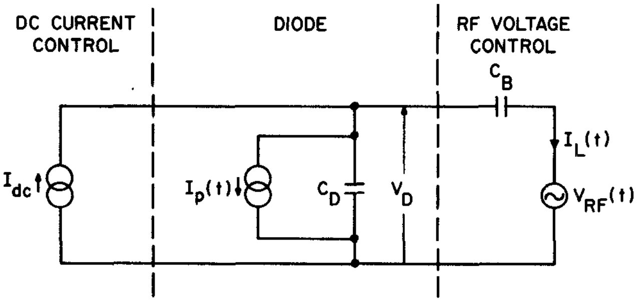

Fig. 3. Load configuration for dc current and RF voltage control.

If $V_{RF}(t) = V_{RF}\sin \omega t$ and $I_p(t)$ is assumed to vary linearly between $I_p(t_0)$ and $I_p(t_0 + \Delta t)$, then

$$V_D(t_0 + \Delta t) = V_D(t_0) + (C_B + C_D)^{-1} \cdot \left(I_{dc}\Delta t + \frac{\Delta t}{2}\left[I_p(t_0 + \Delta t) + I_p(t_0) \right] + C_B V_{RF}\left[\sin \omega (t_0 + \Delta t) - \sin \omega t_0 \right] \right).$$

The value of C_B is chosen to avoid parametric and bias instabilities [3].

ACKNOWLEDGMENT

It is a pleasure to acknowledge useful discussions with Mr. J. East, Dr. R. K. Mains, and Professors G. I. Haddad and D. F. Peterson.

REFERENCES

[1] K. Hiraoka, "Transient analysis of two semiconductor devices under circuit-loaded conditions," *IEEE Trans. Electron Devices*, vol. ED-29, pp. 1617–1621, Oct. 1982.
[2] W. J. Evans and D. L. Scharfetter, "Characterization of avalanche diode TRAPATT oscillators," *IEEE Trans. Electron Devices*, vol. ED-17, pp. 397–404, May 1970.
[3] T. J. Brazil and S. O. Scanlan, "Self-consistent solutions for IMPATT diode networks," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 26–31, Jan. 1981.
[4] R. K. Mains, N. A. Masnari, and G. I. Haddad, "Theoretical investigations of TRAPATT amplifier operation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 1070–1076, Oct. 1980.
[5] P. A. Blakey, R. A. Giblin, and A. J. Seeds, "Large-signal, time-domain modeling of avalanche diodes," *IEEE Trans. Electron Devices*, vol. ED-26, pp. 1718–1728, Nov. 1979.
[6] R. K. Froelich, "Computer modeling of millimeter-wave IMPATT diodes," Ph.D. dissertation, The University of Michigan, Ann Arbor, MI, May 1982.
[7] D. Potter, *Computational Physics*. New York: Wiley-Interscience, pp. 88–91, 1973.

Letters

Comment on "Heat Transfer in Surface-Cooled Objects Subject to Microwave Heating"

T. C. GUO, SENIOR MEMBER, IEEE, W. W. GUO, SENIOR MEMBER, IEEE, L. E. LARSEN, SENIOR MEMBER, IEEE, AND J. H. JACOBI, SENIOR MEMBER, IEEE

In the above paper[1], Foster *et al.* derived the following equation for the temperature T^* at the center of a spherical tissue:

$$T^* - T_0 = \frac{Qa^2}{6k}\left(1 + \frac{2}{\mathrm{Bi}(U_\infty)}\right) \quad (1)$$

where T_0 is ambient temperature of the cooling fluid, Q the volumetric heat generation by the microwave irradiation, a the radius of the sphere, k the thermal conductivity of the tissue, U_∞ the free-stream velocity of the cooling fluid, and Bi the Biot number. The value of $2/\mathrm{Bi}$ depends on the coolant-flow velocity, vanishing for rapid coolant flow and approaching $2k/k_f$ for a stagnant coolant, with k_f being the thermal conductivity of the coolant.

While the above formulation agrees with our recent conclusions [2], Foster *et al.* have exaggerated the expected temperature rise for ocular lens by statements in the abstract and the concluding remarks. Take $k = 0.7k_f$ and $Q = 100$ mW/cm^3, as the authors suggested, and $k_f = 6.23$ mW/cm $-$ °C, then the temperature rise at the center of a spherical tissue with 0.15-cm radius is between 0.086°C and 0.21°C, where the upper limit applies to a spherical tissue in a stagnant coolant. With respect to thermally mediated pathogenicity, this range of temperature increase is negligible; but the authors stated in the abstract that there would be significant temperature rise without providing a specific value or justification.

