A REVIEW AND ASSESSMENT OF MICROWAVE ENERGY FOR SOIL TREATMENT TO CONTROL PESTS

S. O. Nelson

ABSTRACT. Reports of experimental work on controlling pests such as insects, nematodes, weed seeds, and fungi in soil with microwave energy are reviewed. The assessment of the practicability of microwave radiation for soil treatment to control pests involves estimation of energy costs for heating soil to lethal levels for devitalization of weed seeds and consideration of parameters affecting microwave energy attenuation in the soil, conditions for selectively heating organisms in soil, and other factors that need to be taken into account for practical use. It is concluded that little probability exists for practical application of microwave energy for field control of these pests without major new discoveries of lethal mechanisms other than heating. Reasons include the severe attenuation of microwave energy in soils, the improbability of effective, selective heating of organisms, and the extremely high costs of energy and equipment for such applications. Keywords. Microwave energy, Soil, Pests.

Over the past 30 years, the use of microwave energy has been proposed frequently as an alternative method for controlling pests in the soil, such as weed seeds, insects, nematodes, and soil-borne plant pathogens. Even earlier, radio-frequency dielectric heating was considered for sterilizing soils for use in greenhouses. Since the question of the practicability of using microwave energy for soil treatment to control pests has been raised so often, it seems worthwhile to examine what is known about such applications and to offer an assessment of its potential.

Early studies with 27-MHz, high-frequency dielectric heating of different greenhouse soils showed that damping-off fungi infecting crimson clover could be controlled by 5 min exposures that raised soil temperatures to 86 to 101°C without destroying the nitrogen-fixing Rhizobium bacteria necessary for normal plant growth (Eglitis et al., 1956; Eglitis and Johnson, 1970). Work by Baker and Fuller (1969) with 2,450-MHz microwave heating of soils revealed large differences in the heating rates of soils and problems with uniformity of treatment. They concluded that commercial microwave treatment of soils for control of soil-borne pathogenic fungi was impractical. For similar reasons, Barker et al. (1972) concluded that 2,450-MHz treatments of nematode infested soil samples had poor prospects for becoming a practical means of nematode control. The root-knot nematode was controlled in small samples of potting soil exposed to 2,450-MHz energy in a microwave oven when temperatures lethal to the nematodes were achieved (O'Bannon and Good, 1971). In field tests with 30-kW, 2,450-MHz microwave sources applying energy at 800 joule/cm² (J/cm²), Heald et al. (1974) reported that nematodes were controlled in a fine sandy loam soil infested with the reniform nematode at depths of 5 cm, but that the nematodes survived at depths of 10 and 15 cm. Vela et al. (1976) reported, after conducting both laboratory and field studies, that soil microorganisms survived 2,450-MHz exposures at much higher dosage levels than those required for control of weed seeds in soil. Later studies with other soil samples containing additional microorganisms showed that exposures of small samples in a microwave oven could be useful for sterilization, but that results depended on treatment time, amount of soil treated, and soil water content (Ferriss, 1984). Large-scale applications were judged unlikely. Other tests by Van Wambke et al. (1983) and Benz et al. (1984) showed that, for soil samples treated in a microwave oven, seeds, fungi, and nematodes could all be controlled by exposures of a few minutes, but that required exposures depended on soil type, exposure period, depth in soil, and soil moisture content. Treatments of different soils at 2,450 MHz were effective in controlling several plant pathogens, but penetration depths were reduced as soil moisture content increased (Van Assche and Uyttebroek, 1983). Soil-borne pathogens in mushroom casing and rockwool substrates were controlled by passing the materials through a 20-kW dielectric heater operating at 27.12 MHz (Diprose and Evans, 1988).

Interest in weed control by soil treatment with microwave energy in the early 1970s and hope of commercialization stimulated many experiments in the laboratory and in the field on the lethality of such exposures for various kinds of seed. Davis et al. (1971, 1973) and Wayland et al. (1972) reported the germination of seeds of several crop and weed species after exposure in a microwave oven operating at 2,450 MHz. Seeds were treated in a dry state and after several hours of water imbibition. They were found much more susceptible to damage from microwave heating in the imbibed states. Energy levels in joule per gram were given for the various treatments, but since they were based on energy absorbed by 50 mL of water in the same microwave oven for
comparable exposure times, the data probably have little meaning except for relative energy absorption comparisons.

