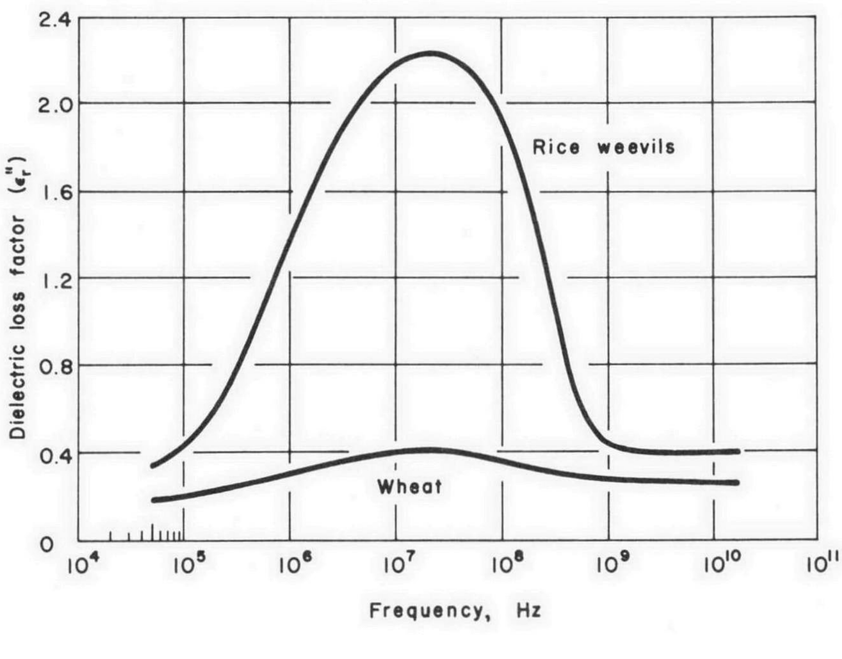

FIGURE 3. Frequency dependence of the dielectric loss factor of adult rice weevils and of 10.6%-moisture wheat, at 24° C.

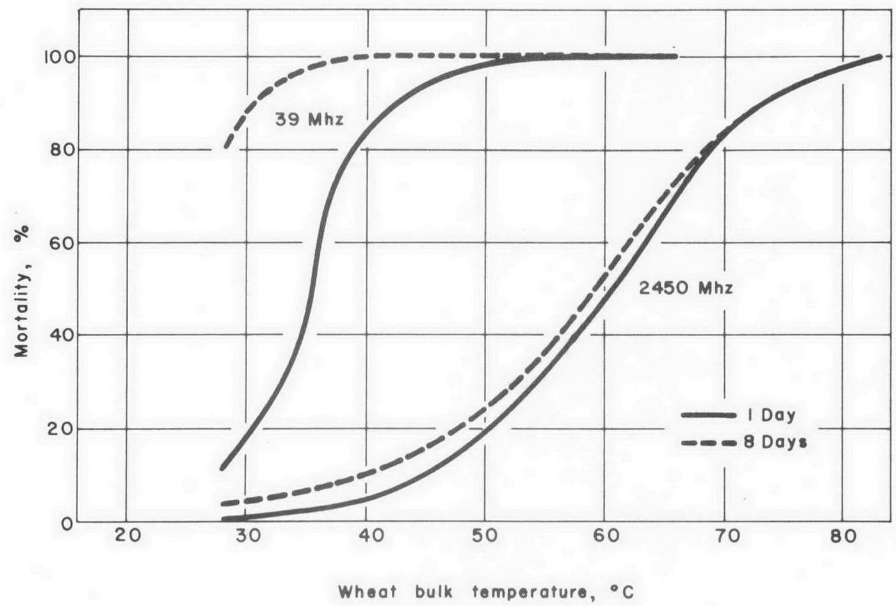

FIGURE 4. Comparison of 1- and 8-day mortalities of adult rice weevils exposed in wheat to RF electric fields at frequencies of 39 and 2450 MHz.

grain was treated at 39 MHz, complete insect mortality was obtained with much lower grain temperature 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 additional mortality of the insects between 1 and 8 days after treatment was also much greater when they were treated at 39 MHz than when they were treated at 2450 MHz.

