Radio-Frequency Electric Fields for Stored Grain Insect Control

S. O. Nelson and W. K. Whitney
MEMBER ASAE

IT HAS been known for many years that insects can be killed by short exposures to radio-frequency (r-f)* or high-frequency (h-f)* electric fields. The literature in this general area has been summarized by Ark and Parry (2)†, Thomas (9), Frings (4) and Peredel'skii (7). Davis (3) in 1934 obtained a patent on a high-frequency method for exterminating insect life in seed grain or other materials. For the most part the literature in this area lacks descriptive information concerning materials and methods. Objective interpretation and comparison of results is therefore difficult. In some instances, misunderstandings of basic electrical theory have resulted in erroneous conclusions. The absence of definitions related to biological criteria in many reports further complicates the problem.

Considerable optimism regarding the eventual application of radio-frequency energy for disinfesting stored grain is evident in many earlier reports. In 1952, Thomas (9), in an excellent theoretical treatment of the general problem of pest control by high-frequency electric fields, concluded that "the running, maintenance, replacement and amortization costs of h-f disinfestation are comparable with conventional fumigation methods," and recommended further experimental investigation. The possibility of selectively heating the insects, the speed with which treatment can be accomplished, the lack of harmful residues, the absence of damage to grain, and the adaptability to continuous-process treatment are advantages in favor of its development.

Soderholm and Dennis (unpublished data) conducted studies to determine the feasibility of using r-f energy for stored-grain insect control. Efforts were made to measure all important treatment variables, to describe the biological material used, and to define the biological criteria by which experimental results would be evaluated. The work herein reported is an extension of the previous studies.

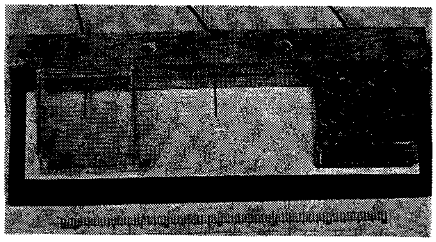

FIG. 1 Polystyrene sample boxes on thermocouple mount.

General Principles

With r-f dielectric heating, electric energy can be transformed into heat energy uniformly throughout the volume of a homogeneous substance by exposing it to an r-f electric field. The power per unit volume thus dissipated in a dielectric is

$$P = kfE^2\epsilon'' \quad [1]$$

where **k** is a constant depending upon the units employed, **f** is the frequency of the alternating electric field, **E** is the field strength or intensity (voltage gradient or potential gradient), and ϵ'' is the dielectric loss factor of the substance, or the imaginary component of the complex permittivity $\epsilon = \epsilon' - j\epsilon''$, the real component, ϵ', being the real permittivity or dielectric constant. ("Permittivity," as used in this paper, is a dimensionless quantity corresponding to the relative permittivity of the rationalized mks system of units.)

It follows from equation [1], neglecting loss of heat to surroundings and excluding any changes in state, that the time rate of temperature increase due to the r-f electric field is

$$\frac{dT}{dt} = \frac{KfE^2\epsilon''}{\rho c} \quad [2]$$

where **K** is another constant dependent upon units, ρ is the specific gravity of the material, and **c** is its specific heat.

Examination of equation [2] reveals that the heating rate is dependent on the electrical and physical characteristics of the material as well as on the frequency and intensity of the field. The heating rate is dependent not only on the dielectric loss factor, but also on the permittivity of the material in that the permittivity influences the value of the field intensity. Thus, for a mixture of two different materials, there is a possibility that one will heat at a faster rate than the other if its characteristics are more favorable for r-f heating.

From information available on these electrical and physical characteristics of insects and products they infest, r-f treatment should be expected to raise the temperature of the insect to a higher level than that of the host material in some cases. There has been some controversy with respect to the existence of an unexplained "specific effect" produced by r-f treatment of biological systems. Thomas (9) concludes that the evidence in favor of its existence is inconclusive and that the results attributed to a "specific effect" can be explained by differential heating in many cases.

Materials and Methods

The insects used in the studies reported here include the rice weevil (*Sitophilus oryza* [L.]), granary weevil (*Sitophilus granarius,* [L.]), confused flour beetle (*Tribolium confusum* [Duv.]), red flour beetle (*Tribolium castaneum* [Hbst.]), lesser grain borer (*Rhizopertha dominica* [F.] and the dermestid beetle (*Trogoderma parabile* [Beal.]). The insects were reared at Manhattan, Kansas‡, under controlled environmental conditions (80 F and 70 percent relative humidity) in accordance with established procedures (10). Two-weeks-old adult insects were used in the experiments for all species except the lesser grain borers which were treated as mixed-age adults. In tests with immature stages the ages were also known.

