PENETRATION OF INFESTED STORED-PRODUCTS BY EHF/SHF MICROWAVE ENERGY

Steven L. Halverson*, Timothy S. Bigelow, and Kathleen Lieber

The work reported here is ancillary to previous efforts by the authors to assess the effectiveness and economics of controlling stored-grain insects with microwave energy in the Extremely High Frequency (EHF) and Super High Frequency (SHF) range of the free-water relaxation band. This band was chosen because of the coincidence of free water in the insect and the development of extremely high-power microwave oscillators in that range that makes continuous processing of a dynamic product at high throughput rates a realizable goal (Halverson et al. 1997, Plarre et al. 1997). However, since the penetration depth in a dense lossey dielectric medium is inversely proportional to frequency, it was important to demonstrate by direct measurement at these frequencies that the penetration of the product can be increased sufficiently by controlling the volume percentage of grain in a mixture of air and grain in a flowing bulk product to ensure that a practicable applicator can be designed and built. One-way path attenuation measurements were made on controlled air-grain mixtures of flowing soft white wheat, hard red wheat, and rice over a range of 18 to 50 GHz. The attenuation tests were performed on the test fixture shown in the semi-schematic of Fig. 1. The fixture comprised a wedge-shaped hopper to hold the sample, a manually operated hopper orifice plug (to release the sample into the interaction volume) a wooden support frame, a diffuser to distribute the grain uniformly as it flowed into the interaction volume, thin low-loss mylar sheeting to contain the flowing sample and provide low transmission loss, transmitting and receiving horns to illuminate the flowing sample, and a compartmented sample collector to hold the flowing sample and gage the uniformity of cross sectional distribution. The controlled factors in this test were sweep frequency range (3 bands: 18 to 26.5 GHz, 26.5 to 40 GHz and 33 to 50 GHz) and uninfested grain species (3: hard red wheat, soft white wheat and long grain brown rice). Each sample was loaded into the hopper and released manually by lifting the valve plug. Initially, timing runs were made at a fixed frequency on 750 mg samples to determine the mass flowrate of the rectangular hopper outlet orifice. The signal generator was then placed in a sweep mode, the hopper reloaded, and the swept frequency data obtained. Three replicate samples of each grain were run sequentially at each of the three ranges. The exposed samples were collected in a removable segmented sample collector. Upon removal, after each exposure, the individual segments of the sample collector were inspected to determine the uniformity of grain distribution in the flowing stream as gauged by the height of the grain in each segment.

To correlate the measured one-way path attenuation with the volume percentage of grain in the flowing stream it was necessary to know the density of a single kernel of each of the grains. The mean density of each of the three grain species was determined by weighing 10 kernels of each grain species and then immersing the kernels in acetonitrile (CH3CN) and measuring the displacement volume. The density of acetonitrile was less than that of the grain thereby permitting total submergence of the grain. The densities of each of the grains tested are given in Table1. (The wet basis moisture content (MC) was measured on a 250 g samples using a Steinlite Model SB 900 moisture meter.) The volumetric ratio (*v2*), defined as the ratio *Vg/V* in %, was then calculated by determining the effective total volume (*V*) of a free falling mixture of grain and air from the product of the cross sectional area of the flowing stream and the distance a single grain would travel in the measured flow time at the velocity of the grain in the beam interaction volume. The volume occupied by the grain (*Vg*) in the flowing stream was determined from the quotient of the 750 g mass (*m*) of the flowing sample and the density of the individual kernels given in Table 1. The velocity of grain (*v*) in the free falling stream was obtained from Bikalski et al. 1962 at a distance of 24.15 cm from the hopper orifice at the interaction volume of the grain and the beam radiating from the transmitting sectoral horn. The time of flow (*t*) was measured for each of the three replications over each of the three frequency ranges and averaged to obtain the value shown. The calculated average value and standard deviation of *v2* for each of the three grains tested is given in Table 2.

Log-linear plots of the attenuation versus frequency in each of the three frequency ranges and three replications revealed the linear relationships shown in Table 3. Each sample was swept in two consecutive 50 ms sweeps during the flow period and therefore the data used to obtain the relationships are the log of

Using the above relationships, the maximum and minimum attenuations of Table 3 were translated into the penetration depths shown in Table 4.

