# A New Method for the Control of Moisture and Insect Infestations of Grain by Microwave Power*

M. A. K. Hamid and R. J. Boulanger†

ABSTRACT

*A new method for the control of three common types of wheat and flour insects* (Tribolium confusum, Sitophilus granarius, *and* Cryptolestes ferrugineus) *by microwave power is presented. The method is based on the detection of the dielectric properties of these insects and the design of microwave apparatus of sufficient capacity to disinfest reasonable quantities of grain by selective dielectric heating. Experimental arrangements for the drying of wheat using single- and double-stage dryers are also described, and the resulting effects on the milling and baking qualities of wheat dried by this method are discussed. Finally, it is shown that the equipment assembly may safely and effectively serve the dual function of moisture and insect control of wheat at low cost, and compete favourably with gas schemes and chemical sterilants now used to dry wheat and eliminate its infestations.*

## 1. Introduction

In a previous paper, Hamid, Kashyap, and Van Cauwenberghe[1] concluded that the illumination of wheat in bulk quantities by microwave power was impractical for the control of wheat insects on a large scale. The largest drawback was found to be the small penetration of microwaves (4 inches), which made the method impractical. However, it was suggested that circulation of the wheat in a region of high electric field should be investigated, but no workable design was proposed.

Initial investigations to achieve a practical and efficient design indicated that several problems had to be overcome before large-scale circulation of the wheat could be implemented. Thus, it was necessary to use commercial magnetrons (e.g., the Philips DX260 magnetron with an available power output of 1.2 kW at 2.45 GHz) and yet ensure maximum dissipation of power in the sample. Furthermore, it was necessary to avoid any leakage from the system which could exceed the maximum permissible level of 10 mW/cm$^2$ for human safety. It was thought that both these problems could be overcome by the design shown in Fig. 1.

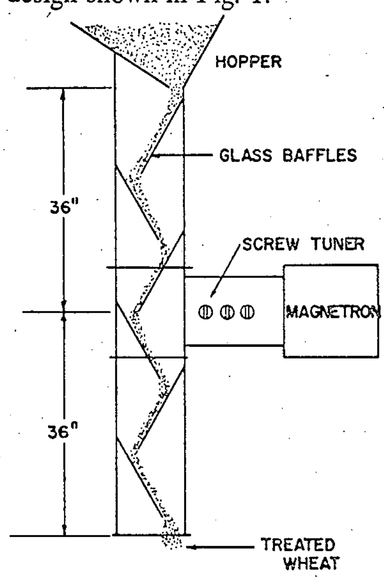


FIG. 1. First design for the control of insects in wheat circulating through a waveguide.

## 2. Description of the Design

Power from the magnetron is split equally in the T-junction, thus illuminating wheat in the vertically oriented waveguide. Since

*Manuscript first received October 5, 1968; in revised form January 2, 1969. The research was supported by the Defence Research Board of Canada, under Grant No. 6801-37.

†Antenna Laboratory, Department of Electrical Engineering, University of Manitoba, Winnipeg, Canada.

the penetration depth had already been found to be about 4 inches, it was safe to assume that there would be very little leakage of power from the open ends of the waveguide if its length was made 72 inches. However, it was not known whether the wheat presented a matched load to the magnetron and whether tuning for a minimum vswr was possible.

In order to control the exposure time of the wheat, a network of plastic baffles was installed inside the waveguide. However, the resulting drift in the tuning could not be easily controlled because of variations in the moisture content of the wheat during the treatment. It was found that all the baffles, except one, could be discarded and complete control still achieved. The final design is shown in Fig. 2, where the adjustable baffle ensures even distribution of the wheat in the waveguide and minimum tuning difficulties. This design also includes thermocouples as well as a thermally insulated container (grain bin) to make use of the residual heat in killing any surviving insects. The excursion in the reflected power corresponded to a fluctuation range of 1.05 to 1.30 for the vswr, which is well within the maximum permissible value of 4.0 for the Philips DX260 magnetron.