Wayland et al. (1973) irradiated wheat and radish seeds in paper envelopes 2.5 cm below the soil surface with 2,450-MHz microwave energy from a 1.5-kW magnetron directed at the soil surface through an applicator at a reported level of 210 J/cm². They concluded that, for the power levels used, energy density and time of exposure were interchangeable, with respect to effectiveness, as long as total energy remained about the same. In field experiments with a 2,450-MHz power applicator, seeds of several weed species were planted in the top 2 cm of irrigated and nonirrigated soils, and control was achieved for various species at energy densities of 180 and 360 J/cm² (Menges and Wayland, 1974). In other field experiments with a mobile microwave power unit consisting of four 1.5-kW magnetrons powered by a gasoline-engine-driven 60-Hz generator, pre-emergence and post-emergence microwave treatments were administered to plots seeded with several weed species (Wayland et al., 1975). Energy densities of 183 J/cm² were required to provide 80 to 90% control in pre-emergence tests, while energy densities of 77 to 309 J/cm² were required in post-emergence trials. Field experiments with the same microwave equipment were also conducted on plots with three replications for evaluation of weed seed, soil fungi, and nematode control (Cundiff et al., 1974). Treatments on dry sandy loam soil at energy densities of 633 to 1727 J/cm² failed to provide effective control of any of the pest organisms. No significant reductions in the presence of any of these pests resulted from even the highest energy-density microwave treatments.

In entirely independent laboratory studies, Hightower et al. (1974), using a horn antenna to irradiate seeds placed on top of soil samples, found that energy densities of the levels reported earlier (Wayland et al., 1973) produced no reductions in seed germination and that only slight reductions were produced by treatments at 300 J/cm². More detailed tests were then conducted with fescue grass seed, both dry and water soaked, on and under the soil surface, in samples of three different soils. The soil samples were irradiated with a dielectric-loaded waveguide applicator for improved impedance matching, higher power densities, and a more uniform radiation pattern. Results showed that energy densities of at least 1,500 J/cm² were required for control of seed germination, that moist seeds in wet soil were more susceptible, but that the high energy requirement rendered the proposed application impractical. In other laboratory tests on wild oats seeds exposed in glass test tubes inserted into the waveguide attached to a 1.5-kW, 2,450-MHz source, moist seeds and seeds in soil were damaged more than dry seeds (Lai and Reed, 1980). Because of the high energy requirements, high costs of equipment, and low travel speed, field use was judged impractical.

Olsen (1975) conducted an interesting theoretical analysis, based on physical principles and available data for the necessary properties of soils and seeds, and concluded that for unimbibed seeds in a mineral soil, an energy density of at least 800 J/cm² would be required for germination control.

An optimistic review of the reported work on microwave soil treatment for pest control was presented by Vela-Muzquiz (1983), indicating promise for UHF radiation control of agricultural pests and at costs similar to those for chemical pest control. However, the viewpoint appears to be tempered by a strong concern for the environmental influence of continued use of chemical controls and an apparent naivete with respect to physical principles of electromagnetic energy absorption.

INITIAL ASSESSMENT

When the author was first contacted about the possibility of using microwave energy for devitalizing weed seeds in soil about 25 years ago, the innate response was that it would be impractical. Some simple calculations confirmed that impression. They were based on the assumption that the lethal mechanism was thermal, that selective dielectric heating was unlikely to be a major factor, and that it would probably be necessary to raise seed temperature to about 100°C for a short period to completely inhibit germination. These assumptions are still most likely reasonable. Calculating the energy required to raise the top 2 in. of soil from 25 to 100°C, assuming a soil bulk density of 1.6 g/cm³ and a specific heat of 0.3 calories/g·°C [1256 J/(kg·°K) in SI units], gives 766 J/cm². Converting this to a more familiar electric energy unit and a more practical scale, gives 8,611 kW-h/acre (21,277 kW-h/ha). Since conversion of 60 Hz electric energy to microwave energy absorbed in the soil is only about 50% efficient in a field application, the electric energy requirement is about 17 MW·h/acre. At a cost of $0.05/kW-h, this would amount to $850 per acre just for the electric energy alone. Costs for the high-power microwave equipment and gasoline- or diesel-driven electric generating equipment and other equipment required would have to be added to these costs to estimate a total cost per acre for microwave soil treatment.

Examining the assumptions upon which the above estimates are based, there seems to be little opportunity for major reductions in either required energy or costs. In fact, the microwave energy cannot be confined to the upper 2 in., so to achieve the heating necessary, more energy would be required. Neither are the weed seeds confined to the 2 in. surface layer, so a larger amount of soil would need to be raised to the 100°C level for effective control.

