ever, the rate would most probably decrease because the effects of the parasympathetic system are stronger than those of the sympathetic. We hypothesize that the microwave power is stimulating the nerve remnants and/or the *boutons terminaux* causing the release of transmitter which induces the decrease in heart rate. Furthermore, at 100-mW total power, the increase in temperature of the heart is not enough to cause an increase in heart rate equal to the decrease caused by the above described system, while at 300-mW total power, the increase in rate due to the microwave heating is greater than the decrease due to transmitter release. This is consistent with tachycardia induced by 300-mW total power.

Further evidence to check this hypothesis could be obtained by blocking the transmitter action and measuring the change in rate. The parasympathetic system can be blocked by the addition of atropine to the Ringer's solution, and if the hypothesis were correct, 100-mW microwave irradiation in the presence of atropine should cause an increase in heart rate, rather than a decrease. Preliminary experiments indicate that this does happen. We have also tried to block the sympathetic system with inderal (propranolol hydrochloride) to see if microwave power would cause a further decrease in rate, but this preparation is not an entirely suitable blocking agent. At present, we have no explanation of how the microwave power might be stimulating the nerves and/or buotons, but we intend to pursue this question along with many others that have been raised by our experimental results.

ACKNOWLEDGMENT

The authors wish to thank D. Olsen and Dr. C. C. Johnson for assistance and helpful suggestions.

REFERENCES

[1] A. H. Frey and E. Seifert, "Pulse modulated UHF energy illumination of the heart associated with change in heart rate," *Life Sciences*, vol. 7, pt. II, pp. 505–512, 1968.
[2] C. C. Johnson and A. W. Guy, "Nonionizing electromagnetic wave effects in biological materials and systems," *Proc. IEEE*, vol. 60, pp. 692–718, June 1972.

Microwave Effects on Thermoluminescence and Thermally Stimulated Exoelectron Emission

DONALD R. ELLE, DANIEL J. FEHRINGER, RICHARD J. VETTER, AND PAUL L. ZIEMER

***Abstract*—In a pilot study to determine phosphor response after microwave exposure, a reduction in the expected amount of light emitted during thermoluminescent (TL) analysis was observed after exposure to microwave radiation of a phosphor preirradiated with cobalt-60 gamma radiation. Investigation of the thermoluminescent response of some high dielectric-constant materials after microwave exposure revealed the fading phenomenon in the powdered and ceramic states of the phosphors.**

I. INTRODUCTION

Critical reviews of the literature on the hazards and biological effects of microwave radiation reveal the limitations and inadequacy of much of the work performed thus far [1], [2]. One of the most important limitations is the lack of adequate dosimetric metholology for determining power density or absorbed energy in or around a biological specimen or tissue equivalent medium. The use of a reduction in thermoluminescent (TL) response (fading) from a preirradiated phosphor as a result of exposure to microwave radiation as a method of microwave dosimetry has been suggested in a report by Conover, but studies using a well-known phosphor have yielded no such reduction [3].

Manuscript received May 15, 1973; revised July 26, 1973. This work was supported in part by the U. S. Public Health Service under Training Grant 2 T01-ES00071 from the National Institute for Environmental Health Sciences.

D. R. Elle was with the Bionucleonics Department, Purdue University, West Lafayette, Ind. He is now with the Operational Safety Division, Atomic Energy Commission, Albuquerque Operations Office, P.O. Box 5400, Albuquerque, N. Mex. 87115.

D. J. Fehringer, R. J. Vetter, and P. L. Ziemer are with the Bionucleonics Department, Purdue University, West Lafayette, Ind. 47907.

Thermoluminescence use in personnel radiation dosimetry was initiated by Daniels [4]. Since then the literature concerning the theory, development, and use of thermoluminescence has become very comprehensive. Briefly, the TL process can be depicted in terms of crystal lattice defects. The interaction of ionizing radiation with the crystal causes electrons to be raised from the valence band to the conduction band where the electron wanders until it falls into an electron trap. When the crystal is heated, the trapped electron is raised back to the conduction band where it wanders and falls back to the valence band emitting a quantity of light. The amount of light emitted by the crystal is proportional to the radiation dose received by the crystal.