The insects and host materials were confined in Bradley§ No. 3 polystryene plastic boxes during treatment. These boxes are about 1⅞″ square and ¾″ high and have a capacity of about 30 cc (Fig. 1). Samples were prepared by filling the boxes uniformly with wheat or wheat shorts†† and then introducing ten insects except where internal forms were used. For experiments with internal forms, the boxes were filled with infested wheat after thorough

Paper presented at the Annual Meeting of the American Society of Agricultural Engineers at Ithaca, N.Y., June 1959, on a program arranged by the Electric Power and Processing Division. Published with approval of the Director as Paper No. 962, Journal Series, Nebraska Agricultural Experiment Station.

The authors—S. O. NELSON and W. K. WHITNEY—are, respectively, agricultural engineer, farm electrification research branch (AERD, ARS), USDA, and instructor in entomology, Kansas State University, Manhattan, formerly entomologist, biological sciences branch (MRD, AMS) USDA.

* The terms "radio frequency" and "high frequency" have both been used rather generally and interchangeably. However, the term "high frequency" has come to mean specifically the range of frequencies from 3 to 30 magacycles per second, while "radio frequency" refers to a much wider range of the spectrum.

† Numbers in parentheses refer to the appended references.

‡ Stored-Grain Insects Laboratory (AMS), USDA.

§ Use of trade names of specific equipment is for the purpose of identification and does not imply endorsement by the U.S. Government.

†† Shorts are composed of small particles of bran, germ, and flour.

This article is reprinted from the TRANSACTIONS of the ASAE (vol. 3, no. 2, pp. 133, 134, 135, 136, 137 and 144, 1960), the Transactions of the American Society of Agricultural Engineers, Saint Joseph, Michigan

mixing to insure uniformity of infestation. Ten replicates were employed for each exposure, each replicate consisting of one box with at least ten boxes held for the untreated check or control. For the adult insects and the free larvae, each point shown in the figures therefore represents the average for one hundred insects. Mortality counts were made for each replicate at predetermined intervals. Criterion for death in adult insects and free larval forms was complete immobility as determined by visual examination with prodding or air-current stimulation at stated periods after treatment. For internal immature forms the criterion was failure to emerge at stated periods in an environment favorable to development.

Two r-f power oscillators were used to treat the samples. One, operating on a fixed frequency of approximately 39 megacycles per second, is a slightly modified General Electric Model 4HD3B2 electronic dielectric heater. This unit, with a sample box resting on the lower electrode, is shown in Fig. 2. The adjustable grounded electrode

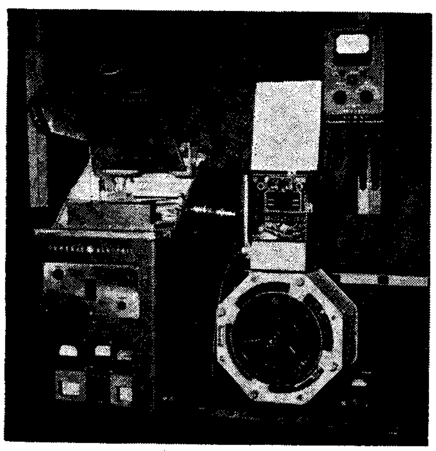

FIG. 2 Dielectric heater used for 39-mc treatments and associated equipment, including variable transformer, vacuum-tube voltmeter, electronic timer and grid-dip meter.

is mounted in the top cover, which is hinged to the frame and brings the grounded electrode down and parallel to the stationary electrode when the cover is closed. These electrodes and the sample or load constitute the capacity of the plate tank circuit as shown in the simplified schematic diagram (Fig. 3). Frequency of operation is therefore somewhat dependent on the load. The unit employs a grounded-plate Hartley oscillator circuit and has an output rating of 3 kw. A Powerstat, type 1256, variable transformer was connected in the primary circuit of the plate transformer in the high-voltage power supply to provide for complete adjustment of the plate voltage applied to the oscillator. It can therefore be used to adjust the r-f voltage at the treatment electrodes to the desired value. Other modifications and additions have been made in the timer-control circuits to provide for shorter intervals and control by an external electronic timer.