The temperature level of 100°C is much higher than the 60°C level mentioned for soil temperatures in field trials (Wayland et al., 1973); however, Menges and Wayland (1974), did achieve such high temperatures near the soil surface in some trials. Treatment of soil samples containing seed of oat, *Avena sativa* L., and indigenous weeds for 2,450-MHz produced soil temperatures of 90°C and reduced weed emergence to low levels (Barker and Craker, 1991). Early work on determining thermal death points of weed seeds representing seven species and five families showed that seeds subjected to heat treatments for 15 min in sealed brass tubes immersed in an oil bath required temperatures varying from 85 to 105°C for complete lethality (Hopkins, 1936). Exposures to high temperatures in soil for seeds of several weed species required seven days at 70°C for control in dry soil, and some seeds
survived several days at 60 and 70°C even in moist soils (Egley, 1990). At much shorter exposure times to elevated temperatures, which are certainly required for any practical field treatment, these seeds could survive much higher temperatures.

Susceptibility of plant seeds to damage by dielectric heating exposures is heavily dependent on the moisture content of the seed at the time of exposure. Dry seed can tolerate higher temperature exposures than seed with higher moisture contents. Samples of hard red winter wheat exposed for 4 to 37 s to 39-MHz dielectric heating treatments had 50% reduction in seed germination at seed temperatures ranging from 65 to 109°C with seed moisture content ranging from 18.3 to 6.7%, wet basis (Nelson and Walker, 1961). Seed of several vegetables survived dielectric heating exposures that raised seed temperatures to well over 80 and 90°C (Nelson et al., 1970). The importance of seed moisture content as it relates to responses of alfalfa seed, other small-seeded legumes, and seeds of woody plant species to dielectric heating exposures that raised temperatures well over the 80 and 90°C levels are well documented (Nelson and Wolf, 1964; Stetson and Nelson, 1972; Nelson et al., 1976, 1977, 1978, 1982). Dielectric heating treatments at 40 MHz and at 2,450 MHz were found equally effective for increasing germination of alfalfa by lowering hard-seed contents (Stetson and Nelson, 1972); so the dielectric heating effects at the two different frequencies can be considered nearly equivalent. In all of this research, no responses were observed that could not be attributed to thermal causes. Consequently, the speculated “special effects” of UHF electromagnetic energy on seeds is not likely to provide the selectivity necessary for major improvement in the efficiency of microwave treatment for weed seed control in the soil.

**BASIC PRINCIPLES**

In considering the interaction of electromagnetic energy with matter, the dielectric permittivities or dielectric properties of the materials involved are of utmost importance. The permittivity of a material can be expressed as a complex quantity, the real part of which is associated with the capability of the material for storing electric energy in the material, and the imaginary part is associated with the dissipation of electric energy in the material by conversion of electric energy to heat energy in the material. This is the phenomenon commonly referred to as dielectric heating, or microwave heating if microwave frequencies are used. The complex permittivity, relative to free space, will be represented here as \( \varepsilon^\prime = \varepsilon - j\varepsilon'' \), where \( \varepsilon' \) is called the dielectric constant; \( j \) denotes the complex operator; \( \sqrt{-1} \); and \( \varepsilon'' \) is the dielectric loss factor. The loss tangent, \( \tan \delta \), also often used as an index of energy dissipation or loss in a material exposed to radio-frequency (RF) or microwave electric fields is defined as \( \tan \delta = \varepsilon'' / \varepsilon' \). The ac electrical conductivity associated with the dielectric loss in the material is \( \sigma = \omega\varepsilon_0\varepsilon'' \) siemens/m (S/m), where \( \omega \) is the angular frequency, \( 2\pi f \); where \( f \) is the frequency of the applied electric field; and \( \varepsilon_0 \) is the permittivity of free space, \( 8.854 \times 10^{-12} \) farads/m (F/m). For the purposes of this discussion, \( \varepsilon'' \) will include both losses resulting from dielectric relaxation and ionic conduction.

The power dissipated per unit volume in a nonmagnetic, uniform material exposed to RF or microwave fields can be expressed as:

\[
P = E^2\sigma = 55.63 \times 10^{-12}fE^2\varepsilon'' \tag{1}
\]

where \( P \) is in watts per cubic meter (W/m^3) when \( f \) is in hertz (Hz) and \( E \) is the rms electric field intensity in volts/m (V/m). Power dissipated over a period of time provides energy to raise the temperature of the material, and this time rate of temperature increase (°C/s) is given by:

\[
dT/dt = P/(c\rho) \tag{2}
\]

where \( c \) is the specific heat of the material in kJ/(kg·°C), and \( \rho \) is its density (kg/m^3). If water is evaporated in the heating process, the energy required for the vaporization and release of the water must also be taken into account, and the temperature rise would be reduced accordingly.