The calculated ½ energy penetration depths ranged from a minimum of approximately 8 for all 3 grains in the range of 26.5 to 40 GHz to a maximum of ≥ 140 cm over the frequency range of 18 to 26.5 GHz for mean volumetric ratios of approximately 2 % to 2.8 %. A review of the recorded data, from which the Tables 3 and 4 are derived, indicated that the greatest penetration depth of the flowing grain occurs in the range from 18 to 26.5 GHz. For HRW and SWW in the 26.5 to 40 GHz some anomalous departure from a linear relationship of log attenuation to frequency, noted in other ranges, was evident from 32 to 39 GHz. In those cases attenuation varied between extremes of low attenuation and high attenuation. Anomalies were also noted for rice at frequencies from 22 to 26.5 GHz where the attenuation decreased. However, this decreased attenuation was not confirmed by the data taken on rice at 26.5 GHz in the 26.5 to 40 GHz sweep. Whether or not these anomalies are fact or artifact cannot be determined from the existing data. If fact, then the regions of low attenuation may be windows in the absorption spectrum of grain. Further tests are planned during Phase II to investigate these phenomena and to expand the data over a wider range volumetric ratios.

The importance of these results are that they demonstrate by direct measurement that the penetration depth of a granular complex dielectric medium with high effective loss factors can be increased greatly at frequencies in the EHF and SHF bands by controlling the ratio of grain-to-air in a dynamic stream. This is the sine qua non of treating grain in the specified range at extremely high continuous power levels available from microwave gyrotrons. Increased penetration was previously implied by the dynamic test reported in

Halverson et al. 1997 where a 10.16 cm dia. flowing stream of a controlled grain and air mixture was penetrated at a frequency of 28 GHz and produced high insect mortality for adults, older larvae (and pupae) and younger larvae (and eggs). As a consequence of these results, the design and testing of a practicable prototype system for controlling insect infestation of stored cereal grains can now be undertaken.

the averages of 6 total sweeps for the 3 replications. However, in the 26.5 to 40 GHz range, for both HRW and SWW, a non-linear absorption band was noted between 32 and 39 GHz. This resulted in a steeper slope of the curve fit obtained by linear regression. However, these anomalies were not evident in the in over the common range in the 33 to 50 GHz sweeps. For rice in the 18 to 26.5 GHz range an anomaly above 22 GHz was also noted.

The minimum and maximum one-way path attenuation defined in Table 3 were used to determine the ½ energy density depth of penetration (*L-3dB*). The depth of penetration will be defined here as that path length over which the energy density in the impinging wave is reduced to ½ of the initial value. This relationship is expressed in the following equations where:

dB = Measured attenuation at any frequency in dB
a - Energy attenuation in nepers per unit path length (L = 10.16 cm)
n = number of unit path lengths to diminish energy by ½ = *ln(1/2)/ ln*a)
L-3dB = n(L)

Table 1. Density ( ) of kernels of hard red wheat, soft white wheat, and long grain brown rice used in one-way path attenuation measurements.

Grain	*mass* mg	*volume* ml	g/ml	*MC wet basis* %
Hard red wheat	29.2	0.0212	1.38	11.43
Soft white wheat	40.0	0.0295	1.36	14.55
Rice	24.4	0.0175	1.39	16.50

Table 2. Grain-to-air volumetric ratio for hard red wheat, soft white wheat, and long grain brown rice calculated from the velocity of grain flow in the test fixture shown in Fig. 1.

Grain	***v***		***t***		***V***	***Vg***	***v2***
	cm/s	**g/ml**	**s**	**g/s**	**ml**	**ml**	**%**
HRW	120.67	1.38	2.59	289.24	20186.88	543.48	2.77 ± 0.66
SWW	120.67	1.36	2.79	269.20	21689.42	551.47	2.61 ± 0.52
Rice	120.67	1.39	3.51	213.43	27357.00	539.57	2.01 ± 0.20

Table 3. Summary of linear regression functional dependence of path attenuation in dB on frequency (f) in GHz for hard red wheat (HRW), soft white wheat (SWW) and Rice over the range of 18 to 50 GHz and maxima and minima within the band.

Grain	**f**	**dB(f)**	**dB min**	**dB max**	**Remarks**

-0.0246f + 0.0336

	26.5 to 40.0	-0.1440f + 2.6218	-0.880	-3.485	Anom. 32 - 39 GHz
	33.0 to 50.0	-0.0162f - 0.6525	-0.300	-2.235	
HRW:	18.0 to 26.5		-0.061	-0.404	
SWW:	18.0 to 26.5	-0.0450f + 0.4962	-0.219	-0.862	
	26.5 to 40.0	-0.085f + 0.580	-0.363	-3.840	Anom. 32 - 39 GHz
	33.0 to 50.0	-0.0260f - 0.554	-0.303	-2.475	
Rice:	18.0 to 26.5	0.0199f - .8760	-0.169	-0.660	Anom. 22 - 26.5 GHz
	26.5 to 40.0	-0.0629f - 0.7195	-0.497	-3.196	
	33.0 to 50.0	-0.0462f – 0.4322	-0.233	-2.993	

Table 4. Maximum and minimum ½ energy penetration depth corresponding to attenuation of Table 3