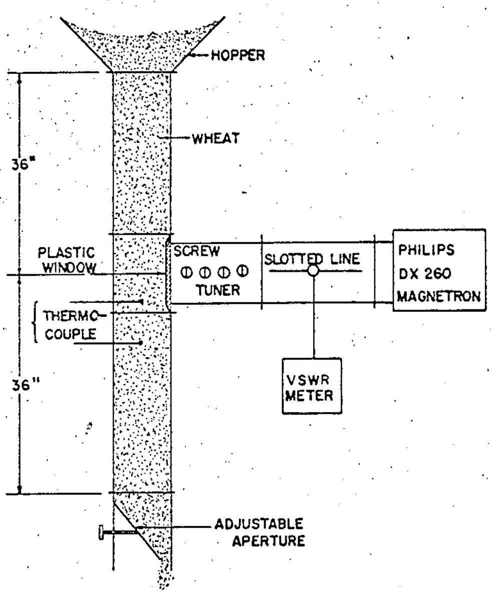


FIG. 2. Final design of the microwave system used for the control of wheat insects.

## 3. Sample Tests

Since the destruction of insects by this method is due to selective dielectric heating, samples of insects were scattered in small plastic containers filled with wheat and allowed to pass through the waveguide. Temperature measurements were made inside these containers as well as at typical positions in the bulk wheat. Several samples of cockroaches were initially tested, and complete destruction was observed at 55°C because of the high moisture content of these insects relative to the wheat. For *Tribolium confusum*, 70 per cent mortality was secured at 55°C and 100 per cent at 65°C similar to the results previously reported in (1). In all cases the test sample was left in the output container of hot wheat for at least 30 minutes.

## 4. Cost Considerations

Tests were also carried out to determine the amount of wheat that could be treated with a given available power, and estimates were made of the cost per bushel in a practical treatment.

From a heat transfer point of view, it is necessary to determine the specific heat of wheat, denoted by $C_{wh}$, for a given moisture content. Using a calorimeter and taking water as a standard, i.e. $C_{wa} = 1$, three different trials gave a specific heat of 0.513 cal/°C or 2.14 joules/g—°C. The following assumptions were also made:

1. The ambient temperature is 22°C and the required temperature of the wheat for a successful treatment (i.e., 100% insect mortality) is 65°C. The required rise in wheat temperature is hence $\Delta T = 43°C$.
2. The output power from the Philips DX260 magnetron is 1.27 kW.
3. All available power is absorbed in the wheat (i.e., the vswr is unity).
4. The magnetron is turned on for an elapsed time of 1 minute.

Using these assumptions, we calculated the amount of wheat treated per minute. Since

$$MC_{wh} = \partial E/\partial t = \Delta E/\Delta T, \quad [1]$$

where $M$ = mass of wheat treated per minute and $\Delta E$ = energy given off by the magnetron per minute, then $\Delta E \doteq 1.27$ kW $\times$ 60 sec. = 76,200 joules and

$$M \doteq \Delta E/\Delta T.C_{wh} = 0.8\text{kg/min or } 1{,}82\text{lb/min}. \quad [2]$$

These calculations were then checked experimentally. Using an ac wattmeter, the line power to the magnetron was measured and the available power was calculated using the manufacturer's efficiency data for the magnetron (60% at 2.45 GHz). It was found experimentally that the magnetron could raise 18.6 lb of wheat 43°C above ambient temperature in 9 minutes. This corresponds to a flow rate of 2.26 lb/min, which may be compared with the theoretical value of 1.82 lb/min. The disagreement is not surprising since the specific heat of wheat varies from 0.3 to about 0.5 depending on the moisture content, and experimental errors in the measurement of $C_{wh}$ could therefore account for the discrepancy.

Assuming that the cost of electrical power is 0.9 cent per kilowatt-hour and that there are 60 lb to a bushel of wheat, the cost of treatment by our method is approximately 0.44 cent per bushel, which is less than 0.5 per cent of the commercial value of the wheat. This is also considerably less than the cost of the fumigation now used to control wheat and flour insects. The specific heat and cost of treatment vs. moisture content of wheat are given in Figs. 3 and 4, while the cost of treatment vs. ambient temperature is given in Fig. 5.