Foster *et al* are frankly mistaken in their calculation of the temperature gradient in the ocular studies of Stewart-DeHaan *et al.* The authors stated that "the maximum temperature increase is 0.6°C to 6°C for SAR's of 120 mW/g to 1200 mW/g." This value is erroneous since it is based upon a lens diameter of 0.7 cm. Such a value is more suitable for bovine than murine subjects. Since the gradient is a function of the radius squared, a difference between an assumed radius of 0.35 cm as opposed to an actual radius of 0.15-cm accounts for the difference between our result of ca. 1°C and their result of ca. 6°C at the highest SAR. Obviously, the gradient scales linearly with SAR such that at the lowest SAR the gradient is comparable to the noise in the thermoregulator.

Manuscript received December 20, 1982.
T. C. Guo and W. W. Guo are with the Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20707.
L. E. Larsen and J. H. Jacobi are with the Walter Reed Army Institute of Research, Washington, D.C.
[1]Foster *et al.*, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1158–1166, Aug. 1982.

0018-9480/83/0900-0783$01.00 ©1983 IEEE

Further, Foster *et al.* indicate that the 6°C gradient may be conservative in as much as that value depends upon coolant flow. Since the flow was ca. 10 cm/s, the coolant flow was well beyond that needed to assure an adequate Reynolds number.

In a recently reported experiment [2], rats of controlled weight with a measured ocular lens radius of typically 0.15 cm were irradiated at 918 MHz with values of Q ranging from 40 to 1200 mW/cm^3, while simultaneously being cooled and tumbled by a 10-cm/s flow of phosphate-buffered saline. The range of temperature elevations at the center of the lenses is then, with the term 2/Bi in (1) equal to 0.12 (assuming $k = 0.7\ k_f$), from 0.04 to 1.16°C, which is still far from being significant [3].

The temperature rise cited above is based on the assumption that $k = 0.7 k_f$, which is disputable. As far as we know, no data exists on murine lens thermal conductivity. Instead, Guy *et al.* [4] suggest a value of about 1/2 that of water based upon scaling thermal and electrical conductivity by reference to normal saline *vis a vis* vitreous humor. This assumption is conventionally based on a measured value of electric conductivity σ, by assuming that k/σ for the tissue is equal to k/σ for a 0.9-percent solution of NaCl in water, for which both k and σ are well known. Although the constancy of the ratio of thermal-to-electric conductivities in metals has been established empirically (the Wiedemann–Franz Law) and theoretically derived [5], there is neither experimental evidence nor theoretical foundation to extend this law to dielectric liquids or to dielectric solids. In metals, both thermal conduction and electric conduction are carried by the electrons in the conduction band, whereas in liquids the electric conduction is carried by the ions on one hand and the thermal conduction is carried by collisions of all molecules on the other hand. Classical references as in the paper by Jager [6] indicate clearly that the pertinent parameter in electrolyte thermal conductivity is the percent weight of solute, not electrical conductivity.

Foster *et al.* assumed a value of thermal conductivity to be 7/10 that of water. We object to that assertion as well. Others have taken the value of ocular-lens thermal conductivity to be 87 percent that of water [7], [8]. The lens is unique among tissues by virtue of the protein concentration gradient tapering from ca. 5 percent to ca. 60 percent from capsule to nucleus [9]. The high solute content may be expected to alter thermal conductivity over that of the solvent (probably by only a few percent, judging by the electrolyte case). Further, the lens may be unique in its percentage of bound water. Estimates of the percentage of bound water in lens range from 20–60 percent of the total water. The structured water would tend to increase thermal conductivity. We note that ice, for example, has a thermal conductivity more than three times that of water. Thus the high protein content leading to the large fraction of the structured water in lens may be expected to increase thermal conductivity over that of the solvent. The electrolyte contribution is less clear in as much as electrolyte effects on thermal conductivity depend upon both the concentration and the ion species. Reidel [10] has derived an expression of the thermal conductivity of electrolyte which is

$$\lambda_s = \lambda_w + \sum \alpha_i C_i \tag{2}$$

where λ_s is the thermal conductivity of the solution, λ_w is the thermal conductivity of the water, α_i is an empirical constant for each ionic species, and C_i is the concentration (moles/liter of solution) of each species. In the case of cations, the values of α_i are negative except for sodium. In the case of anions, the values are variously positive (phosphate, chromate, sulphate, and hydroxy) while most are negative (notably chloride) [11]. The absolute values for α_i, generally, range from 10^{-2} to 10^{-3}. The situation is further complicated by the fact that additional correction factors are needed for pH. In alkaline solutions, the conductivity may go up for a 10-percent solution but go down for a 20-percent solution, and higher concentrations. On the basis of these arguments and the lack of usable empirical data we, therefore, believe that the thermal conductivity of water is a useful estimate of the thermal conductivity of an ocular lens. If the calculations are done for $k = k_f$, the temperature gradient falls from ca. 1°C to ca. 3/4°C at the highest SAR.