The absorption of microwave energy propagating through a material depends upon the variables of equation 1. Thus, the dielectric loss factor of the material is important. The frequency of the wave is also a factor, and the power absorption also depends on the square of the electric field intensity. For a plane wave, the electric field intensity \( E \), which has \( e^{j\omega t} \) dependence, can be given as (von Hippel, 1954):

\[
E(z) = E_0 e^{j\omega t} - \gamma z \tag{3}
\]

where

- \( E_0 \) = rms electric field intensity at a point of reference
- \( t \) = time
- \( \gamma \) = propagation constant for the medium in which the wave is traveling
- \( z \) = distance in the direction of travel

The propagation constant is a complex quantity:

\[
\gamma = \alpha + j\beta = j\frac{2\pi}{\lambda_o} \sqrt{\varepsilon^*} \tag{4}
\]

where

- \( \alpha \) = attenuation constant
- \( \beta \) = phase constant
- \( \lambda_o \) = free-space wavelength

The attenuation constant and phase constant \( \beta \) are related to the dielectric properties of the medium as follows (von Hippel, 1954):

\[
\alpha = \frac{2\pi}{\lambda_o} \sqrt{\varepsilon' \left[ 1 + \tan^2 \frac{\delta}{2} \right] - 1} \text{ nepers/m} \tag{5}
\]

\[
\beta = \frac{2\pi}{\lambda_o} \sqrt{\varepsilon' \left[ 1 + \tan^2 \frac{\delta}{2} \right] + 1} \text{ radians/m} \tag{6}
\]

As the wave travels through a material that has a significant dielectric loss, its energy will be attenuated. For a plane wave traversing a dielectric material, the electric
field intensity at the site of interest can be obtained by combining equations 3 and 4 as follows:

\[ E(z) = E_0 e^{-\alpha z} e^{j(\omega t - \beta z)} \]  

(7)

where the first exponential term controls the magnitude of the electric field intensity at the point of interest, and it should be noted that the magnitude of this term decreases as the wave propagates into the material. Since the power dissipated is proportional to \( E^2 \), \( P \propto e^{-2\alpha z} \). The penetration depth, \( D_p \), is defined as the distance at which the power drops to \( e^{-1} \), which is about 1/2.718 of its value at the surface of the material (Metaxas and Meredith, 1988). Thus, \( D_p = 1/2\alpha \).

If attenuation is high in the material, the dielectric heating will taper off quickly as the wave penetrates the material. Attenuation is often expressed in decibels/m (dB/m). In terms of power densities and electric field intensity values, this can be expressed as (von Hippel, 1954):

\[ 10 \log_{10} \left( \frac{P_o}{P(z)} \right) = 20 \log_{10} \left( \frac{E_o}{E(z)} \right) = 8.686\alpha z \]  

(8)

FURTHER ASSESSMENT
ATTENUATION

The dielectric properties of the soil are very important in evaluating the penetration of energy that can be achieved. The attenuation in decibels, combining equations 5 and 8, can be expressed in terms of the dielectric properties, when \((e'')^2 \ll (e')^2\), as follows:

\[ \alpha = \frac{8.686\pi e'' \lambda_o}{\sqrt{\varepsilon}} \text{ dB/m} \]  

(9)

Thus, since \( e'' \) for soils is relatively small with respect to \( e' \), equation 9 can be used to provide good estimates of attenuation in soils if we know the values for the dielectric properties at the frequency of interest. Values for these properties have been extracted from some of the data in the literature on a few soil types and are presented in table 1. Much of the data were presented graphically, some as permittivity values as functions of gravimetric moisture content (mass of water in percent of soil dry weight) and some in volumetric moisture (mass of water per unit volume of soil). Therefore, the data were converted to the dry-weight moisture content on the gravimetric basis, making an assumption for the likely density of the dry soil. Other data were presented in terms of the dielectric constant and attenuation in dB/cm and in terms of the dielectric constant and electrical conductivity. Values of \( e'' \) were then calculated by use of equation 9 or as \( e'' = \sigma/(\omega\varepsilon_o) \), using the appropriate frequencies.