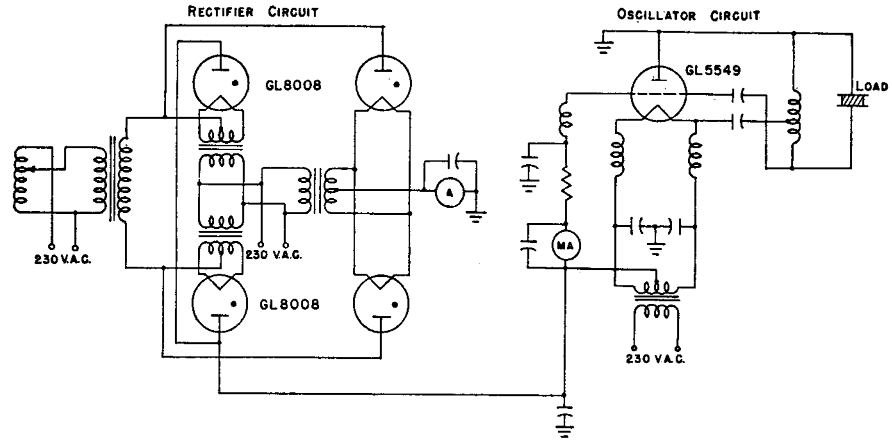

FIG. 3 Simplified schematic diagram of GE Model 4HD3B2 electronic dielectric heater used for 39-mc treatments.

The other r-f oscillator (dielectric heater) was constructed for work at lower frequencies. It operates in the frequency range from 1.5 to 11 megacycles, and has a maximum power output of about 1 kw. It employs a tuned-plate oscillator with inductive coupling to the grid circuit (Fig. 4). It is shown in Fig. 5 where the separate power supply is partly visible below the recording potentiometer. Provisions were made for control of the treatment interval with external timers.

To control time intervals for the dielectric heaters, Cramer Type TE electric timers with maximum ranges of 15 sec and 120 sec, an Eagle 30-sec Cycl-Flex reset timer and Ferrara model T1 and T2 electronic timers were used. When electronic timers were employed their calibration was checked or the interval simultaneously measured with a Standard Electric Model S-1 precision timer.

Measurements of the frequency at which the r-f equipment operated were made using a Millen No. 90651 grid-dip meter.

The r-f electrode voltage was measured with a Hewlett-Packard model 410B high-frequency vacuum-tube voltmeter (VTVM) equipped with a 100:1 Hewlett-Packard model 453A capacitive voltage divider probe and additional 10:1 capacitive dividers which were built into the treatment chambers of the dielectric heaters. These additional dividers were necessary because of the 2000-volt, rms maximum voltage rating of the 453A probe. They were calibrated to provide a 10:1 voltage division at values below the maximum voltage rating of the probe. Treatment electrodes were adjusted to compensate for the capacity added by the 453A probe when connected directly to the electrode. The calibration of the VTVM was corrected to within ½ percent accuracy by comparison with laboratory meters at 60 cps. The maximum probable error in measurement at 40 mc due to frequency response of the instrument is about 5 percent according to the manufacturer. Taking calibration of the capacitive voltage dividers into consideration, r-f electrode voltages should be accurate to within less than 10 percent. The VTVM uses a peak measuring circuit with rms calibration for a sinusoidal input. Voltage and field strength values herein reported are therefore rms values.

Temperature measurements on sam-

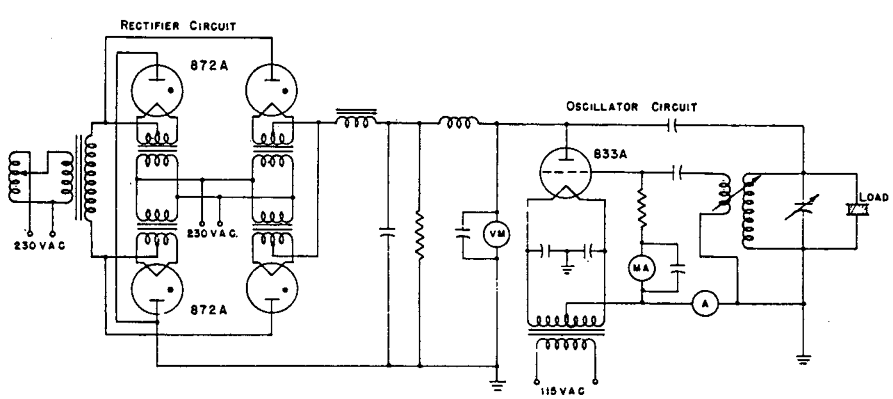

FIG. 4 Simplified schematic diagram of a 1-kw power oscillator used for 5 and 10-mc treatments.

