# High-Power Microwave Radiation as an Alternative Insect Control Method for Stored Products

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ABSTRACT Insect mortality studies were performed with a high-power microwave source operating at a frequency of 10.6 GHz at power levels of 9-20 kW to irradiate samples of soft wite wheat, *Triticum* aestivum (L.), infested with maize weevil, *Sitophilus zeamais* Motschul-sky, and ground wheat infested with red flour beetle, *Tribolium castaneum* (Herbst). These pests are common internal and external feeders in stored products, respectively. Samples at various age intervals from egg to adult were exposed. The results support the hypothesis that the insect-to-host dissipation ratio increases at frequencies >2.45 GHz. Mean mortalities $\geq 93\%$ occurred for all ages of *S. zeamais* and $\geq 94\%$ for adults and larvae of *T. castaneum* for mean specific input energies of $\geq 51$ J/g and 53 J/g, respectively, indicating that S. *zeamais* is more susceptible. Extrapolating the results to the cost of treating the product in bulk volume at a busbar electric energy cost of $0.05 per kW-h (3,600 kJ) indicates a unit cost for electric energy ranging only from $0.056 per bushel of wheat infested with S. *zeamais* to $0.139 per hundred weight of ground wheat infested with *T. castuneum.*

KEY WORDS *Sitophilus zeamais, Triboletium castaneum,* microwaves, pesticide, stored products

The U.S. Government is actively seeking alternatives to chemical pesticides because of general concerns about effects on human health and the environment and because insect resistance to chemical pesticides is increasing. Specifically, in accordance with Section 602 of the Clean Air Act (USC 1995), it has proposed eliminating the use, production, and importation of methyl bromide by the year 2001. Methyl bromide is a widely used agricultural pesticide believed to be involved in the depletion of the ozone layer. The National Agricultural Pesticide Impact Assessment Program (Anonymous 1993) has concluded that unless alternatives to methyl bromide are found its loss will have a serious negative impact on U.S. agriculture. Therefore, incentives exist to explore alternative treatments for infested stored products by microwave radiation at frequencies >1 GHz, previously believed to be the upper limit for effective usage of the microwaves. The purpose of this preliminary study was to test the hypothesis that the mortality of insects in stored products is not a monotonically decreasing function of frequency at specific product temperatures and that high mortality can be achieved efficiently and economically at frequencies above I GHz. This study assesses the effectiveness and economy of microwave treatment of infested product at a specific frequency of 10.6 GHz and at power levels ranging from 9 to 20 kW. The test frequency is not known to be optimum for the intended purpose. However, it is sufficiently higher than the maximum frequency of 2.45 GHz, previously studied (Nelson 1973, 1987; Nelson and Stetson 1974), to test the hypothesis.The hypothesis was developed from a consideration of the factors in equation 1 (Harrington 1961 and Nelson 1973) for the power dissipated within a complex dielectric material of volume v,

$$P_d = \oiiint_v \omega \varepsilon^n{}_{eff} \left|E\right|^2 dv \qquad (1)$$

where $P_d$ is the power dissipated, $\omega$ is the angular frequency, $\varepsilon^n{}_{eff}$ is the effective dielectric loss factor (which is medium-specific and a nonlinear function of frequency) and the square of the magnitude of the electric field intensity, $\left|E\right|^2$. At any frequency the factors $\varepsilon^n{}_{eff}$ and $\left|E\right|^2$ will determine the power dissipated in the dielectric body and consequent Joule heating of the body.

In dielectrics heated by microwaves at frequencies >1 GHz, $\varepsilon^n{}_{eff}$ is dominated by dipolar or re-orientation mechanisms (Metaxas and Meredith

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1988) associated with both bound and unbound water. Water is common to both insects and grain in bound form and is known to have a broad distribution of relaxation frequencies with a maximum between 10 and 100 MHz. However, unlike the relatively dry stored grain (Brooker et al. 1978 and ASAE 1993), a significant amount of free water occurs in insects (Weber 1974 and Nakakita et al. 1989) and is a major constituent of its hemolymph (Seifert 1995). The principal relaxation frequency of free water near 18 GHz is known to have a broad distribution (Collie et al. 1948 and Metaxas and Meredith 1988). Therefore, it is postulated that the effective dielectric loss factor of the insect will gradually increase at frequencies >2.45 GHz whereas that of the product, which is below the critical moisture content, will not. This could lead to more efficient selective heating of the insect and consequent higher mortality at a lower product temperature. Other work at 46.35 GHz by Belyaev et al (1990) and efforts to measure the complex permittivity of Colorado potato beetle, *Leptinotar-sa decemlineata* (Say), by Colpitts et al. (1992) over the range from 100 MHz to 26.5 GHz have also been reported, indicating renewed interest in effects at microwave and millimeter wave frequencies.