## 5. Extension to Tribolium confusum Larvae

In order to treat wheat infested with *Tribolium confusum* larvae, it is necessary to measure their dielectric properties and the number present in a given sample.

The technique described in (1) for the detection of insects in wheat and flour is based on direct power absorption measurements for a given sample in a waveguide. An alternative technique, which proves to have a higher resolution, is shown schematically in Fig. 6. Here the klystron power is split in the T-junction, thus feeding equal power to the two arms of the bridge. One arm consists of a calibrated attenuator and a crystal detector, and the other of an uncalibrated attenuator, sample section, and a crystal detector. The output of both detectors is fed into a differential amplifier, and its output in turn is fed into a variable gain amplifier, such as a standing wave meter, for proper display. With

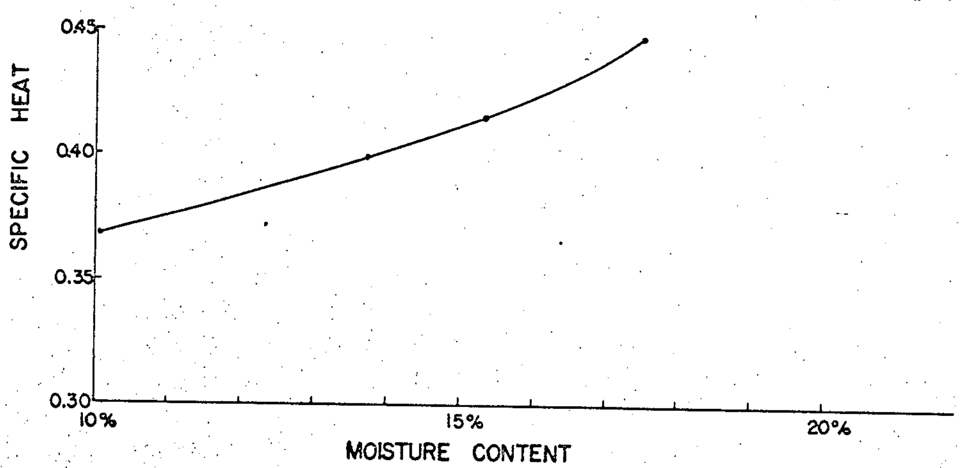


FIG. 3. Specific heat vs. moisture content of wheat.