More recently, a similar phenomenon called thermally stimulated exoelectron emission (TSEE) has been suggested as a radiation dosimeter [5]. In the TSEE process, trapped electrons are raised to the conduction band and emitted from the surface of the crystal. The number of electrons emitted is proportional to the radiation dose received by the crystal.

This short paper describes studies involving the use of powdered and ceramic phosphors, some with high dielectric constants and loss factors, which were used to evaluate TL and TSEE fading after exposure to microwave radiation. When correlated with microwave exposure in terms of energy density, the amount of fading or loss in TL response may provide a method for microwave dosimetry.

II. MATERIALS AND METHODS

The powder phosphors used for evaluating TL response were $BaTiO_3$, activated with dysprosium, and a mixture of $BaTiO_3$ and $SrTiO_3$ in a ratio of 8:2 by weight [$(Ba_{0.8}Sr_{0.2})TiO_3$]. Ceramic phosphors were prepared using an organic binder (methyl cellulose) mixed with these powdered phosphors and firing them for 3 h at 1385°C. The phosphors used for determining TSEE response were CaF_2, $BaSO_4$, $BaTiO_3$, and $(Ba_{0.8}Sr_{0.2})TiO_3$. These phosphors were studied in the pure state and mixed with 25 percent by weight graphite powder. The TL and TSEE properties of these phosphors had been determined previously [6], [7].

Annealed TL and TSEE phosphor samples, placed in paper envelopes or polyethylene vials, respectively, were irradiated with 10^5 R of ^{60}Co gamma radiation and then exposed to microwave radiation in an anechoic chamber, 305×244×213 cm high, with a −40-dB quiet zone. An exhaust fan was located in the ceiling near the back wall to maintain room temperature. A pyramidal horn connected a 1.5-kW 2450-MHz generator to the chamber. The power level was determined with a directional coupler and Hewlett-Packard 432A power meter, and power density was monitored with a Narda 8110 electromagnetic radiation monitor. The TL phosphors were exposed to power densities ranging from 200 to about 5000 mW/cm² in the anechoic chamber while the TSEE phosphors were exposed to 200 mW/cm² in the anechoic chamber and to about 7.4×10^4 mW/cm² in a microwave oven. Phosphors were exposed for 5–40 min in the anechoic chamber and for 1 min in the microwave oven. After the longest microwave exposure, all samples including controls were placed on dry ice until analyzed. Phosphor TL and TSEE response were determined with readers designed and built at Purdue University [8], [9] and were expressed as glow peak height.

III. RESULTS

A statistically significant ($P < 0.05$) reduction in TL response was observed in the $(Ba_{0.8}Sr_{0.2})TiO_3$ phosphor only (Fig. 1). Fading increased with time of microwave exposure and was therefore dependent on the energy fluence at the surface of the phosphor. No reduction in TSEE response was seen in any of the phosphors exposed in the anechoic chamber, but a reduction of up to 80 percent was observed in the phosphors containing graphite when exposed in the microwave oven.

When measurements were made on the temperature of the $(Ba_{0.8}Sr_{0.2})TiO_3$ phosphor during microwave exposure, an increase over the ambient temperature level was noted. This is important to consider since the increased temperature may be the cause of the fading. To examine this possibility, a temperature-fading study was performed using a drying oven as the heat source. The maximum temperature reached by the phosphors during microwave exposure was determined to be 28°C, as measured with a thermocouple; therefore, the fading study was carried out at this temperature. Phosphors were heated for times equal to the microwave exposures. The results indicated an enhanced fading over that of the room temperature (22°C) fading, as expected by the theoretical explanation of thermo-

