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Quantifying Hazardous Electromagnetic Fields: Practical Considerations

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QUANTIFYING HAZARDOUS ELECTROMAGNETIC FIELDS: PRACTICAL CONSIDERATIONS* †

Ronald R. Bowman

Abstract- The usefulness of power density to express the hazard potential of electromagnetic fields is limited to simple fields that are approximately uniform and plane wave. For fields that are complicated by having reactive components or by having multipath interference patterns, power density is not a suitable parameter for quantifying the potential hazards because: (a) such fields can be very strong even though the power density is small, and (b) the power density in such fields is very difficult to measure. Since some of the most important hazardous fields can involve very complicated field configurations (for instance, fields near leaking cracks in microwave ovens), it is important to establish a more rational measure for hazardous fields. A qualitative discussion is given of the many issues involved in selecting a suitable field parameter for quantifying hazardous electromagnetic fields in general. It is concluded that the total energy density of the field is the best parameter, but in many instances the electric energy density alone will be adequate. Some general discussion is given concerning "ideal" instrumentation for quantifying hazardous fields.

Key Words: electromagnetic fields; hazards; quantifying; field parameters; instrumentation.

1. Introduction

The discussion by P.F. Wacker in Technical Note 391 is concerned primarily with analysis and with the problem of realizing an accurate probe for quantifying hazardous electromagnetic (EM) fields under very general conditions. In contrast, the present paper is concerned mainly with the problem of making easy, reasonably accurate

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† This paper is essentially identical to one prepared for the Symposium on the Biological Effects and Health Implications of Microwave Radiation, Richmond, Virginia, September 17 through 19, 1969.

survey measurements of hazardous EM fields. For general survey use, instruments should be rugged, easy-to-use, and should be capable of fast response as well as having long-term averaging capabilities. These, and other considerations to be discussed, place restrictions on practical instrument designs for general survey use.

It is very difficult to determine, even with reasonable accuracy, the biological hazards associated with EM fields. Even in the simple case of a plane-wave field with uniform power density, the energy absorption by biological material is quite complicated[1]. At the present time, only the hazards related to uniform plane waves in free space (i.e., far from the source and any scattering objects) have received extensive study; and the standards, terminology, and most of the measuring instrumentation pertain only to this simple case. Apparently, this is why "power density" (i.e., the time-averaged magnitude of the Poynting vector)[2] is the presently used quantity for stating hazardous EM field levels, despite the serious objections to this practice raised here and by Wacker in Technical Note 391. Since the usefulness of power density to quantify hazardous EM fields is questionable except for uniform plane-wave fields and since some of the most important hazardous EM fields involve very complicated field configurations (for instance, fields near leaking cracks in microwave ovens), it is important to establish a more rational measure.

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[1] See, for instance, H.P. Schwan, "Radiation Biology, Medical Applications, and Radiation Hazards", in Microwave Power Engineering, vol 2, edited by Ernest C. Okress, Academic Press, New York, 1968).

[2] Poynting's interpretation of the energy density and power flow in electromagnetic fields is subject to philosophical difficulties. See footnote 1 in Technical Note 391. Also, see D.S. Jones, The Theory of Electromagnetism, MacMillan, N.Y., N.Y., 1964, pp. 51-53. These considerations are beyond the scope of this paper, and they will not involve us in any concrete errors.

Many complicated issues are involved in selecting a suitable parameter for quantifying hazardous EM fields. The discussion here will be qualitative and is intended merely as a sketchy introduction to the complications considered. It is hoped that the discussion will clarify the basic issues.

2. Complexities of Electromagnetic Fields.

2.0 Discussion.

Undoubtedly, another reason that the use of power density (i.e., energy flow) has become established is that energy flow presents a simple conceptual picture of the interaction of the field with matter. Unfortunately, this conceptual picture is often very inaccurate. EM fields with frequencies below about 10 GHz do not bear much analogy with optical radiation or ionizing radiation. However, they do bear some analogy with audible sonic fields because of the comparable wavelengths involved. The free-space wavelength of a plane-wave 1000 MHz EM field is about 30 cm, and the free-space wavelength of a plane-wave 1000 Hz sonic field is also about 30 cm. Of course, plane-wave EM radiation involves transverse rather than longitudinal vibrations so that polarization is an important additional complication of EM radiation, but otherwise there are useful analogies between microwaves and audio waves. Some of these analogies will be used below in discussing the complexities that will commonly be encountered when surveying for hazardous EM fields.

