RF HOT SPOT FIELDS: THE PROBLEM OF DETERMINING COMPLIANCE WITH THE ANSI RADIOFREQUENCY PROTECTION GUIDE

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ABSTRACT

Determining compliance with radiofrequency (RF) radiation guidelines of the Federal Communications Commission often requires measurements to assess the strength of the RF fields. A major issue in determining compliance with RF protection guides has been the treatment of so-called RF hot spots. This paper addresses RF hot spots by examining the peak specific absorption rate (SAR) which results from individuals contacting objects which are the source of hot-spot fields. Peak SAR was assesssed by measuring the contact current which flows between the hot-spot source and the individual touching the source and calculating the current density in the wrist which represents the area of smallest geometrical cross-section. SAR is proportional to the local current density and tissue conductivity. Several contrived situations including a resonant dipole, a metallic mail box, a filing cabinet, a simulated guy wire and an aluminum frame window in a wooden building were exposed to known RF fields for which surface fields and contact currents were measured. It was shown that the field strengths are not good indicators of either whole-body or local SAR in exposed individuals. In many cases where ambient fields are less than the RF guide but local, hot-spot fields exceed the guide, based on field strength, an evaluation of contact currents reveals that the underlying intent of the protection guide is not, in fact, exceeded.

BACKGROUND

Rarely is there ever an occasion when performing environmental surveys of radiofrequency (RF) fields that the issue of so-called RF hot spots does not come up or does not become a problem in making a decision about whether the site is in compliance with the RF protection guide (RFPG) recommended by the American National Standards Institute (ANSI). Actually, whether the exposure protection guide be the ANSI RFPG or some other guide, promulgated by a state, county or city, makes little difference; commonly, the individual performing the RF survey is ultimately confronted with the problem of interpreting the meaning of very localized regions in which the RF field strengths are excessive while the predominant field values in the general area are well below the RFPG. Figure 1 illustrates a common occurrence during field surveys where a metallic object can enhance the ambient fields in the general region. To what extent do these small regions of space count for declaring the site "off limits"? Can these local regions with high fields actually be considered hazardous despite the fact that most of the space surrounding these points shows field strengths no where near the exposure limits? How do these enhanced fields commonly found on the surface and very near to reradiating objects relate to absorption of RF energy in the body if a person is exposed? The subject of this paper evolved from an indepth consideration of these issues; this paper is an attempt to summarize the some of the key findings of this earlier study (Tell, 1989).

Hot spots occur anytime that ambient RF fields expose objects which are conductive; the RF fields induce currents in the object and these currents, in turn, lead to electric and magnetic fields being produced by the object. The fact that the strength of these surface fields is typically substantially greater than the fields in the surrounding area has led to the common name, RF hot spot. Hot-spot production is a natural and not unexpected consequence of the action of RF fields. That metallic objects like a curtain rod might act like a kind of antenna is not difficult to understand; but anything that is conductive, not just metal objects, will tend to do the same thing. The human body, for example, when illuminated with an RF field, will also exhibit hot-spot production; with outstretched arms in a very-high-frequency (VHF) field, one can easily verify this phenomenon by simply placing a RF sensing probe near the tip of the fingers and observing a substantially elevated field strength when compared to the value without the body present. So, the real issue is one of developing some insight to what these hot spots mean when compared to our understanding of antennas and other common experiences.

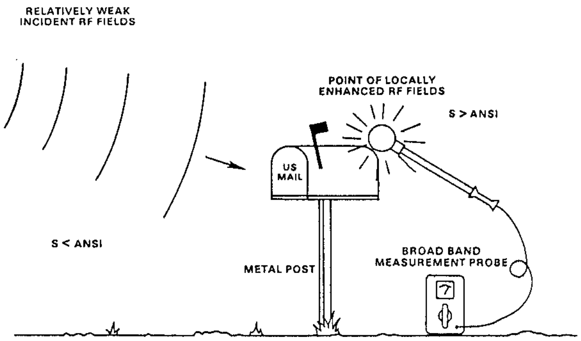

Figure 1. Metal objects exposed to weak ambient RF fields can produce enhanced field strengths near their surfaces, leading to apparent exceedances of applicable RFPGs.

The term hot spot, as used in this paper, refers to limited volumes of space in which RF field strengths are substantially greater than in the surrounding space. Reradiators are sometimes referred to as secondary radiators or scatterers; some form of passive object, a metal handrail, a curtain rod, a metal door handle, a mail box or a child's swing set can all meet the criteria for becoming a reradiator if ambient RF fields exist in its vicinity. Reradiating objects produce enhanced (elevated) RF fields which typically diminish to the ambient levels in the surrounding areas within very short distances of the source. Field strength reduction is generally exponential with the highest strengths on the surface of the reradiating object. Very often, reradiating fields have very high field impedances; i.e., the ratio of the electric and magnetic field strengths at the surface of the object is much larger than the free space impedance of 377 ohms. Reradiator hot spots are also characteristically highly non-uniform in their distribution on the reradiating object and are generally not amenable to calculation.