The results of these studies at 2450 MHz correlated well with those reported earlier by Baker et al.[12], who found no evidence of differential heating of insects treated in wheat and flour at this frequency. Kalina et al.[20] reported that complete mortality of the granary weevil, *Sitophilus granarius* (L.) [=*Calandra granaria*], was obtained by 2375-MHz exposures that produced temperatures of 51° C in soft wheat that was uniformly treated in a waveguide device. Salama et al.[21] also found that temperatures of this level or higher were necessary in flour treated at 2450 MHz to obtain complete mortality of the confused flour beetle, *Tribolium confusum* Jacquelin duVal. Other experiments have been reported on control of stored-grain insects at microwave frequencies[22,23], but sufficient data were not reported to permit valid comparisons with other work.

Because of complementary effects of heat and ionizing radiation treatments, and because immature stages of insects are more susceptible to ionizing radiation treatments than are adults (although more resistant to RF treatments), the study of combination

RF and ionizing radiation treatments was suggested several years ago[2]. In some recently reported work, gamma-radiation and microwave combination treatments of wheat produced higher mortalities of immature stages of the rice weevil, the lesser grain borer, *Rhyzopertha dominica* (F.), and the Angoumois grain moth, *Sitotroga cerealella* (Olivier), than expected in view of results from individual radiation exposures[24,25,26].

Another factor to be considered is the heat loss from the insect to the surrounding medium. An insect in close contact with the host medium may survive brief exposures to higher temperatures if heat that develops in the insect body can be transferred more rapidly to its surroundings. Thomas[27] discussed this point with regard to long exposure times in studying control possibilities for wood-infesting insects at frequencies of 37.5 and 76 MHz. Disinfestation of wood with microwaves has been investigated at 2425 MHz[28], and infested woodwork in a house was successfully treated in this way[29]. Successful treatment of infested wood has also been achieved by 2450-MHz exposures that raised the temperature of the wood to about 50° C[30]. In other 2450-MHz studies, Bletchly[31] concluded that no marked differential heating of the larvae of the furniture beetle, *Anobium punctatum* (De Geer), in birch plywood was obtained. It was expected that the maintenance of temperatures between 51° and 72° C for a few minutes would be required to control these insects.

INFRARED ENERGY: Possible uses of infrared radiation for insect control involve two generally different concepts. One concept involves direct application of the radiation to the infested material in such a way that energy absorption by the insects or the material results in lethal temperatures for the insects. In the other concept, the effectiveness of infrared radiation would depend upon the suspected ability of the insects to sense infrared radiation or upon their speculated use of these wavelengths in communication [5,32,33]. The latter concept will not be considered further here.

Methods in which banks of infrared lamps were used over a conveyor belt to control insects in wheat were described more than 30 years ago[34]. Uniform temperatures were reported to be achieved in a layer of treated grain about 6-mm deep that was conveyed into a closed tunnel to hold temperatures of 60° C for 10 min to kill all stored-grain insects. The infrared treatments did not adversely affect wheat germination, baking qualities of flour milled from the wheat, or the thiamin content of the wheat. About the same time, other experiments with infrared irradiation of the confused flour beetle revealed that adults and larvae suffered about the same mortality when exposed to the same energy from filtered infrared lamps[35]. Yellow mealworm, *Tenebrio molitor* L., adults, however, were killed with much shorter exposures to the same infrared treatment than were the larvae. The difference was believed to be caused by greater absorption of infrared energy by the adults, which are darker than the larvae, and by greater heat retention in the adults' bodies because their body walls are more heavily sclerotized. In these same studies, the confused flour beetles were found to be protected from the infrared radiation by a 6-mm layer of wheat flour.

Infrared radiation from lamps was also found to be effective in killing the pea weevil, *Bruchus pisorum* (L.), in seed peas [36]. Exposures of 3 min to a battery of lamps 25-30 cm from a single-seed layer killed all of the insects without damaging seed germination.