2.1 Elliptical Polarization.

In general, the tip of the electric vector (or of the magnetic vector) will trace an ellipse if the vector is plotted as a function of time. Except for the rotational sense, the polarization of the field can be specified by the axial ratio of the ellipse. Radar, telemetry, and communications systems normally use antennas with either linear or circular far-field polarization, which are special cases of elliptical polarization; but at points near the transmitters of these systems, the polarization can be arbitrary. Very often, the polarization of the field will not be known when making hazard surveys. Furthermore, the polarization of the field may change radically from point to point within the field. For instance, if a microwave oven has a leak from a horizontal crack and also a leak from a vertical crack, the polarization of the resulting field will vary in a very complicated way in the region around the oven. (It should be mentioned that polarization is usually only defined with respect to plane wave propagation. However, it is possible to define polarization for arbitrary waves[3], and it is this general situation that is of interest for hazard surveys.)

2.2 Multipath Interference.

Propagation of fields of the same frequency to a given region of space will cause interference patterns ("standing waves"). This is a familiar phenomenon with sound waves, and the spacing between positions of constructive and destructive interference for audible sound waves will be roughly equal to those for microwave multipath interference because of the comparable wavelengths involved. The net power density in multipath fields can be less than the power density of the individual component waves considered separately. In particular, two plane-wave fields of equal amplitude and frequency but opposite propagation directions combine to give a field with zero net power density. However, the combined field will have electric and magnetic field maxima of twice the amplitude of the component waves. Clearly, if the two component waves are each hazardous, then the combined field is also hazardous despite the fact that the power density is zero. Similar difficulties occur in

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[3] Born and Wolf, Principles of Optics (second revised edition), MacMillan, N.Y., N.Y., 1964, pp. 34-36.

attempting to relate the power density of multipath fields in general to potential hazards. Therefore, power density is a poor indicator of the potential hazards of multipath fields.

2.3 Reactive Near-Field Components.

Within distances of roughly one wavelength of some sources (for instance, inefficient radiators), there can sometimes exist strong EM field components that do not have a time-averaged energy flow (though they will have instantaneous energy flows). That is, the total field in these regions can be divided into a radiation component and reactive components (see almost any text on electromagnetic theory); and the time-average of the Poynting vector for the reactive field components is identically zero. The radiation field represents a flow of energy away from the source, but the reactive field has no corresponding energy loss. The energy associated with reactive fields pulses back and forth between the source and the surrounding space during the period of the oscillation, similar to the energy flow between capacitances and inductances in electrical circuits. (This situation is analagous to the operation of an unbaffled speaker cone. At low audio frequencies, i.e., for wavelengths larger than the dimensions of the cone, a speaker cone operating in open air is an inefficient radiator because the air propelled by the cone merely rushes around to the reverse side of the cone. This produces relatively little sound radiation to points far from the cone even though the instantaneous air flow around the cone can be very great.)

2.4 Interactions Between the Source and Nearby Objects.

A measuring instrument, subject, etc. placed near to a source can establish multiple propagation back-and-forth between the object and the source. This interaction can involve both scattering from the external surfaces of the source and also coupling with the internal regions of the source. In one sense, this can be considered as a complicated case of multipath interference, but it should be remembered that the coupling with the internal regions of the source can substantially (even greatly) change the total amount of energy withdrawn from the source. This interaction can be exceedingly complicated and is determined, for a given wavelength, not only by the electrical composition of the source, the object of interest, and other nearby objects but also by the sizes, shapes, positions, and orientations involved.