Other evidence exists for increased selective heating caused by more efficient energy transfer to the insect at higher microwave frequencies, based on wavelength scaling of its physical size. Experiments performed by Bedi and Singh (1992) indi-cate that lethality effects in rice moth, *Corcyra cephahmica* (Stainton), larvae and adults of lesser grain borer, *Bhyxopertha dominica* (F.), and *Cal-bsobruchas chinensia* (L.) are directly proportional to frequency in the range of 12 – 18 GHz at energy levels similar to those found by us to produce hi mortality at 10.6 GHz. This view is supported y Fano 1950 whose analysis indicates that the impedance of dielectric bodies to an energetic wave will increase as the wavelength of the impinging wave decreases and that the efficiency of energy transfer will increase with impedance. It is also supported by analytical modeling studies reported in Halverson et al. 1995.

## Materials and Methods

Two separate high-power tests were performed at a frequency of 10.6 GHz. The goal of the 1st test was to determine the requirements for energy input to the sample to produce high levels of mortality and to show that mortality was not a monotonically decreasing function of Frequency. It was also intended to determine the effects of the radiation on germination of uninfested wheat. The 2nd test was conducted to define the logistic functional dependence of mortality on energy input and temperature over a range that included the maximum rate of change of mortality and to monitor the depth of penetration of microwave energy into the product. The materials and methods used for each test differ and are described sequentially in the following sections.

Sample Preparation. For the 1st high-power test, 4 groups of four 40-g samples of wheat containing maize weevils, *Sitophilus zeamais* Motschulsky, at each of seven age stages and four groups of four 25-g samples of ground wheat containing red flour beetles, *Tribolium castaneurn* (Herbst), at each of 3 age stages were prepared in Madison, WI, and shipped to Oak Ridge, TN. Three of these groups were designated as A, B, or C, and the 4th group (X) was used as a control. Within each age group, each sample was contained in a covered polystyrene petri dish (100 by 15 mm) and marked with an alphanumeric code that identified species, age group, sample number (within each exposure), and exposure time. Approximately 100 adult weevils, 4-11 d postemergence, were used for each 40-g sample of grain in each of the 4 petri dishes for the adult stage, designated as age group 1. The 5 weevil larval groups in descending age order (age groups 2 through 6) in each of the 4 dishes were 13 – 20, 11–17, 7–14, 5-11, and 5-8 d old. The number of larval weevils or weevil eggs (age group 7) in each 40-g sample of grain was =200 as gauged by the numbers of adults emerging from the controls. Approximately 100 *T. castaneum* adults (age group 1), 1-20 d postemergence, were used in each replicate petri dish with 25 g of whole wheat Hour. Approximately 100 larvae, 22-29 (age group 2), and 25 eggs, 1 – 2 d old (age group 3) were also used in each replicate petri dish.

For the 2nd high-power test, 2 replications of 3 groups (also designated A, B, or C) of 4 vertically stacked covered polystyrene dishes (139.7 mm diameter by 25.4 mm) and 1 control group (X) of 4 were also prepared at Madison, WI, and shipped to Oak Ridge, TN. Each dish contained soft white wheat, with 32 plastic containers (12.7 mm diameter by 17.5 mm) each (16 containing 4 S. z*eamais* adults with wheat each and 16 containing 4 *T. castaneum* adults with ground wheat each). These capsules, each with perforated ends, confined the insects to discrete locations within the wheat to permit the correlation of mortality with both spatial location and temperature.

**High-Power Exposure Facility**. The test samples were exposed to 10.6 GHz microwave power in the range from 9 to 20 kW in the Oak Ridge National Laboratory Fusion Engineering Division (ORNL-FED) microwave heating chamber. The chamber is a cylindrical tank with a volume of 0.5 $m^3$ shown in Fig. l. Although this configuration was not optimized for grain exposure it proved ad-equate for these proof-of-principle tests. Two Varian 10-kW klystron amplifier tubes (VA-864) are used to generate continuous microwave power at 10.6 GHz at an efficiency of 25%. Output power from the klystrons is transmitted in 2.286 cm by 1.016 cm (0.9 in. by 0.4 in.) WR-90 copper rectangular waveguides to ferrite

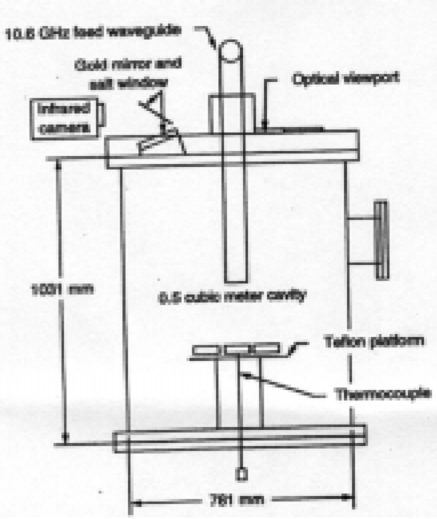


**Fig 1**. Microwave irradiation tank schematic for test 1.

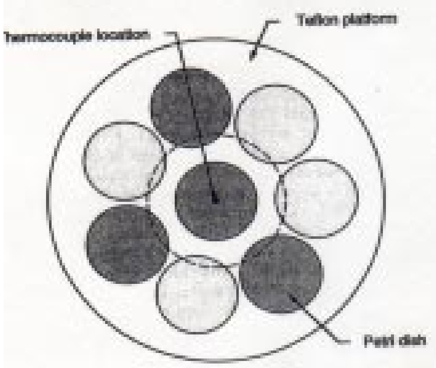


**Fig 2**. Planar arrangement of test samples on the microwave exposure tank Teflon platform for test 1. Four dishes of each of 2 age groups were exposed simultaneously. Shading indicates the positioning of age groups.