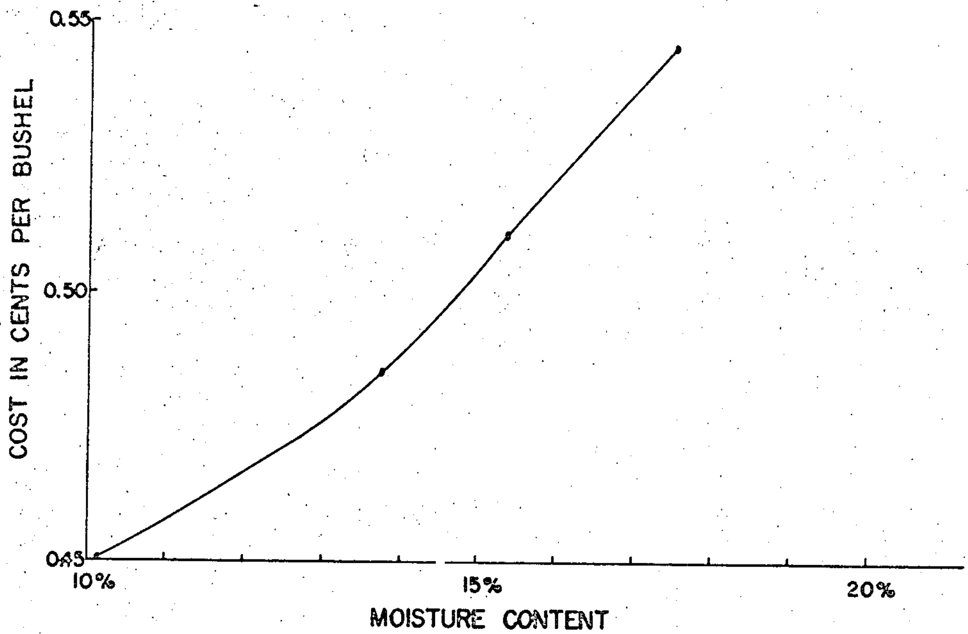


FIG. 4. Cost of treatment vs. moisture content for wheat (ambient temp. = 22°C, $\Delta T = 43$°C).

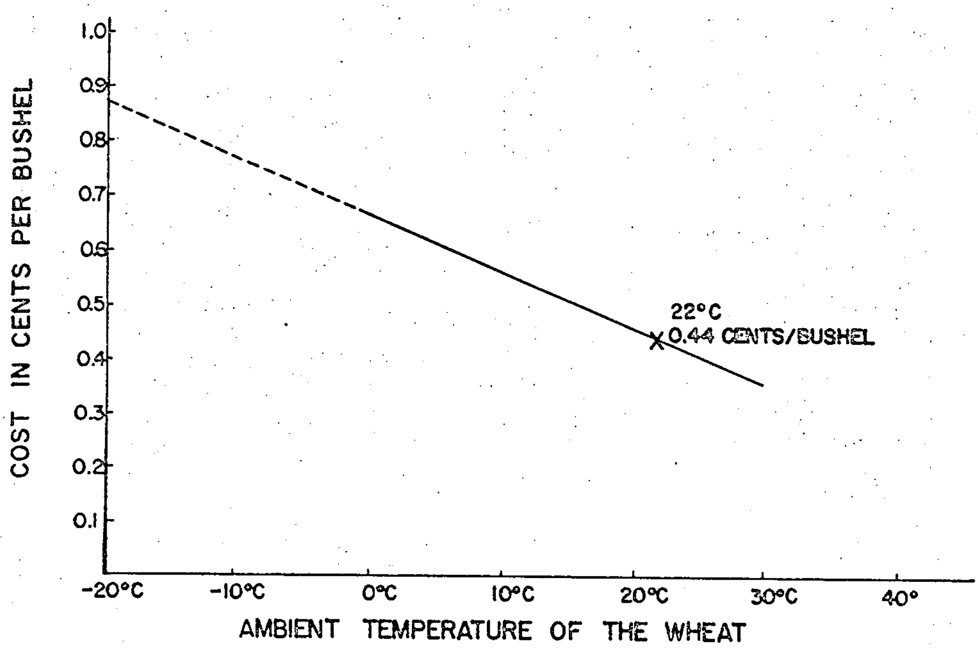


FIG. 5. Cost of treatment vs. ambient temperature for wheat (temp. of treated wheat = 65°C).

no insects present in the sample section, the precision attenuator is set to zero and the uncalibrated attenuator is adjusted until a null is observed on the display meter. Insects are then inserted through a slot in the sample section and the calibrated attenuator adjusted to obtain a null again. The difference in the two readings of the calibrated attenuator was found to be 0.04 dB per insect at 10 GHz. Although the resolution of the apparatus is quite high, it was concluded that, owing to the large