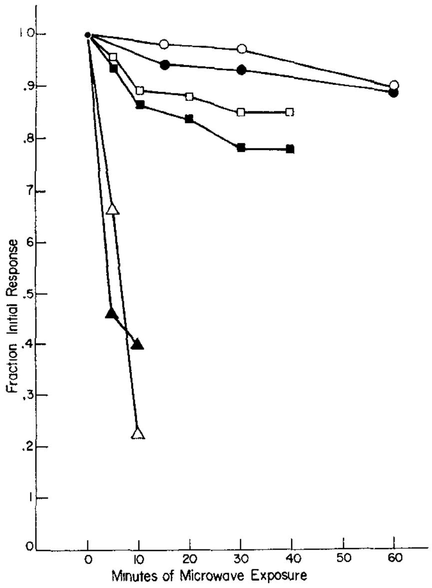

Fig. 1. Effect of microwaves on TL response of powder and ceramic phosphors. Error bars are not shown, but standard error of the mean averaged 0.068. (○—○), $(Ba_{0.8}Sr_{0.2})TiO_3$ stored at room temperature; (●—●), $(Ba_{0.8}Sr_{0.2})TiO_3$ stored at elevated temperature; (□—□), $(Ba_{0.8}Sr_{0.2})TiO_3$ powder exposed to 200 mW/cm^2; (■—■), $(Ba_{0.8}Sr_{0.2})TiO_3$ powder exposed to approximately 5000 mW/cm^2, (△—△), $BaTiO_3$ ceramic, (▲—▲), $(Ba_{0.8}Sr_{0.2})TiO_3$ ceramic. Results of the microwave exposures were normalized to the control to obtain fraction of initial response (no microwave exposure). Results of the elevated (28°C) exposure were not normalized in order to compare them directly with a control (22°C). In the latter comparison the zero time is a phosphor sample stored on dry ice and receiving no exposure to room temperature or to elevated temperature.

luminescence. However, the fading observed at 28°C was significantly ($P<0.05$) less than the fading observed after microwave exposure (Fig. 1). Since an increase in phosphor temperature alone did not account for all the fading, a significant amount of the fading in $(Ba_{0.8}Sr_{0.2})TiO_3$ after microwave exposure may have been due to a nonthermal or "microthermal" interaction.

The polyethylene vials containing the TSEE phosphors began to melt after 1 min of microwave oven exposure suggesting a phosphor temperature of 60–70°C. No temperature fading study was conducted, and it was concluded that the fading seen was strictly thermal.

From a practical point of view, the use of a ceramic and the fading effects seen in the ceramic are of more interest than use of the powdered materials. This interest is due to several reasons, the most significant of which are the more exact knowledge of dielectric properties of the ceramic versus that of powder, and larger values of dielectric constant and loss tangent for the ceramic than the powder. Furthermore, a solid piece is more easily handled than a quantity of loose powder and can be formed in a specific shape before firing. The ceramics were produced from the activated phosphors of $BaTiO_3$ containing 0, 0.1, and 0.5 mole percent Dy, and the combination powder $(Ba_{0.8}Sr_{0.2})TiO_3$. Preirradiated ceramics showed a marked reduction in TL response when compared to a control stored at room temperature (Fig. 1). Because of the difficulty in determining the temperature of a ceramic during or immediately after microwave exposure, a higher-than-room-temperature control was not used. However, the ceramics were not warm to the touch following the microwave exposure.

Ceramic pieces 2 cm or more in length, were placed on a Styrofoam support in the anechoic chamber after ^{60}Co irradiation and exposed to microwaves in a manner similar to the powder samples. Accurate determination of the effect of microwave exposure required multiple readouts of the same ceramic piece. After each readout, the ceramic was annealed for 30 min at 400°C and cooled to room temperature, then reirradiated with ^{60}Co, exposed to microwaves, and read out. Because a limited number of ceramics was available, only the high power density of approximately 5000 mW/cm^2 was used to test for TL fading. The reduction in response was energy fluence dependent; that is, the longer the microwave exposure, the greater the fading. The Dy-activated $BaTiO_3$ ceramics faded at approximately the same rate as the $(Ba_{0.8}Sr_{0.2})TiO_3$ ceramic but for clarity were not plotted in Fig. 1. Because of the preliminary nature of this study, the power density used was admittedly high with respect to personnel safety considerations. It is suggested that ceramics production and phosphor activation be optimized before more reasonable power densities are used.