circulators which absorb rejected power to provide load isolation. The power from two klystrons is launched into a circular waveguide 5 meters long by 63.5 mm diameter (196.85 in. by 2.5 in.) with a dual horn transition. The transition provides no mode preservation into the overmoded circular waveguide. The large diameter of the circular waveguide minimizes losses despite the lack of mode control. Power is launched into the exposure tank from the open-ended waveguide directly at the samples. The klystrons are fed by a low power 10.6-GHz drive signal. The drive signal and pulse duration are varied to control the power and exposure time. The klystron bandwidth can accommodate 25 MHz frequency variation with only a slight decrease in output power. The use of the swept frequency and the 5-m mixed mode waveguide run results in a relatively uniform radiation pattern from the launcher because of mode dispersion and achieves a nearly uniform exposure of the sample to both 1st-pass and multiple-reflected power. The chamber was provided with a video camera and cassette recorder and an infrared camera system (Inframetrics 600L, North Billerica, MA) to monitor the samples during exposure. Temperature was also measured by a metal-sheathed thermocouple inserted into a small hole in the center petri dish.

For each exposure in the 1st high-power test, 8 polystyrene petri dishes were placed in a circular pattern on a Teflon platform supported near the center by a copper cylinder as shown in Fig. 2.

Typically 4 petri dishes from each of 2 distinct age classes were exposed simultaneously. For each exposure in the 2nd test, 4 polystyrene dishes, each holding 32 cylindrical capsules containing adult insects and grain, were stacked vertically as shown in Fig. 3. The capsules in each dish were arranged symmetrically along radial lines spaced 45º apart azimuthally. Four capsules containing S. z*eamais* and spaced 17.5 mm on centers were located on each of the radii at azimuths 0, 90, 180, and 270º. Similarly, the capsules containing *T. castanets'* were located on each of the radii at azimuths 45, 135, 225, and 315º. Each filled dish had a total weight of 270 g. Each dish was coded to identify the dish number, replication, and exposure time period. Each capsule within a dish was coded to identify species, dish, radial and azimuth-al positions, and exposure time period. Hence, the mortality of the insects could be uniquely correlated with spatial position and temperature in the exposed stack.

**Low-Power Tests**. Low-power measurements of the scattering parameters of samples of adult S. *zeamais* and *T. castaneum* alone, wheat infested with S. z*eamais* larvae and eggs, and uninfested wheat and Hour alone were also made to determine the characteristic depth of penetration (5) of fields into the product, as a function of frequency. In a dielectric medium with losses, such as the stored-product investigated here, the depth of penetration into the product is inversely proportional to frequency. Therefore, the characteristic penetration depth is an important parameter in the determination of an optimum frequency of operation and applicator configuration for a practicable microwave grain irradiation system in order to treat the entire mass. (The depth of penetration is defined here as that distance over which the field intensity of a traveling plane wave has fallen to 1/e, or 37%, of its reference value. It has also been defined as that depth [Dp] where the power density decreases to 1/e of its reference value. The authors use the former definition which is greater than that obtained from the latter by a factor of 2.) The log magnitude of the forward scattering coefficient ($S_{21}$) was measured over a range of 50 MHz to 40 GHz with Hewlett-Packard (Santa Clara, CA) model HP 8720C (50 MHz to 20 GHz) and HP 8756A (26.5 GHz to 40 GHz) network analyzers with coaxial (General Radio, Cambridge, MA, model GR 874-L10) and waveguide (WR-62) sample holders to contain the samples. The penetration depth in the static sample at 10.6 GHz was determined from these measurements. For validation of the measured values, the penetration depth was also calculated from standard equations (Metaxas and Meredith 1988) using published data obtained on the dielectric properties of bulk wheat at 10 GHz (Nelson and Charity 1972, Nelson 1991).