2.5 Complicated Time Variation of the Configuration and Intensity of the Field.

We are not concerned here with the periodic variation of the field vectors at the radio frequency. Rather, we are concerned with the longer term variation in the configuration of the field and in the amplitudes of the electric and magnetic vectors. Consider, for instance, a microwave oven that has two widely-separated leakage cracks. Since the microwave sources in many ovens are operated from unfiltered power supplies, the field created by the leakage from these cracks may go on and off at twice the power-line frequency. Further, since most ovens have "mode" stirrers (metal vanes that rotate, typically, every few seconds to "stir" the field configuration inside the oven), the phase and amplitude of the field just outside each crack may change radically every few seconds, independently of the other crack. The resulting time variation in the multipath field outside the oven can be extremely complicated. (It is pertinent to note that a leakage crack in an oven may leak only for the fraction of a cycle of the mode stirrer. Therefore, it is possible for the peak-to-average ratio to be quite high for microwave oven leakage.)

3. Approaches to Quantifying EM Hazards.

3.1 The Dosimetry Approach.

In surveying for hazardous EM fields, one wishes to determine as accurately as possible the potential biological dose (e.g., the temperature rise) or the exposure (e.g., the induced currents or the EM field established) that would result at points of interest inside a subject if introduced into the field. In general, because of the complications mentioned in Section 2, it is not practical to accurately predict the biological dose or exposure from knowledge of the parameters of the unperturbed field (i.e., the field before the biological material is introduced). This means that accurate dosimetry for EM field hazards must be done with phantoms that simulate not only the electrical characteristics of the body but also the size and, to a lesser degree, the shape of the body. Probably, a head-sized sphere or ovoid would suffice for a phantom in most situations of interest. At points inside the phantom, the thermal dose could be measured by the temperature rise or the exposure measured by the currents or the EM field established. The usefulness of this type of instrument is limited because the size and weight of the phantom would seriously hamper general survey measurements of potentially hazardous EM fields. Therefore, even though the dosimetry approach is most accurate, it is felt that it will probably not be used much outside of the laboratory.

3.2 The Field Parameter Approach.

This approach assumes that the biological effects, or at least the possible effects, resulting from the EM field can be adequately predicted from knowledge of one or more parameters that describe the field.

Because the biological effects are so difficult to predict, this approach will always involve a conservative standard for the maximum allowable level of the field parameter used to quantify the field. Though this approach is somewhat arbitrary, it is felt that it is the most practical approach to the problem of making general survey measurements. Some discussion about the choice of a suitable field parameter and the general characteristics of suitable instrumentation will be given later.

3.3 <u>The Arbitrary Approach.</u>

This approach would use an instrument that would respond to the EM field but would not, in general, yield an accurate measurement of either the dose that could be expected from the field or one of the parameters of the unperturbed field. For instance, suppose that the instrument is based on the temperature rise in a small piece of material that simulates only the electrical characteristics of biological material. Since a small piece of material cannot adequately mimic the energy absorption of, say, a human head, this instrument could not be expected to yield an accurate measurement of the dose resulting from complicated EM fields. Further, unless the piece of absorbing material is quite small, the instrument will strongly affect the field near, say, a radiating crack; and thus, a measurement of the unperturbed field would be practically impossible. (If the piece of absorbing material is quite small, it could, under certain conditions, provide an accurate measurement of some parameter of the unperturbed field; but then the instrument would satisfy the more stringent approach outlined in Section 3.2).

The arbitrary approach is considered to be the least satisfactory of the three approaches outlined. However, until very recently, it was the approach that was used in practice due to a lack of better instrumentation. That is, until recently, instruments suitable only for uniform plane-wave fields (and in some cases only linearly polarized fields) were used to measure leakage from ovens at points close to the leaking cracks. Very little quantitative meaning can be assigned to such measurements, though they are probably adequate to establish rough estimates of the hazards involved.

4. Choosing a Suitable Field Parameter for Quantifying Hazardous EM Fields.

4.1 Parameters for Describing Uniform Plane-Wave Fields.

For a uniform plane-wave field traveling in free space, very simple relationships exist between the magnitude E of the electric vector (i.e., the electric field strength), the magnitude H of the magnetic vector (i.e., the magnetic field strength), the time-average S of the energy flow (i.e., the power density), the time-average U_E of the electric field energy density function (i.e., the electric energy density), the time-average U_H of the magnetic field energy density function (i.e., the magnetic energy density), and the time-average U of the electromagnetic field energy density function (i.e., the total energy density). Using root-mean-square values, these simple relationships are as follows:

$$\frac{E}{H} = Z_o \quad \text{(the intrinsic impedance of vacuum)} \tag{1}$$

$$Z_o = \left(\frac{\mu_o}{\epsilon_o}\right)^{1/2} \tag{2}$$

$$S = \frac{E^2}{Z_o} = Z_o H^2 \tag{3}$$

$$U = \frac{1}{2}\left(\epsilon_o E^2 + \mu_o H^2\right) \equiv \left(U_E + U_H\right) \tag{4}$$

$$\frac{U_E}{U_H} = 1 \tag{5}$$

For such fields, the energy density can be considered as propagating through the field point with the speed of light, c. That is,

$$S = cU \tag{6}$$

For comparison, if a uniform plane-wave field has a power density of 10 mW per square cm, the total energy density is $\frac{1}{3}$ pJ per cubic cm (picojoules per cubic cm), and the electric field strength is 1.94 volts per cm.

Because of the simplicity of relations (1) through (6), the "intensity" of this very simple type of EM field can be adequately described by any one of the parameters defined above. However, not all of these parameters are adequate for describing the "intensity" of complicated EM fields. Further, in choosing a suitable parameter for characterizing the "intensity" of complicated fields with respect to biological hazards, one must consider the manner in which biological material interacts with EM fields.

4.2 The Interaction of Biological Material with Electromagnetic Fields.

It will be assumed here that there are no significant "non-thermal" biological effects due to the magnetic component of the field. Then, since biological material does not normally contain more than minute amounts of lossy magnetic substances, there is no significant direct interaction of the magnetic field with biological material. It is emphasized, however, that energy associated with the magnetic field will be indirectly absorbed in the biological material. That is, if the electric field penetration into the material is "damped" because of dielectric losses, energy associated with the magnetic field will be absorbed also. This consideration could be particularly important when interference fields or reactive field components exist since the penetration of the electric field could be considerably greater than one would expect based on "plane wave" absorption concepts.

4.3 Choosing Suitable Field Parameters.

As indicated in the last section, both the thermal and the non-thermal biological effects are caused by the internal electric field. The problem is to determine the most suitable parameter or set of parameters for relating unperturbed fields to the maximum possible internal electric fields resulting when a subject is placed at any possible position and with any possible orientation in the unperturbed fields. Because the resulting internal fields are generally extremely difficult to relate to the unperturbed fields, this problem can not be resolved without introducing simplifications, some of them rather arbitrary. Since it would go beyond the scope of this paper to adequately justify the following statement, it will be merely asserted that: the potential hazards of unperturbed electromagnetic fields are, in general, most closely associated with the electric components of the fields except possibly (a) near the magnetic field maxima in multipath fields and (b) for some reactive near-fields. For the exceptions, the magnetic components of the fields may be equally or more important than the electric components.

The "suitability" of a field parameter for quantifying hazardous EM fields is dependent both on the relevancy of the parameter to the potential hazard and on the ease of measuring the parameter. Except for very simple fields, power density is least suitable because (a) the power density of some very strong fields can be small, and (b) power density is a relatively difficult parameter to measure. The difficulties involved in measuring power density[4] follow from the fact that the power density is given by the time average of $|\overline{E} X \overline{H}|$. Certainly, in complicated

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[4] For some of the difficulties involved in measuring power density, see Moore School Report 63-13, "Study of power density measurement techniques", University of Pennsylvania, Moore School of Electrical Engineering, January 31, 1963 or
Moore School Report No. 63-23, "Feasibility studies of Poynting vector measurements", University of Pennsylvania, Moore School of Electrical Engineering, July 31, 1963.

fields, it is much easier to measure E and H, which are scalars, than it is to measure the time average of $|\bar{E}X\bar{H}|$. The electric and magnetic energy densities are also relatively easy to determine since the simple relations (4) also hold for complicated fields. That is, the electric or magnetic energy density can easily be calculated from E or H; and instruments that respond to E or H can easily be engineered to display U_E or U_H. As shown by Wacker in Technical Note 391, it is even feasible to measure the total energy density with a single sensor. Except, perhaps, for non-thermal biological effects, it is felt that U, U_E, and U_H are the most suitable parameters for quantifying the potential hazards because: (a) the thermal heating is proportional to the squares of E and H, and therefore, directly proportional to U, U_E, and U_H; and (b) it is convenient to have the same units for stating the "intensities" of the total field, the electric field, and the magnetic field. The remaining discussion will be simplified by assuming that the EM field will be quantified in terms of energy density, though it is felt that E and H would also be satisfactory.