Grain	**f GHz**	**L-3dB max cm**	**L-3dB min cm**
HRW:	18.0 to 26.5	501.39	75.70
	26.5 to 40.0	34.76	8.78
	33.0 to 50.0	101.95	13.68
SWW:	18.0 to 26.5	139.66	35.48
	26.5 to 40.0	84.26	7.96
	33.0 to 50.0	100.94	12.36
Rice:	18.0 to 26.5	180.97	46.34
	26.5 to 40.0	61.54	9.57
	33.0 to 50.0	131.26	10.22

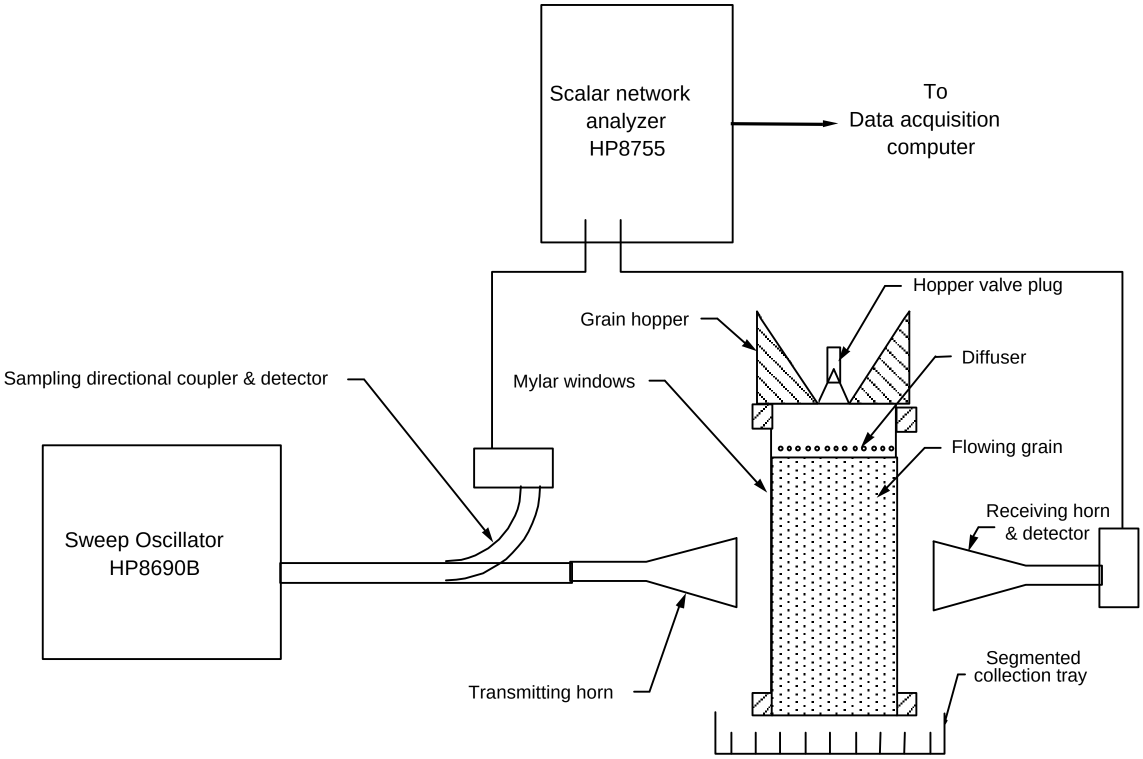

Fig. 1. Semi-schematic diagram showing the equipment arrangement for the one-way path attenuation tests.

References cited

Bilanski, W. K., S.H. Collins and P. Chu 1962. Aerodynamic properties of seed grains. Agric. Engrg 43: (4)216-219

Halverson, Steven L., Rudy Plarre, Timothy S. Bigelow and Kathleen Lieber 1997. Advances in the use of EHF energy as a fumigant for stored products, Paper No. 111, Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions, Nov. 3-5, 1997, Double Tree Hotel, San Diego, CA

Halverson, Steven L., Timothy S. Bigelow ,Rudy Plarre, and Kathleen Leiber 1998. Recent advances in the use of EHF energy for the control of insects in stored products, Paper No. 986052, ASAE Annual International Meeting, July 12-15, 1998, Orlando, FL

Plarre, R., S. L. Halverson, W. E. Burkholder, T. S. Bigelow, M. E. Misenheimer, J. H. Booske and E.V. Nordheim 1997. Effects of High-Power Microwave Radiation on *Sitophilus zeamais* Motsch. (Coleoptera: Curculionidae) at Different Frequencies, ANPP- Fourth International Conference on Pests in Agriculture, Montpellier, France, 6-8 January 1997.