**Experimental Design**. The 1st high-power test was an empirical study. Samples were exposed in a planar array of 4 petri dishes for each of 2 age groups that were exposed simultaneously (e.g., W1A and W2A or T1A and T2A) as shown in Fig. 2. The 1st letter of the sample codes represented the insect species, the next numeral represented age groups, and the final letter represented the exposure. Age groups 1 and 2, 3 and 4, and 5 and 6 represented a pairing of age groups. Age group 7 was matched with 4 dishes of uninfested product. In the case of soft white wheat, these 4 samples were used in subsequent germination studies. Therefore, the total mass of product exposed was 320 g per exposure period for S. *zeamais* and 200 g per exposure period for *T. castaneum*. Three of these groups were exposed separately for 1 of 3 calculated time periods A, B, or C, subsequently identified. The 4th group (X) was used as an unexposed control for each species. Each species was exposed separately. The groups were always exposed in the order A, B, and C. The measured variables were exposure time and input power (from which energy input was derived) and host product temperature. The number of individual insects in each replicate dish was sufficiently large (approx. 100 adults and 250 larvae or eggs) to permit the assumption that the mortality in each group would be distributed normally. After exposure, the mortality of each dish within the planar group was determined by comparing the numbers of surviving adults and emerging instars with those of the appropriate controls over a period of 41 d.

The experimental design for the 2nd high-power test was a randomized complete block design with nested factors, resulting in a split-plot model. Each treatment consisted of exposing a stack of 4 dishes for a given exposure time. A block was composed of 3 stacks exposed for 1 of 3 different times, A, B, or C. The exposure times were always run in the order A, B, and C. There were to be 2 replications for each of the exposure times. Because of an unintentional overexposure of the 1st replication of stack A, another stack was prepared and exposed separately for the required length of time as a substitute for replication 1 of stack *A*. Therefore, the as-run experiment was treated as a randomized complete block design with 2 blocks. Stacks B and C of the 1st replication and the 2nd replication of stack A became block 1. Block 2 consisted of the 2nd replications of stacks B and C and the 3rd replication of stack A. Within each stack there were 3 nested factors comprising the axial, radial, and azimuthal cylindrical coordinates of the capsules in each dish. Thus, in any constant axial, radial, or azimuthal surface there was a set of 16 capsules for each species. The data for each insect species were analyzed separately.

**Calibration and Exposure**. Before the infested samples were exposed in the 1st high-power test, the coefficient of coupling between the microwave source and the uninfested host medium in the pe-tri dishes was determined by calibration of the source with samples of uninfested host medium as a load. Temperature increases in the host medium were calculated for an assumed unity coupling factor using the ' c heat of 1.602 J/g per ºC for soft white wheat (ASAE 1995) at 10% moisture content (wet basis). An identical value was assumed for the specific heat of the wheat Hour. (No data are known to exist on the c heat of insects. However, because the mass of insects in the sample relative to the mass of host product is negligible, it was assumed to be negligible in the calculation of exposure time for the infested samples.) The calculation used the published value of the specific heat of soft white wheat, the sample mass, the difference between the ambient temperature (29.6  1.3ºC) and the desired temperature, and the assumed maximum klystron output power of 10 kW to arrive at an exposure time. The study/experiment periods were calculated to keep the maximum temperature of the host product at or below the viability critical temperature of 62.8ºC (145ºF, Brooker et al. 1978) for grain and at or above a minimum temperature of 51.7 C (assumed to be at or near the region of maximum rate of change of mortality) and varied between 1.92 and 4.2 s. The samples were then exposed at 10.6 GHz for the required time to deposit the calculated energy in the sample under the assumed unity coupling and the temperature and input power were monitored. The measured temperature rise and input power were then used to calculate the actual energy coupling coefficient between the klystron source and the sample load. Values for the coupling coefficient for wheat and wheat flour in the first test were 0.54 and 0.62, respectively. The facility was also calibrated similarly with water as a load instead of the host medium using the standard  heat of 4.1868 J/g per ºC (1.00 Btu/lb m per ºF) yielding a coupling coefficient of 0.84. The temperature of the water in each dish was measured and compared for uniformity. The standard deviation was 1.4ºC, indicating that the energy density within the chamber is equivalently uniform.

During all exposures, input power in kilowatts was measured with an accuracy of 4.0%. Temperature was measured with a stainless-steel-sheathed chromel-alumel ('Fype K) thermocouple, with standard limits of error (2.2ºC), inserted through the bottom of the tank into a small hole in the center petri dish and monitored by an Omega 871A digital thermometer. The tip of the thermocouple was in direct contact with the product. The temperature of the central dish was also monitored and recorded during exposure by an Infra Metrics 600L infrared camera. Immediately after exposure, the bulk temperatures and time of each measurement of each of the 8 exposed samples were taken using the previously described stainless steel sheathed thermocouple probe. The probe was inserted directly into the exposed sample where it came into direct surface contact with the host product. All samples were shipped back to Madison, WI, for confirmation of adult insect kill and for mortality and germination studies.