Although the soils listed in table 1 are all different, attenuation increases with moisture content of the soils and, in general, with frequency as expected. However, soils are extremely variable in their makeup and properties, and data in table 1 represent a very limited sampling. For plant growth, the available water, the range between field capacity and wilting point, varies greatly. For soils, these moisture contents can range from less than 4 and 2%, respectively, for a sandy soil to greater than 45 and 30%, respectively, for a clay soil (Perkins, 1987). For 10 to 20% moisture soils in table 1, attenuation varies from 1.3 to 4.3 dB/cm. Nevertheless, it is instructive to consider a reasonably conservative attenuation of 2 dB/cm and examine the penetration characteristics for microwave energy incident upon the soil surface. A plane wave incident upon the soil surface will have some of the power reflected, and the rest, \( P_t \), will be transmitted into the soil. The relationship is given by the following expression:

\[ P_t = P_o (1 - |\Gamma|^2) \]  

(10)

where \( P_o \) is the incident power and \( \Gamma \) is the reflection coefficient. For an air-soil interface, the reflection coefficient can be expressed in terms of the complex relative permittivity of the soil as (Stratton, 1941):

\[ \Gamma = \frac{1 - \sqrt{\varepsilon}}{1 + \sqrt{\varepsilon}} \]  

(11)

The power density diminishes as an exponential function of the attenuation and distance traveled (eq. 7) as the wave propagates through the soil:

\[ P = P_t e^{-2\alpha z} \]  

(12)

with \( \alpha \) expressed in nepers/m. For attenuation in decibels, dB/cm = 0.08686 x (nepers/m).

Considering again an attenuation of 2 dB/cm in soil, the attenuation at a 5-cm depth (about 2 in.) will be 10 dB, which corresponds to a power density of just 10% of that at the surface. At a 4-in. (10-cm) depth (20 dB attenuation), there would be only 1% of the power left, and at 15 cm (6 in.) it would be reduced by 30 dB to only 0.1%. Since the soil heating is directly proportional to the power density, this means that, for heating as effective at a 2-in. (5-cm) depth as at the surface, 10 times as much power would be required, at 4 in. (10 cm) 100 times as much.

### Table 1. Permittivity, \( e' - je'' \), and attenuation, \( \alpha \) (dB/cm) values for soils at indicated microwave frequencies and dry-basis moisture contents

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Soil Texture</th>
<th>Freq. GHz</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoekstra and Delaney (1974)</td>
<td>Clay</td>
<td>5.0</td>
<td>4.3</td>
<td>0.7</td>
<td>1.2</td>
<td>14.8</td>
</tr>
<tr>
<td>Hipp (1974), 1.6 g/cm³</td>
<td>Clay loam</td>
<td>2.5</td>
<td>5.4</td>
<td>0.8</td>
<td>0.8</td>
<td>8.8</td>
</tr>
<tr>
<td>Jesch (1978)</td>
<td>Sandy loam</td>
<td>4.0</td>
<td>4.0</td>
<td>0.8</td>
<td>1.4</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Silt loam</td>
<td>2.0</td>
<td>3.4</td>
<td>0.6</td>
<td>0.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Ulaby et al. (1982)</td>
<td>Sandy loam</td>
<td>5.0</td>
<td>5</td>
<td>0.5</td>
<td>1.0</td>
<td>9</td>
</tr>
</tbody>
</table>

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power would be needed, and at 6 in. (15 cm), the ratio would be 1,000:1. Thus, the attenuation problem alone renders the use of microwave soil treatment impractical. Even in an extremely dry soil, if attenuation were as low as 0.6 dB/cm, two times the power needed for surface soil treatment would be required for effective treatment at 2 in. (5 cm) in depth, and four times as much power would be required to deliver the necessary energy at 4 in. (10 cm).

### Selective Heating

If selective microwave heating of seeds relative to the soil were possible, the case for microwave control of weed seed germination would be improved. Therefore, consider the variables in equations 1 and 2 with respect to the relative heating effects of the microwave energy on the seeds and the soil. The frequency for the two materials will be the same. However, the dielectric loss factor for the seeds and the soil might be different, and in that instance, the electric field intensities in the seeds and the soil might also differ. Dielectric properties of a few crop and weed seed samples measured in 1971 by the short-circuited waveguide technique (Nelson, 1972a, 1973) at frequencies of 1, 2.45, and 10 GHz are listed in table 2. The samples were all conditioned to equilibrium moisture content at 24°C and 40% relative humidity, and the moisture contents at time of measurement were determined by drying samples for 24 h in a forced-air oven at 103°C.Bulk densities of the seed (seed and air-space mixtures) were those measured in the dielectric sample holders at the time of the permittivity measurements. Comparing the loss factors of the seed samples at 2.45 GHz with those of soils shown in table 1, there appears to be little likelihood of selectively heating the seeds. In fact, on the basis of loss-factor values only, the soils would be expected to heat more rapidly than the seeds. However, we must also consider the influence of the $E^2$ term in possible differential heating of the seeds and the soil. Also, the $\varepsilon''$ values in table 2 are for the air-seed mixtures, and perhaps it would be more realistic to consider the dielectric properties of the seeds themselves embedded in a uniform medium with the dielectric properties of the soils as given in table 1.