At frequencies above about 1 GHz, that is for wavelengths shorter than about 30 cm, a measurement of the electric energy density alone is probably adequate. In part, this simplification is possible because reactive fields are seldom stronger than radiation fields at distances greater than about one half wavelength from the source. Also, for wavelengths shorter than about 30 cm (and longer than about 3 cm), it is usually very easy to probe the interference patterns caused by multipath propagation and thus locate the electric field maxima. Then U_E for each maximum should be a reasonably good indication of the potential hazard in the immediate region of the maximum. Magnetic field maxima will exist between adjacent electric field maxima, but it is very unlikely that these magnetic field maxima will represent a greater hazard than the electric field maxima.

For wavelengths longer than about 30 cm, the magnetic energy density becomes increasingly important. At the present time, hazardous electromagnetic fields below about 1 GHz are not nearly so common as those at higher frequencies[5] so that the measurement of total energy density or of magnetic energy density is perhaps not a crucial issue. However, there are important needs for such measurements (for instance, around powerful radars that operate well below 1 GHz).

5. Instruments for Quantifying Hazardous Electromagnetic Fields.

5.1 General Characteristics.

From the preceeding discussions, it is felt that a good instrument for survey measurements of electromagnetic hazards should have the following characteristics;

(1) the instrument should measure in terms of energy density (or, alternatively, E and H);

(2) the sensor of the field probe should be much smaller than the shortest wavelength of the fields to be measured;

(3) the probe should not cause significant scattering of the field;

(4) the probe should be independent of its angular orientation in the field (i.e., independent of both the polarization of the field and the directions of the vectors of the field);

(5) the instrument should be capable of reading either peak or average values for complicated waveforms;

(6) the instrument should have a dynamic range of at least 20 dB without having to change probes;

(7) the instrument should be direct reading, that is it should not need a calibration chart, nulling, or frequent re-zeroing.

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[5] In large part, this situation is due to the existence of large numbers of microwave ovens.

In addition to the above characteristics, the instrument should, of course, be stable, rugged, lightweight, battery operated, etc..

5.2 Realization.

It is not apparent that instruments can be realized that have characteristics even approximating those outlined in the last section. Recently, commercial instruments have become available[6] that provide some of these characteristics, but it would appear that there is no available instrument that approximates a good instrument as defined here. However, these new instruments are vast improvements over previously available instrumentation, and they are considered to be very useful despite their limitations.

There are a number of possibilities for realizing "next generation" instruments (for instance, see the references outlined in Footnote 4). In fact, there are a number of efforts in progress to develop improved or lower cost instruments for measuring hazardous EM fields. It is felt likely that excellent instrumentation, at least for measuring U_E or E, can be realized.[7]

5.3 Dosimetry.

It is worth emphasizing that the problem of measuring the electric field strength E or the electric energy density U_E in complicated unperturbed fields is essentially the same problem as measuring the complicated internal electric field within a phantom. Therefore, if it is

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[6] See the paper by P.W. Crapuchettes presented at the Symposium on the Biological Effects and Health Implications of Microwave Radiation, Richmond, Virginia, September 17 through 19, 1969.

[7] As of January, 1970, a prototype instrument has been developed by the National Bureau of Standards, Boulder, Colorado. This instrument is limited to measuring U_E (or E), but otherwise it appears from preliminary tests to exceed the essential characteristics outlined in Section 5.1. Descriptions of this instrument will soon be available.

possible to realize an electric field measuring instrument having the characteristics outlined in Section 5.1 (having a very small field sensor in particular) it should be fairly easy to incorporate the sensor of this probe into a phantom to accurately measure the potential exposure (i.e., the dose rate) for very complicated fields. The realization of such a dosimeter is very important since much work needs to be done to determine the potential hazards of complicated fields and how these hazards relate to the parameters of the unperturbed fields.

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