Infrared radiation from a gas-fired, ceramic-panel, infrared heater was used in studies on insects that infest rice[37, 38]. In rice of about 12% moisture, immature rice weevils were completely controlled by infrared exposures that produced a temperature of 56° C in the rice. Immature lesser grain borers required a grain temperature of 68° C for complete control. Results of later experiments, which included treatments of immature stages of these two species and the Angoumois grain moth in 14%-moisture rice, indicated that rice temperatures in the range from 65° to 70° C might be necessary to control all three species completely. The lesser grain borer was the most resistant, and the rice weevil was the least resistant[39]. Results of sublethal infrared-radiation treatments of immature stages of these same three insect species later showed that the exposure to infrared radiation did not inhibit reproduction by adults that developed from the immature stages that survived the treatment[40].

Adults of 12 Coleopteran species of stored-product insects suffered mortalities of nearly 100% when exposed in wheat to infrared radiation from a gas-fired, ceramic-panel, infrared heater (peak energy emission at 2.5 μ) that produced grain temperatures of 64° to 67° C[41]. When used in combination with gamma-radiation treatments that produced an average mortality of 54% for immature stages of lesser grain borers, infrared exposures that produced 55% mortality alone achieved 99% mortality in combination with the gamma-radiation treatments[25]. Combination infrared- and gamma-radiation treatments also showed complementary action in reducing the fecundity of adults that survived the combination treatments.

Some studies have been conducted on the effects of laser radiation, including lasers with output in the infrared region, on larvae of *Trogoderma* species. Cuticular pigmentation influenced resulting mortality. The darker *T. variable* Ballion (=*T. parabile* Beal) was killed at lower doses than was the lighter colored *T. inclusum* LeConte[42].

ULTRAVIOLET ENERGY: Investigations of the potential use of ultraviolet radiation for insect control also have taken two different avenues of approach--direct irradiation with intensities that produce adverse effects on the insects, or low-level illumination to study attractive, behavioral, or photoperiodic influences of the radiation. A vast amount of literature is available on insect response and attraction to visible and ultraviolet radiation. Much of this literature has been reviewed previously[5], so comments here will be limited to a few studies that relate specifically to ultraviolet radiation and stored-product insects.

Spectral-response studies on seven stored-grain insect species revealed that several species exhibited primary response peaks at a wavelength of 500 nm in the visible part of the spectrum with a secondary peak in the near-ultraviolet region between 334 and 365 nm[43]. The major peak for the Indian-meal moth, *Plodia interpunctella* (Hübner), was in the ultraviolet region, with a secondary peak at 500 nm. The rice weevil responded equally well at all wavelengths between 334 and 546 nm. The response of all species was low at 600 nm, and still lower at 280 nm. The phototactic response of several stored-product insects was tested over a wider range of intensities of 366-nm ultraviolet radiation to learn whether attraction of stored-product insects could be improved for trapping purposes[44]. Positive responses were obtained for all species tested except for the rice weevil. The response of most species increased with radiation intensity. One species exhibited a negative response at high intensities.

Traps equipped with green panelescent and fluorescent blacklight lamps, both separately and in combination, were tested in simulated warehouse conditions to determine the relative effectiveness of these lamps for attracting several species of stored-product insects[45]. The blacklight lamp, which emitted much more radiation than did the green panelescent lamp, was more attractive for most species; however, two species exhibited a preference for the lower intensity green panelescent lamp.

Damage to confused flour beetles exposed as pupae to ultraviolet radiation from a germicidal lamp (principally 253.7-nm energy) included abnormal wing development, reduced longevity, and mortality[46]. Sufficiently long exposures of insect eggs to germicidal ultraviolet radiation have been found to reduce egg hatching [47]. In these studies, the time for larval and pupal development was not affected by the irradiation of the eggs, nor was there any change in the longevity of the resulting adults.