The calibration procedure for the 2nd test was modified because of the attenuation of energy with penetration. The coupling between the source and sample decreased exponentially with distance into the sample mass, and a constant coupling coefficient could not be defined as in the 1st test. Therefore, the calibration procedure determined an effective coupling coefficient, based on the total sample mass, which would limit the maximum temperature at any point within the sample to a selected value. After calibration the replicate stacks were exposed separately for periods that were calculated to limit the maximum temperature of the bulk grain to 60°C for exposure period A (4.57 s), 48.9 C for exposure period B (2.76 s), and 54.4°C for exposure period C (3.72 s), assuming a maximum output power of 20 kW. The mean ambient temperature measured during the test was 29.1 + 0.3°C. The exposure times were selected to be at or below that necessary for 100% lethality and levels where the slope of the logistic mortality curve as a function of temperature is the greatest and where maximum sensitivity of insects to temperature changes occurs. During the actual test the measured power ranged from 14 to 19 kW. During exposure the center temperature of the bottom dish was measured by the type K thermocouple. After exposure the dishes were removed in sequence and the spatial temperature distribution and time of measurement recorded for each dish at the periphery of each of the 8 radii and at the center using a hand-held Heimann (Pyrometrics, Millington, NJ) model MS-10-1-1-4 infrared pyrometer. Temperatures along each radius between the measured endpoints were determined by interpolation using an exponential function of the radius. This was done to limit the manual scanning time to 30 s per dish, thus preventing any detectable cooling during the scanning period. Simultaneously, the temperature was monitored by the Infra Metrics 600L camera that had been mounted to a platform on which the dish was placed after exposure. The videotape recording obtained from the latter permitted the spatial correlation and verification of the temperatures determined by the manual scanning technique. The depth of penetration of the fields into the mass was then inferred from the temperatures measured and compared with the penetration depth calculated from the measurement of scattering parameters with the HP 8720C.

**Table 1. Mortality of *S. zeamais* in soft white wheat and *T. castaneum* in wheat flour at 10.6 GHz and 9 kW input power to test chamber, test 1**

| Sample code[a] | Exposure, s | u/g in W-s/g | u/g load W-s/g | $T_{max}$, °C | Mean ± SD, % |
|---|---|---|---|---|---|
| W1A | 3.80 | 106.87 | 57.71 | 57.83 | 98.25 ± 2.87 |
| W1B | 3.29 | 92.50 | 49.95 | 50.27 | 93.10 ± 5.70 |
| W1C | 4.20 | 118.13 | 63.79 | 64.11 | 96.40 ± 2.73 |
| W2A | 3.80 | 106.87 | 57.71 | 57.83 | 98.31 ± 2.80 |
| W2B | 3.29 | 92.50 | 49.95 | 50.27 | 95.24 ± 1.19 |
| W2C | 4.20 | 118.13 | 63.79 | 64.11 | 98.64 ± 1.22 |
| W3A | 3.80 | 106.87 | 57.71 | 60.44[c] | 99.501 ± 0.38 |
| W3B | 4.20 | 112.50 | 60.75 | 59.61 | 98.49 ± 0.501 |
| W3C | 3.00 | 84.38 | 45.56 | 51.02[c] | 84.60 ± 7.70 |
| W4A | 3.80 | 106.87 | 57.71 | 60.44[c] | 97.90 ± 1.99 |
| W4B | 4.20 | 112.50 | 60.75 | 59.61 | 97.10 ± 2.22 |
| W4C | 3.00 | 84.38 | 45.56 | 51.02[c] | 52.90 ± 28.99 |
| W5A | 3.40 | 95.63 | 51.63 | 55.66 | 93.58 ± 4.00 |
| W5B | 4.20 | 112.50 | 60.75 | 58.08 | 94.73 ± 5.13 |
| W5C | 3.00 | 87.38 | 45.56 | 47.72 | 73.66 ± 19.10 |
| W6A | 3.40 | 95.63 | 51.63 | 55.66 | 95.50 ± 4.47 |
| W6B | 4.00 | 112.50 | 60.75 | 58.08 | 97.79 ± 2.42 |
| W6C | 3.00 | 87.38 | 45.56 | 47.72 | 80.20 ± 23.81 |
| W7A | 3.40 | 95.63 | 51.63 | 55.55 | 98.41 ± 1.92 |
| W7B | 4.00 | 112.50 | 60.75 | 58.05 | 99.90 ± 0.20 |
| W7C | 3.00 | 87.38 | 45.56 | 47.72 | 88.35 ± 6.12 |
| T1A | 2.88 | 57.60[b] | 35.42 | 52.39 | 66.90 ± 14.30 |
| T1B | 2.88 | 129.60 | 79.70 | 62.35[c] | 99.82 ± 0.35 |
| T1C | 2.00 | 90.00 | 55.35 | 57.43[c] | 94.60 ± 3.69 |
| T2A | 2.88 | 57.60[b] | 35.42 | 52.39 | 89.79 ± 4.49 |
| T2B | 1.92 | 86.40 | 53.14 | 56.46 | 97.91 ± 1.70 |
| T2C | 2.00 | 90.00 | 55.35 | 57.43[c] | 97.75 ± 1.82 |
| T3A | 2.88 | 129.60 | 79.70 | 62.35[c] | 98.87 ± 2.10 |
| T3B | 1.92 | 86.40 | 53.14 | 56.46 | 82.50 ± 10.30 |
| T3C | 2.00 | 90.00 | 55.35 | 56.99[c] | 76.30 ± 13.60 |

[a] Codes. First position: W= S. *zeamais*; T=T.*castneum*. Second position: age. Third position: exposure time.