ples were taken immediately after treatment using a Leeds and Northrup Type G, Model S, strip-chart, ten-point recording thermocouple potentiometer (Fig. 5) and thermocouples made from No. 30 B & S gage duplex copper-constantan wire with glass braid insulation. A ten-pole, ten-position switch, also shown in Fig. 5, was constructed for use with copper-constantan thermocouples, which permits rapid selection of any desired combination of thermocouple to recorder-point connections. The thermocouples were clamped in a mount and inserted through a No. 60 hole drilled in one side of the plastic boxes as they were placed on the thermocouple mount as shown in Fig. 1. The elapsed time, *t*, between the end of treatment and the first temperature measurement recorded on the chart was measured with a stopwatch and the temperature-time curve extrapolated, as illustrated in Fig. 6, to find the sample temperature at the end of treatment. Studies of semilogarithmic plots of temperature and time indicated that grain-sample temperatures may be slightly higher than those obtained by the above procedure. This procedure, however, was selected as a practical compromise.

Calculation of field intensity was simplified by treating all samples with the electrodes in contact with the top and bottom of the boxes, and with the boxes completely filled with wheat or wheat shorts. The average intensity for the sample was calculated as follows:

$$\mathbf{E} = \frac{\mathbf{V}}{\mathbf{d}_1 + \mathbf{d}_2 \frac{\epsilon_1}{\epsilon_2}} \quad \ldots\ldots\ [3]$$

where **V** is the r-f electrode voltage and $\mathbf{d}_1$ and $\mathbf{d}_2$, and ϵ_1 and ϵ_2 are the thicknesses of the materials between the electrodes and their permittivities for the grain and polystyrene respectively. The thickness for the grain, $\mathbf{d}_1$, was given by the assembled height of the box less $\mathbf{d}_2$, the combined thickness of the lid and bottom of the box. The permittivity of polystyrene, ϵ_2, is approximately 2.56. The permittivity of the wheat and wheat shorts used in each experiment was obtained by measurement at room temperature following the method previously reported (5).

At the same time that electrical measurements were taken, moisture content determinations were made on samples from the same source in accordance with an approved oven method (6).

Results

Only those results illustrating pertinent engineering information are presented here. A subsequent publication emphasizing the entomological aspects of these studies will be forthcoming.

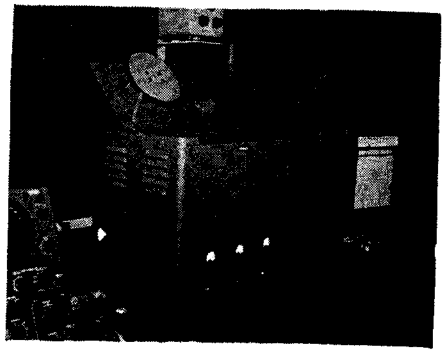

FIG. 5 One-kilowatt oscillator used for 10 and 11-mc treatments.

For treatment of adult rice weevils in wheat, high field intensities were found to be much more efficient than low values. This is illustrated in Fig. 7, where mortality curves for treatments at 3.6 and 1.2 kilovolts per inch are compared. An important delayed mortality effect is also shown in Fig. 7, where mortalities one day after treatment and one week after treatment are compared for each of the two field intensities. The difference between effects of high and low field intensities, however, does not appear in Fig. 8 where the emergence curves for mixed stages of immature rice weevils are not significantly different at the 5 percent probability level. The better efficiency of the higher field-intensity treatment may also be noted in Fig. 9, where two mortality curves are shown for 39-mc treatment of dermestid beetle larvae.

Fig. 9 also shows a curve for treatment at 11 mc. Comparison of the two different frequencies at the same field intensity indicates that the 39-mc treatment is considerably more effective. Fig. 10 shows a comparison of 39 and 10-mc treatments on adult rice weevils from the same population in wheat from the same source where heating rates were equalized by adjustment of field intensity. There was no significant difference at the 5 percent probability level in the resulting mortality curves. One cannot conclude, however, that the rate of heating is the all-important factor in these comparisons, because in Fig. 9, the 11-mc treatment resulted in a heating rate intermediate between the two 39-mc treatments and still was the least efficient.

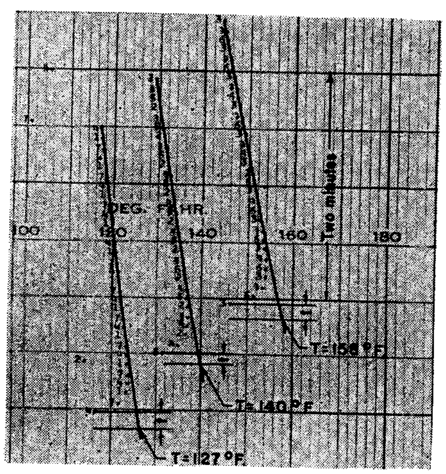

FIG. 6 Temperature-time record on a strip chart showing elapsed time, t, grain-mass temperature, T, and method of extrapolation.