Studies concerning possible suppression of development and control of the almond moth, *Cadra cautella* (Walker) [=*Ephestia cautella* Walker], with ultraviolet radiation at 253.7 nm showed that the sensitivity of the egg to radiation increased with age[48]. Ninety-five-percent mortality was obtained with about 1 minute of exposure of 3-day-old eggs, whereas nearly 5 minutes of exposures were required to obtain a comparable percentage of mortality of 1-day-old eggs. A plausible explanation for the increased sensitivity of older eggs was suggested and further work was recommended to determine whether ultraviolet radiation might be useful to control certain insect pests.

Insects of different species and of different life stages within some species were exposed to 254-nm ultraviolet radiation in studies aimed at explaining the mechanism of action for this type of radiation[49]. Some were found to be very sensitive, whereas others were not. The differences were explained by the ultraviolet transmittance of surface membranes. DNA was suspected as the sensitive target in some instances. Under certain conditions, it was suggested that ultraviolet radiation might be an effective insect-control agent.

In studies of the influence of ultraviolet and visible radiation on different developmental stages of the American cockroach, *Periplaneta americana* (L.), it was found that avoidance reactions to ultraviolet radiation (mainly 254 nm) became more rapid as the age of the insects increased[50]. First- and second-instar insects, in which avoidance reactions were slow, displayed a more rapid avoidance reaction when they were exposed to ultraviolet radiation than when they were exposed to longer wavelength visible radiation. The mortality levels of the insects exposed to ultraviolet radiation were highest among the younger instars. This greater sensitivity of younger instars to ultraviolet radiation was also observed in studies on nymphs of five species of cockroaches[51]. In these studies ultraviolet radiation at 254 nm produced the highest mortality level, but 280-nm and 297-nm radiation also produced high mortality levels. Ultraviolet radiation of 313-, 350-, and 365-nm wavelengths was not lethal to these insects at the intensities used. The sensitivity of nymphs to ultraviolet radiation was greater when they were irradiated slightly before or immediately after molting than at other times during the period of a given instar. The ultraviolet component in the radiant output of a high-intensity light-flash apparatus was also suspected to be the effective agent producing mortality and sterility in adult mosquitoes, *Aedes aegypti* (L.), exposed to this type of radiation[52].

PROSPECTS FOR PRACTICAL APPLICATION: So far as is known, none of these types of electromagnetic energy (radiofrequency, infrared, ultraviolet) has ever been used to an appreciable extent for commercial control of insect infestations. A 120-kw industrial RF dielectric-heating installation was operated for several years to destroy animal disease organisms in bales of feed bags so they could be safely reused[53]. Any insects present in the feed bags were also controlled in this operation.

It is difficult to predict the eventual probability for practical application of these types of energy to control insect infestations. Further information is needed on several aspects of their effects of insects before their utility can be evaluated for particular applications. Then, of course, the economics of any new method must appear to be competitive before it can be seriously considered. Some of these factors will now be considered for the three types of radiation discussed in this paper.

Radiofrequency Energy - The selective heating capability of RF electric fields has been proven in principle for controlling insects in certain materials such as grain and cereal products. Estimated costs of 3 to 4 cents/bu for treatment of grain in a practical application [8,14,22], however, are several times greater than those of current chemical methods. The main factor that contributes to the high cost of RF treatment is the energy absorbed by the grain. Although the grain is not heated as much as the insects, significant amounts of energy are involved when large quantities of grain are heated to the 60°-C level that appears to be necessary, at the present time, to control all stages of stored-grain insects. If the amount of energy that goes into the grain when it is processed could be reduced, the handling capacity of an RF-treating system could be increased, thereby reducing the costs for equipment.

For these reasons it appears that the efficiency of the RF method must be increased before it can compete with chemical control methods economically for controlling stored-grain insects. Suggestions have been made for selecting the most effective frequency range (Fig. 3), and for possibly improving the efficiency of RF treatment[54]. Because the dielectric properties of materials are temperature dependent, the peak of the absorption curve (relaxation frequency) for the insects (Fig. 3) is expected to shift to higher frequencies as the temperature of the insects rises.