[b] input power, 4kW klystron malfunction

[c] Thermocouple malfunction. Max temp determined from postexposure measurements.

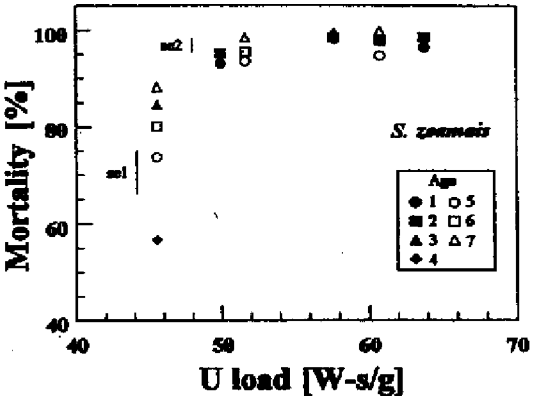


**Fig 4**. plot of Mean Mortality of 7 ages of S. *zeamais*, adult (1), larvae (2-6), and egg (7) as a function of specific energy input to the infested sample of soft white wheat for test 1. The adult mortality is for 6d postexposure, the older larvae(2) is for 35d postexposure, and the remaining age stages (3-7) for 41d postexposure.

## Results

**Mortality**. During the 1st test the effects of exposure on most of the adults of both species appeared to be instantaneous. Immediate cessation of movement of all individuals was observed on the video monitor. This effect occurred before the bulk product reached its maximum temperature for all levels of exposure. The thermal blooming of the host medium, recorded by the infrared monitor, was a much slower process and required 3-5 s for the maximum temperature to develop. The state of the adult insects was monitored during the post-exposure period until repackaged for shipment back to Madison, WI. Those adults that were killed during the exposure remained in a moribund state. A reconfirmation of adult mortality was obtained upon return of the samples 6 d after the exposure. The remaining samples with larvae and eggs were then observed for emergence over an additional period of 35 d.

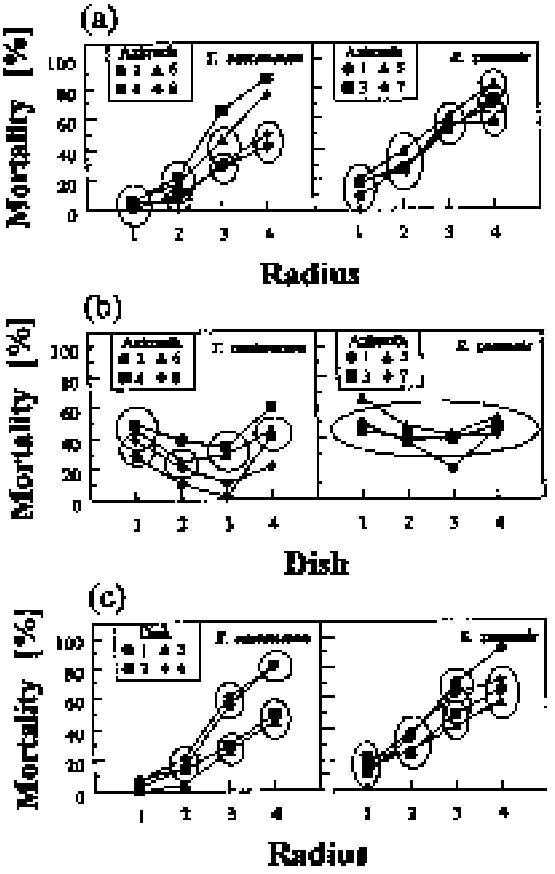
Shown in Table 1, for both S. z*eamais* and *T. castaneum* for each of the duplicate age groups studied, are the exposure time in seconds, the specific energy input ($U_{in}$) to the chamber and the specific load energy ($U_{load}$) actually coupled to and dissipated in the sample mass in J/g (±4.0%), and the temperature of the samples at the sensing thermocouple in Celsius (±2.2ºC). The corresponding mean value and standard deviation of the mortality for the four dishes of a given age group in an individual planar array is given in percent. The mortality of adults was determined with greater precision than that for eggs and larvae. Fig. 4 is a plot of mean mortality versus $U_{load}$ in W – s/g$^{(u/g)}$ by age group for the S. z*eamais* data of Table 1. The adult (1) mortality is at 6 d postexposure, the older larvae (2) is at 34 d postexposure, and the remaining age stages (3 to 7) at 41 d postexposure. The variability between replicate dishes, represented by the standard deviation in Table l, was greater at the load energy of 45.6 J/g compared with the other load energy levels. This difference in variability is indicated in Fig. 4 by the 2 lines which represent approximate standard errors for the mean mortalities. The line labeled standard error 1 (sel) is for the 45.6 J/g results. The line labeled standard error 2 (se2) is for the results at all the other load energies.