The characteristics of the medium in which the insects are treated also influence the effectiveness of the treatment as shown in Fig. 11. When adult confused flour beetles were treated in wheat shorts, much more energy was absorbed by the medium for a given insect mortality than when they were treated in wheat. Comparison of Figs. 11 and 7 also reveals much less delayed mortality for adult flour beetles than was found with adult rice weevils. Considerable differences were found among species of insects and also between developmental stages within species in their reaction to r-f electrical treatment, which indicates the advisability of using more than one species or stage in tests of this nature.

Treatments required for 100 percent mortality of the most resistant stages used in these laboratory-scale studies produced momentary mass temperatures of 140 to 150 F in the wheat. According to Soderholm (8), such treatments do not reduce the germination of wheat when the moisture content is below about 14 percent. Subsequent germination tests have verified this report. In some preliminary studies, Soderholm (unpublished data) also found no appreciable difference in milling and baking qualities of wheat due to r-f treatment which raised the wheat to temperatures as high as 168 F. It is possible that treatment temperatures higher than 150 F might be required for some species of insects not yet tested. With adult rice weevils, 100 percent mortality has been obtained with treatments of less than one second which did not raise the temperature of wheat above 100 F.

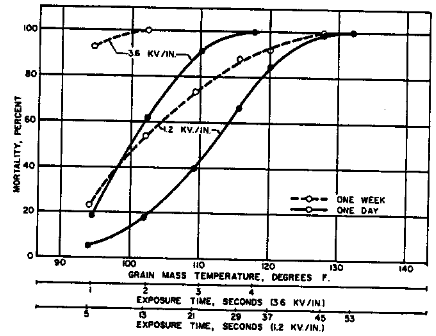

FIG. 7 Mortality of adult rice weevils at indicated times after treatment in 12.8 percent-moisture wheat at 39 mc and indicated field intensities. Wheat characteristics: $\epsilon' = 4.15$; $\epsilon'' = 0.50$.

Some experiments were conducted

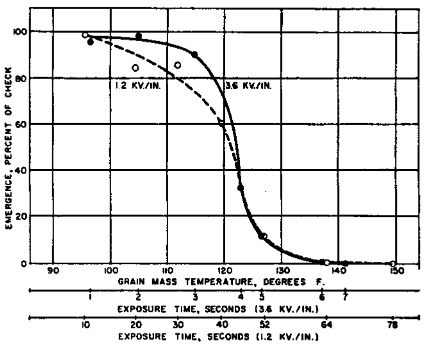

FIG. 8 Emergence of rice weevils six weeks after treatment of mixed immature stages in 13.6 percent-moisture wheat at 39 mc. Wheat characteristics: $\epsilon' = 4.34$; $\epsilon'' = 0.49$.

at higher field intensities with some indications of improved efficiency. Difficulty with arcing and consequent burning of the kernels is encountered if the field intensity is too high. The degree of difficulty with arcing is also somewhat dependent upon the length of treatment. With clean wheat, little arcing was observed at intensities below 4.8 kv per inch. For treatment completely free of arcing problems, a field intensity of 3.6 kv per inch was selected for many experiments.

Discussion

Some of the foregoing results may be explained by differential heating of the insects and the medium in which they were exposed to the r-f electric field. The expected heating rate for any particular substance is given by equation [2]. Consider the treatment of a few insects in a quantity of grain. The values for **K** and f in equation [2] will be the same for both materials. All other factors determining the heating rate may be different for the insects and the grain. Values for the dielectric loss factor, ϵ'', and the real permittivity, ϵ', have been obtained for masses of adult rice weevils and confused flour beetle using the same method employed for measurement of the dielectric properties of grain samples (5). Values for the density and specific heat of wheat are available in the literature (1), and reasonably good estimates can be made for the density and specific

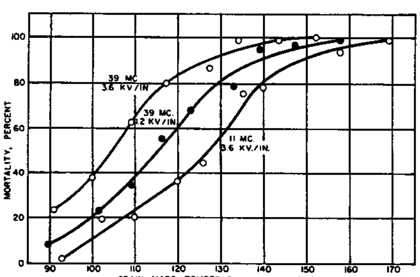

FIG. 9 Mortality of dermestid beetle larvae five weeks after treatment in 12.6 percent-moisture wheat. Wheat characteristics: $\epsilon'_{11} = 4.17$; $\epsilon''_{11} = 0.37$; $\epsilon'_{39} = 3.96$; $\epsilon''_{39} = 0.49$.