Shifts in relaxation frequencies of one or two orders of magnitude may occur in the range through which the temperature of the insects must be elevated to achieve complete mortality. If such 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 exposure, and the relatively large selective heating advantage possible at the beginning of the exposure may be reduced during later stages of exposure. Therefore, it may be possible to improve the efficiency of RF treatment materially 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. Information on the temperature dependence of the dielectric properties of insects and their host materials is required to determine the degree of improvement that may be possible in treatment efficiency.

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 to improve the effectiveness of RF insect-control methods.

The use of RF insect-control methods may be feasible for some high-value products with which infestation problems occur. The feasibility assessment for achieving control can be aided by determining the relative dielectric properties of the insect and host as shown, for example, in Figs. 2 and 3.

The interpretation of experimental data here has been based on the assumption that lethal effects of RF exposure are due to thermal processes. Frequently, the question has been raised concerning possible nonthermal effects[55,56]. No conclusive evidence is available concerning the existence of nonthermal effects that would be useful for insect-control applications. The establishment of any nonthermal effects that 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 technique may be especially well suited.

Infrared Radiation - Direct application of infrared radiation to control insects by heating infested products also has been proven possible. Although the source of energy for gas-fired infrared heaters has been more economical in the past than the electric energy necessary for RF applications, the significant amount of energy that goes into the product when infrared radiation is used to control insect infestations also appears to be an economic disadvantage.

Because infrared radiation is absorbed at the surface of irradiated materials, penetration is limited, and selective energy absorption is not possible for insects that are within the product or that are otherwise shielded from the radiation by the host material. In such instances, the host material must be heated to the temperature level that is lethal to the insects. For rice, this temperature level is probably in the range from 65° to 70° C [39].

When the insect surfaces can be exposed to infrared radiation, some selective absorption may be possible. If so, the chances for practical application should be improved. A study of the infrared emissivity of the insect and host surfaces might then reveal that certain wavelengths could offer advantageous energy absorption by the insects. Then suitable infrared radiation sources could be selected that would provide the proper wavelengths of radiation.

Ultraviolet Radiation - Since several stored-product insect species have been found to be positively phototactic, visible and ultraviolet radiation sources in traps may be useful in detection and survey functions connected with insect-control programs.

The use of ultraviolet radiation for direct irradiation of insects as a control measure has apparently received little attention, and sufficient information is not yet available from which to fully assess the potential of this type of radiation for insect-control applications. However, studies that have been conducted provide a basis for expecting that some degree of control might be achieved in certain situations. Ultraviolet radiation is also absorbed on the surface of materials, so it would be necessary that the insects to be affected be free for exposure at some time during their development, preferably in stages that are most sensitive to damage from the radiation. Energy requirements for this type of treatment should be low.

Further research on the mechanism of lethal action, on effective wavelengths and intensities, and on sensitivities of the different developmental stages of target species may provide information that will permit development of ultraviolet-radiation techniques for insect control.

General Observations - Radiofrequency, infrared, and ultraviolet radiation all offer possibilities for use in insect control. An obvious advantage of such insect-control methods is the absence of potentially harmful residues that frequently result when chemical methods are used. An equally obvious disadvantage of radiation treatments is the absence of residual protection that some chemical controls provide. Therefore, sanitation procedures for stored products that were disinfected by radiation treatments would have to be stringent to prevent reinfestation and the need for periodic retreatment. However, the proper application of a treatment such as a radiofrequency exposure before material goes into storage could ensure a product completely free of insect life.

The principal obstacle to the application of RF and infrared treatments to control insects appears to be the attendant energy cost. Costs of equipment are also important factors. In the current era of increasing energy costs and decreasing energy supplies, any new process that requires appreciable quantities of energy must offer definite advantage to compete effectively for available energy.

A careful assessment of the total energy requirements for alternate insect-control methods appears to be in order. Such evaluations should include all energy requirements for the manufacture, distribution, and application of existing chemical control agents for comparison with other methods being considered.

The application of radiation insect-control methods may be practical for high-value products or for materials for which no other suitable control methods are available.

More information on the interaction of the different kinds of radiant energy is needed before their potential for insect-control applications can be evaluated properly. Further research in these areas may point the way to significantly important applications.

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