THE ANSI RFPG AND RELEVANT DOSIMETRY CONSIDERATIONS

Introduction

Interpreting human exposure to RF fields usually reduces to a comparison of measured field strengths with the limits specified in applicable RF protection guides (RFPGs). For purposes of this study, the relevant RFPG is that recommended by the American National Standards Institute (ANSI, 1982). The ANSI RFPG, as well as several other recommended limits on human exposure to RF fields including those of the International Radiation Protection Association (IRPA, 1988) and the National Council on Radiation Protection and Measurements (NCRP, 1986), is based on the observation that the vast majority of biological effects caused by RF fields in experimental animals are directly related to the rate at which RF energy is absorbed from the exposure field. The quantity used to specify energy absorption is called the specific absorption rate (SAR). The SAR is expressed in units of watts per kilogram of body mass (W/kg) and is related to the internal electric field strength in the tissue by the relationship:

$$SAR = sE^2/p \qquad [1]$$

where

SAR = specific absorption rate (W/kg);
s = conductivity (S/m);
E = electric field strength in tissue (V/m);
p = density of tissue (kg/m^3).

In practice, experimental studies of SAR in exposed objects rely on either a measurement of the field strength in the exposed tissue or the increase in temperature caused by absorption of the RF energy.

Through a critical examination of the technical literature, ANSI elected to use the SAR, determined as an average over the mass of the entire body, as a fundamental basis for the RFPG. But because direct measurements of whole-body averaged SAR in individuals is not practical, ANSI chose to establish guides on maximum values for the electric and magnetic field strengths or plane-wave equivalent power density. In actuality, the external field limits are in terms of the squares of the electric and magnetic field strengths (E^2 and H^2). For a plane wave in free space, the power density can be related to the squares of the electric and magnetic fields as follows:

$$S\ (mW/cm^2) = E^2/3770 = 37.7\ H^2 \qquad [2]$$

where

S = plane wave equivalent power density (mW/cm^2)
E = electric field strength (V/m)
H = magnetic field strength (A/m)

and the factors 3770 and 37.7 are factors associated with the impedance of free space (377 ohms) and conversion to appropriate units of milliwatts per square centimeter.

For convenience, ANSI chose to round the value for the impedance of free space from 377 ohms to 400 ohms. So, the actual ANSI limits are expressed in slightly different form from equation [2] as follows:

$$S\ (mW/cm^2) = E^2/4000 = 40\ H^2 \qquad [3]$$

Frequency dependence

To arrive at practical limits on the external exposure fields, both theoretical and experimental data have been developed to estimate the SARs associated with various field strengths and frequencies. Perhaps the first effort to examine the ability of the human body to act as an antenna was that of Andersen and Balling (1972). In this classic series of measurements, individuals were stood on a ground plane and the admittance and radiation efficiency of the human body was measured. Radiation efficiency was determined by comparing the apparent gain of the body to that of a metallic whip antenna. Thus, as early as 1972, the concept of body gain was introduced; Andersen and Balling reported that at a frequency of 60 MHz, the gain of the body was about -3 dB relative to that of a vertically polarized, perfect monopole.

More recently, extensive studies, notably by Gandhi and colleagues at the University of Utah and by Guy at the University of Washington, have been conducted. These studies have included experimental dosimetry studies based on calorimetric measurements and theoretical electromagnetic field calculations. Based on modeling the human body as the simplistic shape of a prolate spheroid having a uniform internal constituency, it was found that the body exhibited properties much like a radio antenna. These important findings described how the SAR varied as a function of frequency throughout the radio spectrum. Durney and co-workers have assembled several comprehensive treatments of RF dosimetry data during the past fourteen years (Johnson et al., 1976; Durney et al., 1978; 1980; 1986). The so-called standard man model consists of 70 kg of a muscle equivalent material having dielectric properties similar to muscle tissue and shaped as a prolate spheroid.

Since the SAR of the body will depend on the body dimensions, mainly the length of the body which is parallel to the electric field, there is a band of frequencies over which the SAR is at its maximum value depending on size. Hence, the ANSI RFPG is frequency dependent as shown in Figure 2. The region within the range of 30 to 300 MHz takes into account the fact that different size individuals are in the potentially exposed population, including very tall persons and small children. To compensate for this, the ANSI RFPG is most stringent in this so-called body resonance range of frequencies. At frequencies below body resonance, the SAR decreases typically inversely with the square of the frequency.