heat of the insects. The value of **E** for the grain can be calculated from other known or measured quantities using equation [3]. The value of **E** for the insects is more difficult to obtain. It may be estimated, with caution, by considering the insect as a sphere embedded in an infinite medium and using the dielectric properties of the insects for the sphere and those of the wheat for the medium. From the mathematical model, the relationship between the field in the sphere and that in the medium is

$$\mathbf{E}_1 = \mathbf{E}_2 \left(1 - \frac{\epsilon_1 - \epsilon_2}{2\epsilon_2 + \epsilon_1}\right) \quad . \; . \; . \; [4]$$

in which subscript 1 refers to the sphere and subscript 2 refers to the medium. Using values obtained by separate measurements at about 75 F on rice weevils and wheat of 6.6 and 4.2, respectively, for the complex permittivity, ϵ, the intensity of the field in the insect is estimated to be about

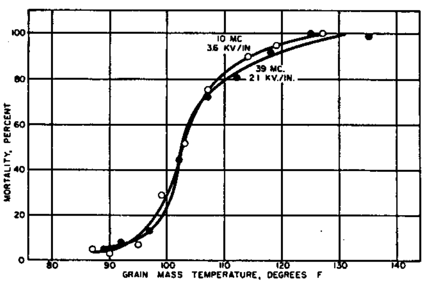

FIG. 10 Mortality of adult rice weevils two days after treatment producing comparable heating rates in 12.9 percent-moisture wheat. Wheat characteristics: $\epsilon'_{10} = 4.39$; $\epsilon''_{10} = 0.39$; $\epsilon'_{39} = 4.23$; $\epsilon''_{39} = 0.51$.

0.84 times that in the wheat.** Values obtained for the dielectric loss factor, ϵ'', for the rice weevils and wheat were 2.2 and 0.5 respectively. The bulk density of the wheat and that of the rice weevils can be expected to be about the same. The specific heat of the wheat was about 0.4 and that of the insects is estimated at about 0.7. Using these figures in connection with equation [2], the expected ratio of the heating rate of the adult rice weevils to the heating rate of the wheat would be 1.8. This ratio of the two heating rates is designated as the differential heating factor, **R**.

Estimates of the values of **R** when confused flour beetles are treated in wheat and in wheat shorts can also be calculated. Values obtained by measurement for the complex permittivity of the wheat and wheat shorts used in the experiments for which the results are shown in Fig. 11, and the complex

** Since the measurements of permittivity and loss factor were made on insects in bulk, the values obtained apply in effect to the insect and its share of the surrounding space. Where "field intensity in the insect" is referred to in this discussion, it must be kept in mind that this intensity is a sort of average for the insect and its associated space envelope.

permittivity of the confused flour beetles were, respectively, 4.26, 2.79, and 7.84. Using equation [4], it is found that the field intensity in the insects may be expected to be 0.77 of that in the medium for wheat and 0.61 of that in the medium for wheat shorts. The values obtained for the dielectric-loss factor of the wheat, wheat shorts and confused flour beetles were 0.51, 0.38 and 2.20, respectively. The density of the wheat shorts, found by weighing a known volume under the same compaction conditions as was used in the treatments, was 0.53. The specific heat of the wheat shorts is estimated at 0.4, since the values for wheat and wheat flour are both 0.4 (1). Using 0.7 for the specific heat of the confused flour beetles, and estimating their specific gravity at 0.7, the expected differential heating factors may be calculated using equation [2]. For adult confused flour beetles in wheat, the value of **R** obtained is 1.6. For the same insect in wheat shorts, the estimate is 0.9. While these figures are based on some estimates and a simple mathematical model, the large difference obtained in expected differential-heating factors for the flour beetles in the two different media is believed to explain the experimental results quite satisfactorily. Differential heating can also explain the complete mortality of adult rice weevils produced by some treatments which did not raise the temperature of the wheat in which they were treated above 100 F. The insects can normally survive exposure for many hours in a hot-air oven at temperatures below 100 F.