Finally, it is pertinent to recognize the spatial distribution of lesions in the lens as reported by Stewart-DeHaan *et al.* The lower SAR cases demonstrated lens abnormalities in the epithelium and cortex, not in the nucleus. Since the thermal gradient is virtually zero in epithelium and cortex even in the highest SAR case, the role of thermalization cannot be considered the dominant factor. The authors correctly concur that in any case, the pulse/CW comparisons are independant of thermal-gradient considerations.

Reply[2] *by K. R. Foster, et al.*[3]

The above letter disputes our suggestion that heating effects were "probably significant" in experiments by Stewart-DeHaan *et al.* [12], in which rat lenses were subject to intense microwave energy while being simultaneously cooled by flowing saline. Our comment was motivated in part by simple calculations based on heat transfer theory [1] and by the authors' own conclusions that the damage observed subsequent to microwave irradiation resembles that produced by simply heating the lenses by about 10°C.

To address the points that were raised above, we agree that the proposed radius of the lens is a better guess for an equivalent radius than the value we rather arbitrarily chose. We disagree with the estimate of the thermal conductivity of the tissue. While the thermal conductivity of the rat lens has apparently never been measured, that of various concentrated protein solutions has, and is known to closely follow the Maxwell–Eucken equation with an intrinsic conductivity of 0.31 times that of water [13]. This provides a basis for estimating the thermal conductivity of the lens without the need for the speculative arguments in the above letter. Since the protein content of the rat lens is about 45 wt % for the whole lens, and about 0.92 g/cm^3 for the nucleus [9] we expect the thermal conductivity of the tissue should be 0.68 times that of water (an average value for the entire lens) and 0.48 that of water (for the nucleus). These calculations assume the partial specific volume of the lens protein to be 0.77 cm^3/g which is typical of proteins in general. We know of no evidence that the thermal conductivity of "bound" water is different from that of the bulk liquid. At the highest level of irradiation, even the choice of parameters in the above letter leads to predictions of a maximum temperature increase of a degree or so, provided that the lens is "optimally" cooled so that its surface temperature is everywhere equal to that of the coolant. Comparable temperature

[2]Manuscript received April 11, 1983.
[3]The authors are with the Departments of Bioengineering and Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104.

increases led to lenticular damage in the control experiments. Thus heating effects are to be presumed significant until experimentally shown otherwise.

The above writers argue against a far stronger claim about their study [12] than was actually made. Moreover, their comments pertain to a paper [2] that appeared some months after our own. For several reasons, neither the calculations of the above authors, nor the experimental evidence in [2, 12] seems able to refute our suggestion, even when extended to the more recent paper.

First, the actual temperature rise within the lens will exceed the minimum values calculated above, by an amount that depends on the very uncertain heat transfer characteristics of the exposure chamber. It appears from sketches in the paper by Stewart-DeHaan *et al.* [12] and the more recent paper [2] that the lens was located at the bottom of a perforated glass tube through and around which the coolant was pumped. The theory that is cited in the above letter pertains to an isolated object located in an unbounded coolant flow, which is quite different from the actual situation. If saline were trapped between the glass surface and the lens and subsequently heated by the microwave energy, or if a substantial portion of the surface of the lens were occluded from the coolant flow by its contact with the glass support, calculations assuming "optimal" cooling would seriously underestimate the temperature rise within the tissue.

Second, the portion of the experimental observations that cannot arise from bulk heating is unknown. Both [12] and [2] reported that damage was observed after exposure to CW microwave energy, that was somewhat less than that observed after exposure to pulsed fields with the same time-averaged SAR, but the results from the CW exposures were not presented for comparison. Presumably, some of the effects that are referred to in the above letter are observed only after exposure to pulse-modulated fields of high-peak SAR and result from other stresses than bulk temperature rise. However, the damage was correlated in [12] and [2] with variations in only one field parameter, the time-averaged transmitted power from the generator. If the experiment was well controlled, this would be proportional to the bulk temperature rise in the lens. Therefore, there is fundamentally no way to experimentally separate bulk heating from "nonthermal" effects from the data that are given, without the rather questionable speculations in the above letter. And there is at present no other established mechanism for microwave-induced damage to the lens. It might be, as the above writers suggest, that their results are completely unexplained, but that does not appear to us to be a constructive argument.