Table 1 indicates mean S. z*eamais* adult mortality between 93.10 and 98.25% aver an input energy range of 29.6-37.8 kJ (the product of input power and exposure time) or a specific energy input ($U_{in}$) of 92.5 – 118.1 J/g to the test chamber containing the 320-g sample load. The coupling coefficient for the load determined during calibration was 0.54 and therefore the specific load energy ($U_{load}$) delivered to the 320-g load per unit mass was 49.95 to 63.79 J/g. Mortality studies on S. *zeamais* larvae and eggs indicate that for specific load energy inputs of 51.63 to 63.79 J/g, the mean mortality ranges from 93.10 to 99.90% compared with the controls. It was noted that the survival of both larvae and eggs began to increase for energy inputs under 27 kJ or specific load energy inputs of 45 J/g. Therefore, the former energy levels appear to be at or near a nonlinear kill threshold for this species under the conditions of this test. It is clear that most of the data taken were at or above the 90% kill threshold and that more data are necessary at lower input energies to define the logistic mortality curve in the region of maximum slope. Because of the variability of the data at the lowest input energies it was not possible to make a comparison of relative susceptibility of the various age stages. To answer that question more data at lower energy inputs will be required. For the adults, this deficiency was removed by the data taken in the 2nd test.

The results obtained for samples of ground wheat flour infested with *T. castaneum* at various age intervals confirmed ultimate mean adult kills between 66.90% (note b) and 99.82% over an input energy range of 11.50 (note b) to 25.92 kJ, or a specific energy input ($U_{in}$) to the test chamber of 57.60-129.60 J/g. The coupling coefficient for the load determined during calibration was approximately 0.615; therefore, the specific load energy ($U_{load}$) delivered to the 200 g load per unit mass was 35.42-79.70 J/g. In some cases (note 3) it was necessary to calculate the initial maximum temperature from postexposure temperature measurements taken 5-7 min after exposure because of suspected high-voltage arcing at the tip of the thermocouple during exposure. The mortality studies on *T. castaneum* larvae, pupae, and eggs indicate that the ultimate mean mortality for larvae and pupae ranges from 89.79 to 97.91% and for eggs ranges from 76.30 to 98.87% compared with the mortality in the unexposed controls. Note that the precision of measuring mortality is higher for adults and larvae than for eggs because the former could be counted in the flour.

A comparison of the Table 1 mean mortalities at specific load energies for S. *zeamais* in wheat and *T. castaneum* in wheat flour indicates that S. *zeamais* is more susceptible than *T. castaneum.* Published data are available on the relative moisture content of these species that indicate that the former is slightly greater than the latter (as described subsequently in Physical Factors Section), but no published data are available on the comparative dielectric loss factors of the 2 species at the test frequency that could be used to explain this result. The relative dielectric properties of the host media, wheat and ground wheat, are known to be similar for similar densities at 11.67 GHz (Nelson 1984) and are probably very similar to that at 10.6 GHz. A review of the infrared monitor recordings indicated that the temperature distribution in the ground wheat samples infested by *T. castaneum* was more uniform spatially than for the whole grain samples infested by S. *zeamais*. This was also confirmed in the postexposure temperature scan of the sample dishes. A comparison of the temperatures of the peripheral petri dishes in the planar array with the maximum temperature of the center dish, measured with the thermocouple at the center dish during exposure, was made. The mean variation of the peripheral dish temperatures, derived from the time-corrected postexposure measurements made in each dish with the same thermocouple probe, was 4.4ºC for water, 6.8ºC for wheat, and 1.1ºC for wheat Hour. Average variations in temperature of the infested wheat samples were 6.7 C and of the infested flour samples were 5.9ºC. Because the 4 replications of each age group were exposed simultaneously, the variability in age group mortality may be caused by variability in exposure conditions. A visual inspection of the dead insects with a scanning electron microscope at Madison, WI, indicated no morphological differences compared with the controls.

The 2nd high-power test determined mortality as a function of temperature over a wider temper-ature range than was achieved in the 1st test to provide a better definition of the logistic mortality curve and permitted a visualization of the limited penetration depth of microwave energy, previously described, at 10.6 GHz. The mean mortality at 5 d postexposure for *S. zeamais* and *T. castaneum* adults as a function of spatial location (height, radius, and azimuth within each stack) of the insects is shown in Fig. 5a-c. Dish numbers are ordered by descending height in the stack (i.e., dish No. 1 is at the top). The interior regions of a stack exhibit decreased mortality, which was expected, caused by microwave attenuation. This ensured a relatively wide temperature distribution in the product and hence permitted the determination of the functional dependence of mortality on temperature shown in Fig. 6. Both the infrared videotape recordings and the hand-held infrared scanner showed that in each of the stacked dishes the lines of constant temperature were approximately concentric circles with a maximum 1.3 cm from the outer radius of the petri dish. The radial temperature distribution then decreased exponentially to a minimum at the center of the dish. The highest maximum radial temperature appeared consistently along the arc between the 90 and 180º azimuthal angles and the lowest maximum on the opposite arc. Therefore, this asymmetry is believed to be an artifact associated with asymmetry of the exposure facility itself rather than with the load. Along any given radius the characteristic depth of penetration inferred from the radial temperature distribution was approximately 5 cm, which is in close agreement with the value measured with the network analyzer.