In order to obtain experimental evidence of differential heating, prepared sample boxes of wheat with adult rice weevils were preconditioned over night at four different temperatures – held at these temperatures until treatment, and the resulting mortality curves plotted as shown in Fig. 12. In analyzing this experiment, it was assumed that there is a critical temperature, T_c, which results in a given mortality if the insects

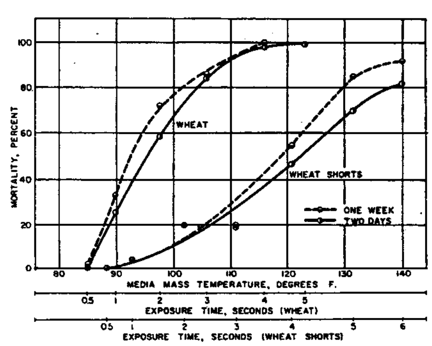

FIG. 11 Mortality of adult confused flour beetles after treatment in 13.3 percent-moisture wheat and 13.0 percent-moisture wheat shorts at 39 mc and 3.6 kv per in. Wheat characteristics: $\epsilon' = 4.23$; $\epsilon'' = 0.51$. Wheat shorts characteristics: $\epsilon' = 2.76$; $\epsilon'' = 0.38$.

themselves are raised to this temperature momentarily under the existing conditions. Taking **R** as the ratio of the average heating rate of the insects to that of the grain, the following equation may be written

$$T_c = T_{ig} + R\,\Delta T_g \quad . \; . \; . \; . \; . \quad [5]$$

in which T_{ig} represents the initial grain temperature, which is also the initial temperature of the insects, and ΔT_g is the elevation of the grain temperature produced by the treatment. Since T_{ig} is known and ΔT_g can be determined from the curve for any particular mortality, two unknowns remain in equation [5], T_c and **R**. For any given mortality, an equation may be written using each curve in Fig. 12. Any pair of curves thus provides two equations which may be solved simultaneously for **R** and T_c. The mean values for **R** and T_c from the six possible combinations of pairs of simultaneous equations set up using the curves in Fig. 12 are listed in Table 1 for 40, 50, 60 and 80-percent mortality levels. The values for the 20-percent mortality level are the mean solutions of three combinations of equations, since one of the curves does not provide information at 20-percent mortality.

TABLE 1. MEAN SOLUTIONS TO EQUATION [5], DIFFERENTIAL HEATING FACTOR, R, AND CRITICAL TEMPERATURE, T_c, FOR INDICATED MORTALITIES

Mortality	Mean R*	Mean T_c
20 percent	2.27	112.8 deg F
40 percent	1.71	113.2 deg F
50 percent	1.52	113.4 deg F
60 percent	1.46	116.0 deg F
80 percent	1.24	116.7 deg F

* Means are significantly different at the 1 percent probability level except those for 50 and 60 percent mortality.

The values for the differential heating factor derived from this analysis indicate that the adult rice weevils, when treated in wheat, do heat at a faster rate than the wheat. The factor, however, appears to be temperature-dependent, as might be expected, and decreases as temperatures increase toward the point required for complete mortality of the insects. This is apparent from the convergent tendency of the four curves in Fig. 12. The experimental values for **R** at the 20 and 40-percent mortality levels agree reasonably well with the theoretical estimate of 1.8 which was based on measurements of the dielectric properties in the lower temperature range.

No special study of costs of r-f electrical treatment to control insect infestations in grain has been undertaken. A general estimate, however, has been made considering the cost of a 200-kw generator with a capacity of 400 bu per hour operating 2,000 hr per year and the r-f energy required to raise the temperature of wheat from 80 to 150 F. Considering depreciation, interest, electric energy at 2 cents per kilowatt-hour, vacuum tube and condenser replacement, and maintenance labor, it is estimated that wheat could be treated at a cost of about 3½ cents per bushel. This is five to seven times the present cost for large-scale commercial treatment using chemical fumigants. Also, many elevators handle grain at a rate of 2,000 bu per hour. R-f treatment at this rate would require considerable improvement in efficiency of treatment or equipment with higher power ratings than that which is now commercially available in a single unit. For economical application, very significant improvement in efficiency, additional uses for the equipment, or other benefits would be necessary.

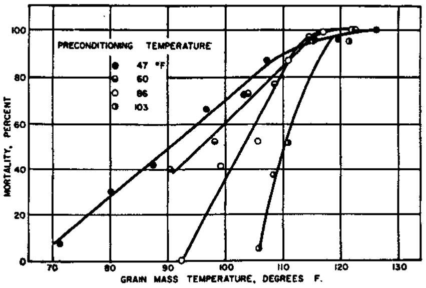

FIG. 12 Effects of initial temperature on mortality of adult rice weevils one day after treatment in 13.2 percent-moisture wheat at 39 mc and 3.5 kv per in. Wheat characteristics: $\epsilon' = 4.19$; $\epsilon'' = 0.47$.

Further research is needed to establish the most effective combination of treatment parameters for r-f insect control. Additional studies are recommended to evaluate the benefits of seed treatment in stimulating germination and of wheat treatment to improve baking qualities of flour milled from the wheat. Possible application in grain drying processes or other conditioning should also be investigated.