Limited data are available on the dielectric properties of wheat kernels at 9.4 GHz (Nelson, 1976a) and corn and wheat kernels and soybeans at 11.5 and 22 GHz (Nelson and You, 1989). From these data, and the known frequency dependence of the dielectric properties of bulk samples of wheat (Nelson, 1982b) it appears that the permittivity of the wheat kernel at 2.45 GHz will be about 5 – j0.5. This loss-factor value, 0.5, is less than those of the soils listed in table 1 for similar frequencies.

To examine the relative electric field intensities in the seed, $E_s$, and that in the soil medium, $E_m$, we can consider that for a plane wave interacting with a spherical seed in a uniform, infinite soil medium, the electric field in the seed is (Stratton, 1941):

$$E_s = E_m \left( \frac{3\varepsilon^*_s}{2\varepsilon^*_m + \varepsilon^*_s} \right)$$

where $\varepsilon^*_s$ and $\varepsilon^*_m$ represent the complex relative permittivities of the seed and the soil, respectively. If we take the permittivity of the wheat kernel for a “spherical” seed and the values of the clay loam soil at 2.5 GHz and 10% moisture from table 1 for the medium, we obtain a value of 1.37 for $(E_s/E_m)^2$, which gives us the ratio of the fields contribution to the power dissipation per unit volume in the seed to that in the soil. However, this tendency for selectively heating the seed is offset by the lower $\varepsilon''/\varepsilon''$ ratio of 0.29. If we take the 2.0 GHz, 10% moisture sandy loam permittivity data from table 1 as another example, we get 1.22 and 0.20 for the $(E_s/E_m)^2$ and $\varepsilon''/\varepsilon''$ ratios, respectively. The product of these two figures gives the estimated power absorption ratio for the seed in relation to the soil, and it would be 0.40 and 0.22 for the two soils respectively. This power absorption ratio for the same two soils at 20% moisture content would be 0.24 and 0.12, respectively. Thus, selective absorption of the microwave power by the seeds seems most unlikely to occur.

For selective dielectric heating of the seeds, one must also consider the other two variables that, along with power absorbed, affect the heating rate in the two different materials (eq. 2). The specific heat of wheat at 10% moisture content is about 0.39 calories/g°C (1.65 J/kg·°K) (ASAE, 1984). The specific heat of dry mineral soils is about 0.20 c/g·°C (0.84 J/kg·°K), while at 20 and 30% moisture, the specific heat rises to 0.33 and 0.38 c/g·°C, respectively (Lyon and Buckman, 1947). Estimating the specific heat for 10% moisture soil as 0.28 c/g·°C (1.17 J/kg·°K), the seed-to-soil specific heat ratio would be 0.39/0.28 = 1.39.

The density ratio is the other factor for consideration. Densities of soils vary, but taking an intermediate value of 1.6 g/cm³, which was the density of the clay loam soil in table 1, and 1.4 g/cm³ for the density of the hard red winter wheat kernel at 10% moisture content (Nelson, 1976a; Nelson, 1984; Nelson and You, 1989), the seed-to-soil density ratio is about 0.88. Both the seed-to-soil specific heat and density ratios have an inverse influence, since $c$ and $\rho$ appear in the denominator of the right-hand side of equation 2, and the product of these ratios is $1.39 \times 0.88 = 1.22$. The reciprocal value is 0.82, which taken times the 0.40 and 0.22 power absorption ratios for 10% moisture soils, based on loss factor and field considerations, gives 0.33 and 0.18. This clearly indicates that selective dielectric heating of the seed, based on these dielectric properties, cannot be expected.

Differences in the seed and soil moisture contents can change the values of all variables on which these estimates...
were based. In particular, if seeds take up moisture from the soil and begin to germinate, they may be more susceptible to heat damage. However, many seeds have moisture-impermeable seed coats, and they will not take up moisture until the seedcoat permeability changes (Ballard et al., 1976; Nelson, 1976b). Many weed seeds have dormancies of other types and do not germinate until certain conditions have been satisfied. Even without dormancy, it is not likely that most of the weed seeds would be in a susceptible stage at any given time for microwave heating to be effective.