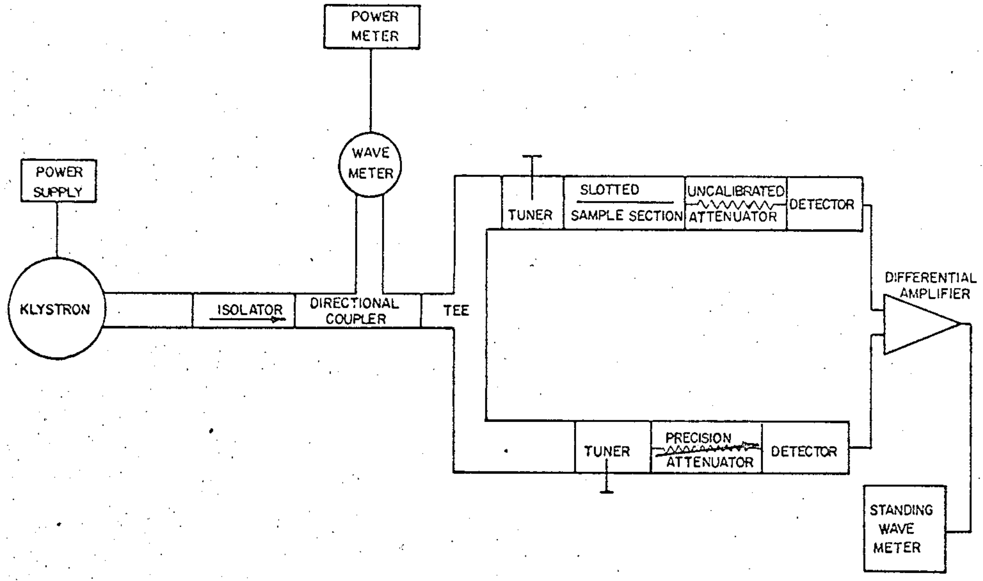


FIG. 6. High-resolution insect detection system.

sensitivity, the results could not be reproduced quantitatively unless the volume and compactness of the sample were carefully controlled to remain the same.

The scattering coefficients and dielectric constant of *Tribolium confusum* larvae were determined experimentally by the Deschamps graphical method in the same manner as described in (1). The results are:

| Scattering coefficient | Magnitude | Phase (degrees) |
|---|---|---|
| $S_{11}$ | 0.56 | 180 |
| $S_{22}$ | 0.60 | 180 |
| $S_{12}$ | 0.715 | 255 |

with $S_{21} = S_{12}$, relative dielectric constant $= 2.80 + j0.46$, and loss tangent $= 0.164$.

The smallness of the Deschamps circle indicates that these larvae are relatively lossy dielectrics and that treatment by selective dielectric heating is therefore feasible. This was confirmed using the apparatus in Fig. 2. The results indicated that the mortality of the larvae at different temperatures was virtually the same as for the adult *Tribolium confusum* as already given in (1).

## 6. Quality Tests of Treated Wheat

In order to determine the effects of high-frequency irradiation on the milling and baking qualities of wheat, three samples corresponding to 55°C, 65°C, and 80°C were compared with the control sample. The results, which are given in Table I, indicate that there is no effect on the milling quality or protein content of the wheat. However, the breadmaking quality is affected deleteriously and progressively more as the treatment temperature increases. The effects noted are similar to those produced by improper drying of grain. This suggests that further tests are necessary to determine the fundamental changes in wheat components that lead to the decrease in loaf volume. These are now being carried out in a factorial experiment with moisture, temperature, and time as the variables.

## 7. Extension to the Drying of Wheat

It is well known that storage difficulties and infestation of wheat by insects occur most frequently when the wheat has a relatively high moisture content. It is therefore

TABLE I

MILLING AND BAKING QUALITIES OF HIGH-FREQUENCY-IRRADIATED WHEAT

| Property | Control sample | Sample temperature | | |
|---|---|---|---|---|
| | | 55 °C | 65 °C | 80 °C |
| Wheat | | | | |
| Moisture, % | 12.7 | 12.3 | 12.1 | 11.5 |
| Protein, % | 9.8 | 9.8 | 9.8 | 9.8 |
| Flour yield, % (total) | 74.9 | 74.4 | 74.0 | 74.0 |
| Flour | | | | |
| Protein, % | 9.3 | 9.3 | 9.3 | 9.3 |
| Colour, units | −0.8 | −0.3 | −0.2 | 0.0 |
| Baking absorption, % | 60.1 | 61.1 | 60.5 | 59.8 |
| Bread | | | | |
| Loaf volume, cc (remix) | 550 | 435 | 360 | 315 |
| Farinogram | | | | |
| Absorption, % | 65.1 | 65.1 | 64.5 | 63.5 |
| Development time, min | 1.5 | 2.0 | 1.25 | 1.5 |