The above comments were limited to the physics of the experiment. The more important question is what was the mechanism for the damage that was observed. This question can only be answered by the experimentalists themselves. Nevertheless, we offer the following observation. It appears that the lenses were cooled by calcium-free solutions during irradiation. Brief exposure to calcium-free media will produce damage in (calf) lenses that resembles that reported in [12] and [2] subsequent to microwave irradiation. (J. I. Clark et al., "Cortical opacity, calcium concentration and fiber membrane structure in the calf lens", *Exp. Eye Res.*, vol. 31, 399–410, 1980). Calcium removal, being a diffusion-controlled process, might be expected to depend critically on the temperature of the lens and other experimental factors. Moreover, it is widely considered that calcium efflux from tissues is sensitive to perturbation by electromagnetic fields, although the physical mechanism is not yet established.

References

[1] K. R. Foster, P. S. Ayyaswamy, T. Sundararajan, and K. Ramakrishna, "Heat transfer in surface-cooled objects subject to microwave heating," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1158–1166, Aug. 1982.

[2] P. J. Stewart-DeHaan, M. O. Creighton, L. E. Larsen, J. H. Jacobi, W. M. Moss, M. Sanwal, T. C. Guo, W. W. Guo, and J. R. Trevithick, "*In vitro* studies of microwave-induced cataract: Separation of field and heating effects," *J. Exp. Eye Res.*, vol. 36, pp. 75–90, 1983.

[3] P. O. Kramar, A. F. Emery, A. W. Guy, and J. C. Lin, "The ocular effects of microwaves on hypothermic rabbits: A study of microwave cataractogenic mechanisms," *Ann. New York Acad. Sci.*, vol. 247, pp. 155–164, 1975.

[4] A. W. Guy, J. C. Lin, P. O. Kramar, and A. F. Emery, "Effect of 2450 MHz radiation on the rabbit eye," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 492–498, 1975.

[5] P. Drude, *Ann. Physik*, vol. 1, p. 566, and vol. 3, pp. 370, 869, 1900; also H. A. Lorentz, *Electroentheorie der Metalle*. Leipzig, 1909.

[6] G. Jager, "Ueber die Wärmeleitungsfähigkeit der Salzlösungen," *Repertorium der Physik*, vol. 27, pp. 42–60, 1891

[7] P. S. Neelakantaswamy, and K. P. Ramakrishnan, "Microwave-induced nonlinear thermoelastic vibrations of the ocular lens in the human eye," *J. Biomechanics*, vol. 12, pp. 205–210, 1979.

[8] ——, "Microwave-induced hazardous thermal stresses in the ocular lens of the human eye," *Biomedizinische Technik*, vol. 23, pp. 109–113, 1978.

[9] B. Philipson, "Distribution of protein within the normal rat lens," *Invest. Opthal*, vol. 8, pp. 258–270, 1969.

[10] L. Riedel, "Warmelect fähigkeitsmessunges an natronund kalilange verschiedarer kanzentration und temperatur," *Chemie Ingenieur-Technik*, vol. 22, pp. 54–57, 1950.

[11] N. V. Tsederberg, *Thermal Conductivity of Gases and Liquids*. Cambridge, MA: MIT Press, ch. X, 1975.

[12] P. J. Stewart-DeHaan, M. O. Creighton, L. E. Larson, J. H. Jacobi, W. M. Ross, and J. R. Trevithick, "Microwave and temperature effects on the murine ocular lens *in vitro*," in *Proc. 1980 IEEE MTT-S Int. Symp.*, 1980, pp. 341–344.

[13] J. Y. Kong, "The 'intrinsic' thermal conductivity of some wet proteins in relation to their hydrophobicity: Analysis on gelatine gel," *Agri. Biolog. Chem.*, vol. 46, pp. 783–788, 1982.

Comments on "Hollow Image Guide and Overlayed Image Guide Coupler"

A. PRIETO, E. RUBIO, J. RODRIGUEZ, and J. L. GARCIA

The authors of the above paper[1] failed to acknowledge several publications dedicated to the same subject. The so-called hollow image guide has already been studied by the E.D.C. method with the name of π guide, as well as another dielectric structure named T guide [2]. The same paper shows a good agreement between the theoretical and the experimental results which were measured by means of a movable electric field probe with the end of the dielectric waveguides finished in a short circuit.

In a second paper published later [3], we have studied the former dielectric guides and the image guide, the isolated image guide and the inverted strip dielectric waveguide by Schelkunoff's method. This study allows us to determine the dielectric and metallic losses presented by any kind of dielectric guide. We have also proven that being the guides equivalent (with the same transversal surface), the losses of guides T and π are similar, and lower than the equivalent image guide. However, the quality

Manuscript received April 12, 1983.

The authors are with the Departamento de Electricidad y Magnetismo, Facultad de Ciencias, Universidad de Santander, Santander, Spain.

[1] J. F. Miao and T Itoh, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1826–1831, Nov. 1982.

0018-9480/83/0900-0785$01.00 ©1983 IEEE