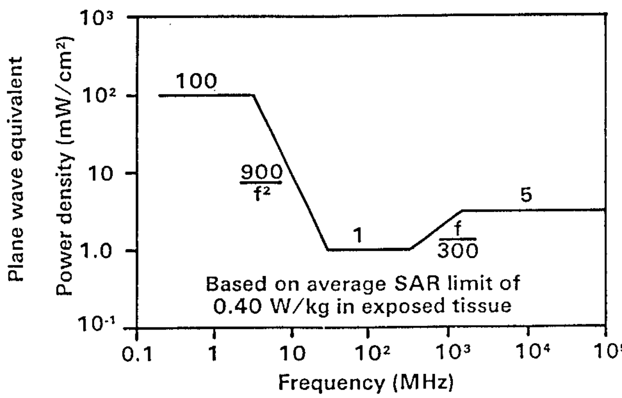

Figure 2. Frequency dependence of the ANSI RFPG (ANSI, 1982) for plane-wave equivalent power density. Values are to be time-averaged over any 6-minute period.

The ANSI RFPG field limits are based, however, not on free-space SARs but rather the SAR which occurs when an individual is standing on the ground. Under this circumstance, the body acts more like a monopole antenna above a ground plane and its gain is increased over that of the simple dipole suspended in space, far removed from ground and the resonance frequency is decreased. Results from Gandhi et al. (1977) have verified that the SAR of the grounded body is very close to about 0.4 W/kg/(mW/cm^2), being approximately 3 dB greater than for the free space situation. It is on the basis of grounded SARs that the field limits in the ANSI RFPG were derived, this being the more conservative case for exposure. Thus, in the body resonance range, the recommended power density limit is set at 1 mW/cm^2 which will result in limiting the whole-body SAR to 0.4 W/kg.

Local SAR Limitations

The underlying basis for the ANSI RFPG is limiting the whole-body averaged SAR to no more than 0.4 W/kg. This specific value is related to the observation in experimental animals exposed to strong RF fields that thermally mediated alterations in trained behavior were relatively reliably induced when the whole-body SAR reached a value of about 4 W/kg. ANSI incorporated a safety factor of ten in arriving at a working level of 0.4 W/kg for application to human exposure. It was clear from numerous dosimetry studies, however, that the actual distribution of SAR within the body of the experimental animals was considerably nonuniform with local, spatial peak values as great as about 20 times the whole-body average value. So, while the average SAR over the body mass associated with behavioral disruption was about 4 W/kg, there were some areas within the body that could be absorbing energy from the external exposure fields at a rate as high as 80 W/kg. Hence, the present ANSI RFPG limits the whole-body averaged SAR to 0.4 W/kg but permits the spatial peak SAR to rise to 8 W/kg to account for the fact that, in the experimental studies on animals, such nonuniformity in the energy absorption rates undoubtedly existed.

A very important note is in order, however, relative to the 8 W/kg spatial peak SAR limit of the ANSI RFPG. The limiting value of SAR was derived from the nonuniformity of SAR within free-space irradiated experimental animals. Virtually no experimental results reported in the literature have been for the case of animals situated on a ground plane. Experimental studies of human models exposed on a ground plane and theoretical studies have shown, nevertheless, that in the grounded condition, much higher ratios of the local to average SAR over the body can occur. In some of these studies, local, spatial peak SARs up to 60 times the body average have been observed for the grounded condition and far-field exposure. But because the vast majority of the data base that existed prior to the issuance of the 1982 ANSI RFPG was for free space, ungrounded exposure conditions, ANSI elected to maintain a local SAR limit of 8 W/kg. More recently, numerous studies have been conducted which have explored the issue of local SARs resulting from near-field exposures. These studies have also been primarily restricted to models of the human body, continuing to leave the question open as to the biological impact of near-field exposures and high level, local SARs. Thus, on a dosimetry basis, the ANSI RFPG restricts whole-body SAR including the condition of an individual standing on earth but restricts the elevation in spatial peak SAR to a factor of 20 times the average, consistent with free-space, ungrounded exposures.

SAR and Current Density

The SAR in the body can be expressed in terms of the local current density according to the following relationship:

$$SAR = J^2 \text{rho}/p \qquad [4]$$

where
- SAR = specific absorption rate (W/kg);
- J = current density in the tissue (A/m^2);
- rho = tissue resistivity (ohm-meters) = 1/s;
- p = density (kg/m^3).