advantageous to lower the moisture content and destroy the insects to prevent spoilage. Gas-fired hot-air grain dryers are now used extensively to lower the moisture content of various types of grain. In this type of dryer, air is heated by a gas flame and circulated through the grain. Large quantities of hot air must be used since, for effective drying, the temperature of the wheat must be raised from ambient to between 40°C and 60°C. Care must be exercised in operating this type of dryer since scorching of the grain can easily occur through the uneven application of hot air to the grain.

Since in our insect control apparatus the wheat is raised to a uniform temperature of 65°C, the circulation of warm air through the irradiated wheat would provide a very effective drying action. Because of the small temperature gradient between the inside of the wheat kernels and the circulating air, no significant scorching would occur. The drying action would then be "from the inside out." A partial source of this warm air could be from the cooling system for the microwave power source, thus making maximum use of the applied power. An experimental system to verify this idea was developed and several measurements were made. It was found that when wheat with a moisture content of 16.5 per cent was passed through the newly developed dryer and raised to a temperature of 65°C, and then subjected to a blast of air, the humidity was reduced to 13.3 per cent. A second run was made in which the wheat temperature was raised to 55°C, and the moisture content was reduced from 16.5 to 13.8 per cent. As mentioned previously, however, some reduction in the loaf volume of bread made from irradiated wheat occurs, and this is particularly significant when wheat with a high moisture content is raised to a high temperature. One way to eliminate this for certain applications would be to use a two-stage dryer, as shown in Fig. 7, where the grain is raised to an intermediate temperature of about 45°C and then subjected to a blast of warm air to lower its humidity content before it is finally subjected to the higher temperature (55–65°C) required for the destruction of the insects. Special wire screens, as shown in Fig. 7, would be located at safe locations in the waveguide with hot air coming in on one side and moisture driven off on the opposite side. Such a system would be very effective in achieving the dual function of drying the grain as well as controlling its insect infestations. Furthermore, the use of a gas-fired