Summary

This paper reports the engineering phases of cooperative USDA studies on the use of radio-frequency electric fields for stored-grain insect control conducted by the Farm Electrification Research Branch, Agricultural Engineering Research Division (ARS-USDA) in cooperation with the Nebraska Agricultural Experiment Station and the Stored-Grain Insects Laboratory, Biological Sciences Branch, Marketing Research Division, AMS, Manhattan, Kansas.

Important reviews of the pertinent literature and previous studies are cited. General principles of radio-frequency heating as they relate to the problem are discussed briefly. Experimental methods, equipment used for treatment of samples, and instruments used for measurement of important treatment variables are described.

Several species of stored-grain insects were treated in wheat or wheat shorts with r-f electric fields at frequencies of about 10 and 39 megacycles per second and field intensities ranging from 1.2 to 3.6 kilovolts per inch (rms).

Graphical results of some of the experiments are presented in the form of mortality and emergence curves which show the effects of different treatment variables. High field intensities were found much more efficient in killing adult rice weevils in wheat, but for treatment of immature stages of the same insect, low or high field intensities produced the same results. Treatment of confused flour beetles in wheat and wheat shorts revealed that much longer exposures were required in wheat shorts for comparable mortality. Treatment at 39 and 10 mc produced the same mortality curve for adult rice weevils in wheat when the heating rates were equalized by adjustment of field intensity, but treatment of dermestid beetle larvae in wheat at 39 mc was found more efficient than treatment at 11 mc regardless of heating rate. Complete mortality was obtained with all species tested by treatments which did not reduce germination of the wheat when its moisture content was below about 14 percent. Treatments for 100 percent mortality of the most resistant insect stages used produced momentary mass temperatures of 140 to 150 F in the wheat, but higher treatment temperatures may be required for some species of insects not yet tested. Treatments with resulting grain temperatures of less than 100 F have produced 100 percent mortality of adult rice weevils when treated in wheat.

A theoretical discussion is presented on the differential heating of insects and grain due to their different electrical characteristics. An estimate of the value of the differential heating factor is given based on actual measurement of dielectric properties of the grain and masses of insects. Experimental results are also analyzed to provide empirical values for the differential heating factor. The values arrived at by the two methods are in reasonable agreement. The empirical values obtained indicate that the adult rice weevils do heat at a faster rate than the wheat, but that the differential heating factor is temperature dependent and decreases as treatments approach the level required for complete mortality.

A simple, liberal cost estimate for disinfestation of grain using r-f energy, considering cost of electric energy, depreciation, interest, and maintenance, results in a figure of about 3½ cents per bushel, which is considerably more expensive than present commercial treatments with chemical fumigants.

Further research is recommended

which may result in the development of more economical treatment and application of the method for other seed and grain treatment purposes as well.

References

1 Agricultural Engineering Data 1, Engineering data on grain storage, AE Index 11.732, published by the American Society of Agricultural Engineers, St. Joseph, Mich., May 1948.

2 Ark, P. A., and Parry, Willet. Application of electrostatic fields in agriculture, **The Quarterly Review of Biology,** 15:2, 172-191, June 1940. Campbell, F. L. (see ref. 10).

3 Davis, J. H. High-frequency method of and apparatus for exterminating insect life in seed or grain or other materials, U.S. Patent No. 1,-972,050, August 28, 1934.

4 Frings, Hubert. Factors determining the effects of radio-frequency electromagnetic fields on insects and materials they infest, **Journal of Economic Entomology,** 45:3, 396-408, June 1952.

5 Nelson, S. O., Soderholm, L. H., and Yung, F. D. Determining the dielectric properties of grain, **Agricultural Engineering,** 34:9, 608-610, September 1953.

6 Official methods of analysis of the association of official agricultural chemists, seventh edition. Section 22.8, Published by the Association of Official Agricultural Chemists, 1950.

7 Peredel'skii, A. A. The problem of electrotechnical measures for combatting harmful insects, (In Russian) **Uspekhi Soveem Biol.,** 41, 228-245, March-April 1956.

8 Soderholm, L. H. Effect of dielectric heating and cathode rays on germination and early growth of wheat, **Agricultural Engineering,** 38:5, 302-307, May 1957.

9 Thomas, A. Morris. Pest control by high-frequency electric fields—Critical resume, Technical Report W/T23, Published by the British Electric and Allied Industries Research Association, Thorncroft Manor, Dorking Road, Leatherhead, Surrey, 1952.

10 Campbell, F. L. and Moulton, F. R. Laboratory procedures in studies of the chemical control of insects, American Association for the Advancement of Science, (Publication No. 20) 206p, 1943.