SOIL INSECT AND NEMATODE TREATMENT

The same principles can be applied for assessment of the potential for microwave energy in controlling soil insects and nematodes. The same problems prevail with attenuation of the energy as the waves travel into the soil. Less information is available on the dielectric properties of insects, and none has been noted on those properties of nematodes.

Insects can be expected to have higher natural moisture contents than seeds, although little is known to the author on water content of soil-infesting insects in various stages of development. In work with adult rice weevils, Sitophilus oryzae L., which infest cereal grains, moisture content was determined to be about 49%, wet basis, and insect density was 1.29 g/cm² (Nelson, 1972b). Adult rice weevil permittivity was determined to be 32 – 7j13 at 9.4 GHz (Nelson, 1976a). Using equations 1 and 13, and arguments similar to those in the previous section, the insects treated in hard red winter wheat were predicted to absorb RF power at levels about 2 to 3.5 times greater than the wheat at frequencies in the 1- to 100-MHz range (Nelson and Charity, 1972). At the microwave frequency of 2.45 GHz, however, the power dissipation ratio dropped to about 1.1. These predictions were confirmed in laboratory exposures of rice-weevil-infested wheat to 39-MHz and 2.45-GHz dielectric heating, in which complete insect mortality was achieved by treatments raising grain temperatures briefly to 40°C for the 39-MHz treatments and to 80°C for the 2.45-GHz treatments (Nelson and Stetson, 1974).

If the insect permittivity values, 32 – 7j13, are used with the same soil permittivity data used in the previous section for the selective heating calculations with equations 1 and 2, insect-to-soil power absorption ratios of 1.99 and 1.86 are obtained for the 10% moisture clay loam soil and the 10% moisture sandy loam soil, respectively. In the 20% moisture soils, the respective power dissipation ratios are 0.99 and 1.04. These estimates indicate the possibility for some selective dielectric heating of insects in very dry soils. Specific heats of insects may be somewhat higher than those of the soils, because of their greater moisture content, and this would tend to reduce the heating rate of the insects with respect to the soil. The insect-to-soil density ratio, 1.29/1.6 = 0.81 in this instance, would tend to provide a slight increase for the insect heating rate. These factors all taken together do not indicate any likelihood of a very significant differential heating advantage for insect control, except possibly in a very dry soil.

The experimental results cited earlier for nematodes indicated control at a 5-cm depth in a fine sandy loam soil with a reported applied energy of 800 J/cm², but the nematodes survived at 10- and 15-cm soil depths, which might be expected because of microwave power attenuation in the soil.

DISCUSSION

There are still many unknown factors that can influence the absorption of microwave energy transmitted into the soil. As the soil absorbs the energy, its temperature rises. The dielectric properties of all materials are temperature dependent. The dielectric behavior of hygroscopic materials, with respect to change in temperature, depends on the frequency used and the nature of the water in the material. If water is bound, both the real and imaginary parts of the permittivity can be expected to increase with increasing temperature. If there is any significant amount of free water in the soil, its dielectric behavior will be influenced by the dielectric relaxation of free water, and that relaxation frequency, which is about 20 GHz at 25°C, shifts to higher frequencies as temperature increases. This would tend to increase the dielectric constant slightly, but the overall influence of increasing temperature would reduce the dielectric constant and would also tend to lower the loss factor value. At lower frequencies in the microwave range, the soil chemistry could exert an influence due to the effects of ionic conduction, which disappear at frequencies around 10 GHz (Hasted, 1973). At this time, no temperature induced changes in the dielectric properties are obvious that would significantly improve the opportunity for selective heating of the pest organisms with respect to the host soil materials.

The attenuation of energy with waves penetration into the soil appears to be a very limiting factor. Useful penetration would appear possible only in soils with a minimum amount of water, and even then, large amounts of power would be required to raise the soil temperature rapidly to levels effective in controlling pest organisms. The general order of susceptibility, in decreasing order, based on available experimental data and principles considered in this article, appears to be insects, weed seeds, nematodes, soil fungi, and soil bacteria. Since the beneficial effects of soil microbes are extremely important, their lower susceptibility to population reduction from microwave heating is fortunate. However, harmful plant pathogens would also benefit from this lower susceptibility. The large variation in soil characteristics, including texture, organic matter content, soil chemistry, and subsequent variation in density and specific heat, as well as the variations among the living organisms in the soil, can be expected to introduce large degrees of variation in the survival of these organisms when exposed in soil to microwave energy.