IV. Conclusions

The results of these studies, using both powders and ceramics, show microwave-induced TL fading to be energy fluence dependent, with increasing microwave exposure time resulting in decreased TL response. Further, most of the fading observed after microwave exposure is probably due to some interaction other than thermal. A mechanism of action is not suggested at this time, but it is suggested that the fading phenomenon observed in these studies may provide a method of microwave dosimetry. No microwave-induced fading was observed in TSEE phosphors except when they were mixed with graphite and exposed to extremely high power densities. It was concluded that the TSEE fading observed was completely thermal in nature.

Acknowledgment

The authors wish to thank D. L. Conover for designing the anechoic chamber used in this study.

References

[1] S. M. Michaelson, "Biological effects of microwave exposure—An overview," *J. Microwave Power*, vol. 6, pp. 259–267, 1971.

[2] D. I. McRee, "Environmental aspects of microwave radiation," *Environ. Health Perspect.*, pp. 41–52, Oct. 1972.

[3] D. L. Conover, "Evaluation of lithium fluoride for microwave dosimetry application," U. S. Dep. Health, Ed. and Welf., Rep. BRH/DEP 71-6, Apr. 1971.

[4] F. Daniels, "Early studies of thermoluminescence radiation dosimetry," in *Proc. Int. Conf. Luminescence Dosimetry*, F. A. Attix, Ed. (Stanford, Calif.), Apr. 1967, pp. 34–43.

[5] K. Becker, "Principles of thermally stimulated exoelectron emission (TSEE) dosimetry," *IAEA At. Energy Rev.*, vol. 8, p. 173, 1970.

[6] D. R. Elle, "Thermoluminescence and microwave induced thermoluminescent fading of high dielectric constant inorganic materials," Ph.D. dissertation, Purdue Univ., Lafayette, Ind., Dec. 1972.

[7] D. J. Fehringer, "The effects of microwave radiation on thermally stimulated exoelectron emission," M.S. thesis, Purdue Univ., Lafayette, Ind., May 1973.

[8] R. H. Wallace and P. L. Ziemer, "Studies on the thermoluminescence of manganese-activated lithium borate," in *Proc. 2nd Int. Conf. Luminescence Dosimetry* (Gatlinburg, Tenn.), Sept. 1968, pp. 140–147.

[9] P. L. Ziemer, W. C. McArthur, V. L. McManaman, and G. D. Smith, "Characteristics of selected phosphors for stimulated exoelectron emission dosimetry," in *Proc. 3rd Int. Conf. Luminescence Dosimetry*, Danish AEC, Riso, Roskilde, Denmark, RISO Rep. 249, 1972.

Environmentally Controlled Waveguide Irradiation Facility

HENRY S. HO, MEMBER, IEEE, EDWARD I. GINNS, AND CHRISTOPHER L. CHRISTMAN, MEMBER, IEEE

***Abstract*—Research has shown that the determination of absorbed microwave energy as well as the control of environmental parameters are important in relating biological-effect data to radiation protection. This short paper describes the development of an environmentally controlled waveguide irradiation facility for the exposure of small animals to 2450-MHz CW microwave energy. Integral dose rate is determined without perturbing the microwave field interacting with the irradiated animal.**

Glossary

Exposure Rate: Incident power density (mW/cm^2) of an EM wave.

Integral Dose Rate: Time rate of absorption of EM energy (W) by the entire biological body.

Integral Dose: Total amount of EM energy (J or cal) absorbed by the entire biological body.

Average Dose: Integral dose per unit weight of the animal (J/g or cal/g).

Distributed Dose Rate: Time rate of absorption of microwave energy per unit mass (W/kg or W/g). It is usually nonuniform in biological bodies even though the incident power density (exposure rate) may be uniform.

Manuscript received May 10, 1973; revised August 8, 1973.
The authors are with the Division of Biological Effects, Bureau of Radiological Health, FDA, USPHS, Rockville, Md. 20852.