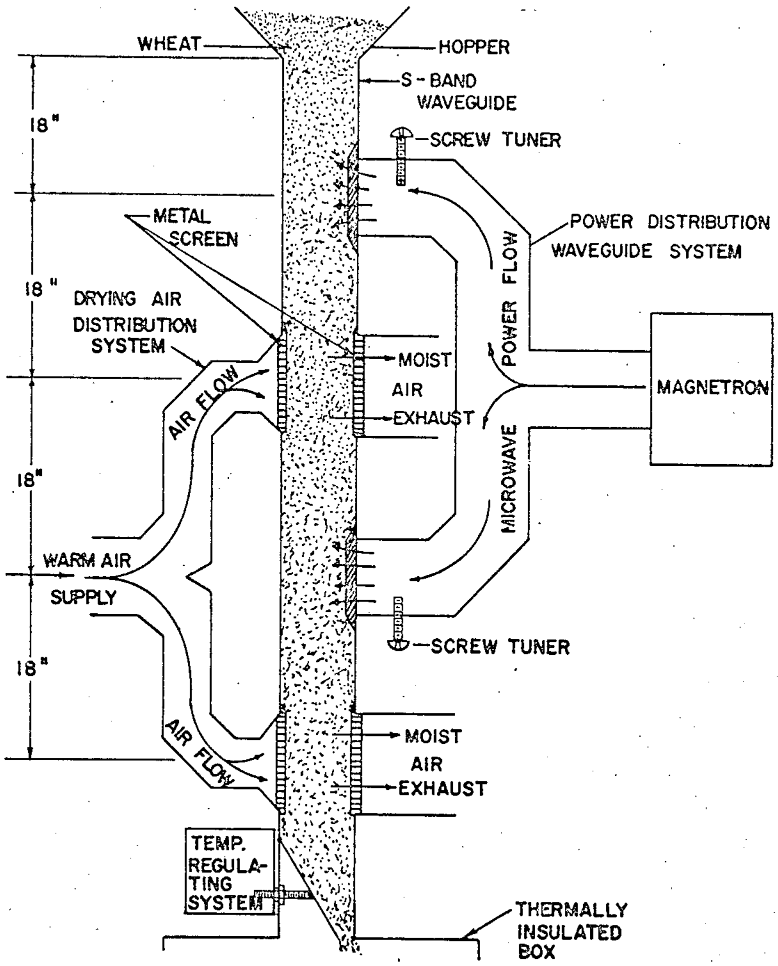


FIG. 7. Practical system for control of insects in wheat and flour and drying of grain.

warm air supply in combination with the microwave power source would reduce the microwave power requirements considerably. If the control of insects is not necessary or not desired, the drying capacity would be considerably increased since the temperature of the wheat could be kept lower (about 50°C) and effective drying action would still occur.

## 8. Conclusions and Suggestions for Future Research

Preliminary experiments reported here indicate that circulation of wheat and flour through a waveguide sustaining a high-frequency electric field presents an effective and economical means for controlling both insect and insect larvae infestations as well as the moisture content. A working setup would require a higher-powered magnetron of about 10 kilowatts in order to process approximately 20 bushels of wheat per hour. Furthermore, a temperature slightly lower than 65°C, which corresponds to 100 per cent insect mortality, may be used since large quantities of grain would hold the heat longer. The cost of such treatment would probably be less than half the cost of fumigation, the method of extermination now used, and could represent a substantial saving in terms of millions of bushels of wheat and flour as well as smaller amounts of expensive food products.

Suitable control devices could also be incorporated into the design shown in Fig. 7 in order to produce a completely self-operating unit. For a more efficient energy transfer, it would be desirable to monitor either the vswr or the reflected power at the T-junction and correspondingly tune the load continuously by automatic servo-devices. A trombone-type tuner would probably be best for this purpose since there would be only one adjustment required. Temperature-sensing devices would also be necessary and in turn be used to control the flow rate by means of an adjustable aperture.

Another area for future investigation is the use of a lower-frequency power source for the irradiation of wheat in order to improve the efficiency of drying and disinfestation schemes already known (2–4). A low-cost high-power class C amplifier is at present being considered for this purpose, in which the grain would be passed between the plates of the plate tank capacitor, thus providing dielectric heating action. The economics and effectiveness of both systems would have to be compared in order to make the proper choice.

## Acknowledgments

The authors wish to thank Messrs. W. Alsip and H. Unger for their assistance in the measurement and construction of the experimental apparatus, and Professors F. Watters, R. Brust, and W. Bushuk of the University of Manitoba for their co-operation in providing the experimental samples and wheat quality tests.

## References

1. Hamid, M. A. K., Kashyap, C. S., and Van Cauwenberghe, R., "Control of Grain Insects by Microwave Power," *J. Microwave Power, 3*, no. 3 (1968), 126–35.
2. Nelson, S. O. and Whitney, W. K., *Trans. Amer. Soc. Agric. Engrs., 3*, no. 2 (1960), 133–44.
3. Whitney, W. K., Nelson, S. O., and Walkden, H. H., *Mkting Res. Rept. No. 455, Agric. Mkting Serv.* (U.S. Dept. Agric., March 1961).
4. Baker, V. H., Wiant, D. E., and Tabada, O., *Agric. Eng., 36*, no. 12 (1955), 808.

MEAN: G-MTT's International Microwave Symposium (Dallas, May 5–7 next) includes a panel session on microwave power: Microwave Energy Applications, Non-communications (MEAN). The panel session will include James A. Jolly (Industrial applications), W. C. Brown (Power transmission), K. E. Mortensen (solid-state techniques), G. B. Walker (high-energy physics), and L. Sher (biological effects) covering the expanding use of the power spectrum. W. A. G. Voss is panel chairman. Time for informal discussions, after topic introductions, has been allowed for by the session organizer, M. C. Horton of MTT.