No dynamic conditions have been considered in the principles presented here. Obviously, heat transfer and diffusion of energy would come into play as soon as the temperature equilibrium is upset by microwave heating. Because of attenuation, large amounts of energy absorbed in the first few centimeters of penetration would result in heat conduction to deeper soil levels, but heat would also be lost to the atmosphere, and this would not appear to be an efficient process for heating the soil to the deeper levels required for control of pests.
Costs of equipment for field application of microwave power have not been considered here, because the basic assessment has not appeared to warrant the effort. However, at least two prototype field microwave power applicators were built in the 1970s and tested for field application (Wayland et al., 1973; Cundiff et al., 1974; Anonymous, 1973; Davis, 1975; Wayland et al., 1978). An early prototype was equipped with four 1.5-kW, 2.45-GHz magnetrons, with movement down to 0.003 mile/h (0.005 km/h) provided by a cable winch, and with electric power supplied by a 20-kW gasoline-engine-driven generator (Cundiff et al., 1974). A later prototype had two 30-kW klystron microwave sources, and was powered by a 155-kW diesel-operated generator (Anonymous, 1973). Apparently, the application was not deemed practical, because the anticipated marketing of the method and the equipment did not materialize.

To deliver enough energy for effective control of pests in a time compatible with field operations, very large power capabilities would be needed. For example, if 1 500 J/cm² were the required energy for an application, to treat a band 1 m wide traveling at a speed of 1 km/h, the microwave power delivered to the soil would be 4,167 kW. Even if the energy were applied in a narrow band of 10 cm width along the row in which crops were to be seeded, at least a 417-kW power output would be needed. A figure often used for estimating costs of microwave power source and applicator equipment for industrial use is $3/W ($3,000/kW) of output rating. Economies of the sort that have brought down the costs of fractional-kilowatt magnetrons for domestic microwave oven use and low-power magnetrons for industrial use have a long way to go for higher-power microwave sources.

Another aspect of microwave energy applications at the extremely high power levels that would be required for soil pest control, is that of safety for operating personnel. Since some energy is reflected by the soil surface, proper shielding design would be needed to insure that energy radiated to surroundings is maintained below safe levels for human exposure.

For application to the sterilization of greenhouse or potting soils, or similar uses, where quantities of material to be treated are lower, and efficient application of electromagnetic energy would be easier to achieve, potential practical use could be more likely. However, high-frequency or microwave dielectric heating would have to offer important advantages to justify costs of treatment. The saving of time would be the principal advantage apparent today, but other advantages may be important in particular applications. The often speculated “nonthermal” effects of microwaves on living organisms have yet to be demonstrated convincingly for any useful pest control purpose. The lethal mechanisms appear to be thermal in nature, and in many instances, differential or selective dielectric heating can account for observed results attributed to “nonthermal biological effects” (Johnson and Guy, 1972; Schwan, 1972; Stuchly, 1979; Polk and Postow, 1986; Michaelson and Lin, 1987; Stuchly, 1995). Even when conditions support the phenomenon of selective dielectric heating, it cannot be depended upon to be especially significant, because of the rapid conduction of heat energy from the target organism into the host medium. Thus, the organisms cool to lower temperatures rapidly, and the benefit of the complementary time-temperature action is not retained.

**CONCLUSIONS**

Upon considering the basic principles of microwave energy absorption by dielectric materials and the experimental work that has been reported, there appears to be little probability for the practical application of microwave power for field use in controlling pests in the soil, such as insects, nematodes, weed seeds, and plant pathogens. The susceptibility to control by microwave heating for pests in soil, in decreasing order, appears to be, insects, weed seeds, nematodes, fungi, and bacteria. Unless some nonthermal lethal effects are discovered that can be utilized, the energy and equipment costs for producing pest mortality or population reductions by thermal heating are far too great for serious consideration. In addition to the energy costs, the rapid attenuation of microwave energy to insignificant levels at shallow soil depths makes potential use of this form of energy impractical. Selective dielectric heating of pest organisms, because of differences in microwave permittivities of these organisms and those of the soil, appears to be highly unlikely, except possibly for insects in very dry soils. Thus, any serious future consideration of microwave electromagnetic energy for control of pests in soil must be subjected to careful and critical analysis, and probably must await uncertain and unlikely breakthroughs in research on physiological effects of microwave radiation on biological organisms.

**REFERENCES**