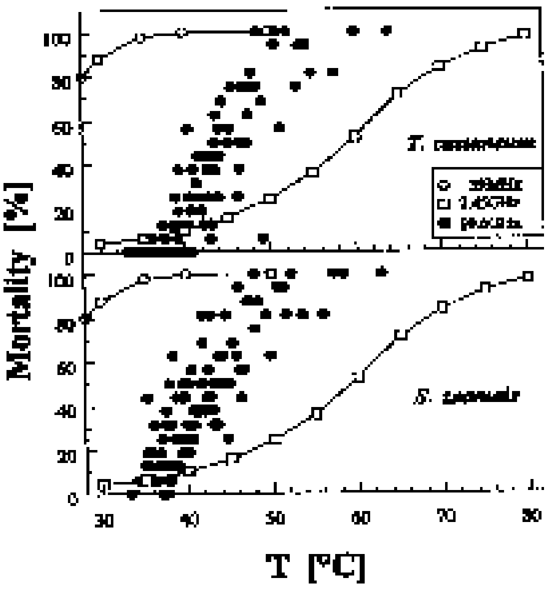


**Fig 5**. Mean mortality at 5 d postexposure versus (a) radius by azimuth, (b) dish by azimuth, (c) radius by dish, for test 2.

**Fig 6**. Mean mortality of S. *zeamais* and T. *castaneum* adults at 5 d postexposure as a function of temperature distribution for test 2 compared with mortalities at 39 MHz and 2.45 GHz for S. *orzae* adults at 8 d postexposure (Nelson and Stetson 1974)

Figure 5a is an interaction plot of radial mean mortality with azimuthal position considered as an independent variable. Contingency table analyses and Pearson chi-squared tests were performed on mortalities within each of the 4 radial planes. Those points that could not be considered as statistically different are enclosed by a loop. For S. *zeamais* there was little difference in the various azimuthal planes. However, azimuthal plane 5 (180º) had a consistently higher mortality. For *T. castaneum,* azimuthal planes 4 (135º) and 6 (225º) had steeper slopes than 2 (45º) and 8 (315º).

Figure 5b is an interaction plot of the dish (axial) mean mortality with azimuth as a variable. Plots for each type of insect are shown. Contingency table analyses and Pearson chi-squared tests were performed on mortalities within the same dish (axial plane). Because the mortalities across dishes for *S. zeamais* were comparable, the contingency analyses and Pearson chi-squared tests were performed on the results as a whole. Those points which could not be considered as statistically significant are enclosed by a loop. For S. *zeamais* there was little statistical difference between the 4 azimuthal positions. However, azimuth position 5 (180º) of dish 1 exhibited a higher mortality for S. *zeamais* than the others. For *T. castaneum* azimuth positions 4 (135º) and 6 (225º) exhibited higher mortalities and greater rates of change than positions 2 (45º) and 8 (315º). These were the location of the hot spots seen with the infrared camera. The slopes of the curves appear to be very similar.

Figure 5c is an interaction plot of radial mean mortality with the dish (axial) position in the vertical stack as a variable. Contingency table analyses and Pearson chi-squared tests were performed on mortalities within each of the 4 radial surfaces containing the capsules. As before, loops are drawn around points that are not significantly different. Both species exhibited an increase in mortality as radial position increased, because of the increased field intensity at the periphery. For *T. castaneum,* dishes 1 (top) and 4 (bottom) exhibited a larger slope than those for dishes 2 and 3. For S. *zeamais,* dish 1 had a steeper slope than the others.

Figure 6 shows the mortality as a function of temperature for all adult developmental stages of each species independent of spatial position. The numbers of 384 capsules exposed were ranked in the order of increasing temperature.

The results of this study support the hypothesis that the effective loss factor of insects, relative to the host product, increases at frequencies above 2.45 GHz. This is implied by the greater relative effectiveness of 10.6 GHz energy in producing mortality at a given product temperature. This may be caused by the presence of free water and he-molymph in the insect or that relative radiative energy transfer to the insect improves at shorter wavelengths, or both. This phenomenon was not investigated in earlier historical studies and could be the basis for a new technological approach to the control of insects in stored products using energy in the 3 to 60 GHz portion of the electro-magnetic radiation spectrum. The question of whether or not an optimum frequency exists in that range cannot be resolved without further testing. Continuing tests are planned by us to identify frequency or frequencies in that range where a coincidence of high-power microwave source efficiency and high insect-to-grain dissipation ratios exists.

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