The resistivity is the reciprocal of the conductivity. Equation [4], when practically applied at 30 MHz for muscle tissue, can be simplified to:

$$SAR = 0.0013 J^2 \text{ (W/kg)} \qquad [5]$$

The practical significance of this expression is that if the induced currents can be determined in the body, the SAR can be estimated. This becomes particularly relevant when considering currents that flow through the legs, ankles and feet or through the hands and wrists when touching objects which have RF currents flowing on them such as reradiating objects. It is in this context that equation [4] will be found to provide a meaningful way to interpret the significance of human exposure to RF hot spots.

Since the local SAR is directly related to the current density, determining the effective cross-sectional areas through which the current flows becomes the critical issue. In general, the two prime areas of potential high SAR are the ankle and the wrist, those two parts of the anatomy having the smallest cross-sectional areas. But even within the ankle and wrist, considerable variation in conductivity exists since there is a variety of tissue types involved including not only muscle tissue but large amounts of bone which is relatively nonconductive. Thus, a major concern becomes the determination of how much high conductivity tissue exists in these regions. One approach to this problem is examining the cross-sectional anatomy of the structure through anatomy text books and assigning physical areas to each of the major tissue types. Gandhi et al. (1986), for example, reported an effective cross-section area of only 9.5 cm^2 for the average adult ankle. This small area of muscle equivalent tissue, having high conductivity, is due to the large amount of bone in the ankle. If the RF current must now flow through this small area, the local current density becomes approximately 300 A/m^2 with a resulting SAR in the smallest area of the ankle of 117 W/kg! This value obviously far exceeds the spatial peak SAR limit of the ANSI RFPG yet the incident electric field does not exceed the RFPG at 30 MHz.

Chatterjee et al. (1986) have also examined the wrist from an anatomical cross section viewpoint and report that the effective conductive cross section is 11.1 cm^2. Their finding that the conductive cross section is greater than their estimate of the conductive cross section for the ankle, despite the ankle's larger gross cross-sectional area, is presumably due to the disproportionately smaller amount of bone in the wrist.

Recently, the Accredited Standards Committee C95 on Non-ionizing Radiation Hazards has recommended the use of a 20 W/kg SAR limit for use in the wrists, ankles, hands and feet (ASC, 1989). The draft rationale states "The 20 W/kg limit for the wrist and ankles allows higher absorptions in the soft tissues produced by the induced currents specified in Table 2 flowing in these bony cross-sectional areas. Relatively high surface area to tissue volume ratios for these parts of the body, the common experience of high-temperature excursions on these parts without apparent adverse effects and the lack of critical function when compared to other organs are considerations which mitigate these higher permitted local SARs." While this statement is still in draft form, it closely parallels the provisions of both the IRPA and the National Radiological Protection Board in the United Kingdom (NRPB, 1989) which allow local SARs up to 20 W/kg as averaged over tissue volumes of 100 g in the extremities.

In summary, the ANSI RFPG (ANSI, 1982) contains limits on both the whole-body average and spatial peak SARs which are not to be exceeded when averaged over any 6-minute period of exposure. For exposure to highly nonuniform RF fields, spatial peak SARs generally become the limiting exposure criterion before the whole-body SAR is reached. This is especially likely when evaluating exposure to RF hot spots where enhanced absorption in the wrists and ankles may become the controlling factors for practical assessments of compliance with the RFPG in the field. Induced RF currents provide one indirect measure of local SAR in these regions which has practical utility during the conduct of routine environmental surveys of RF fields.

TECHNICAL APPROACH USED IN STUDY

In approaching the problem of evaluating exposure to RF hot spots, an underlying concept was envisioned. This concept is straightforward and intuitively apparent. It can be stated simply as whole-body energy absorption rates should be related to the ambient field strengths in a region occupied by the body rather than local fields which may be significantly elevated by comparison with the ambient fields but present only partial body exposure. Stated in another way, there is only so much energy which can be absorbed from the field in a given region of space, regardless of how it may be redistributed by the presence of reradiating objects. Yet another alternative expression of the concept is that the local field strengths, when exposure occurs near or at the surface of a reradiating object, are not necessarily good indicators of absorbed energy in the body and thus not necessarily good measures for determining compliance with the RFPG. Kucia-Korniewicz (1974) discussed long ago the issue of coupling between biological objects and field sources, indicating that the electric field strength alone was not always sufficient to assess the biological action of the fields on exposed specimens.

This underlying concept influenced one of the measurements carried out in the project; a resonant dipole antenna was constructed which was connected to a sensitive power meter as illustrated in Figure 3. The dipole was exposed to RF fields at its resonant frequency which were a small fraction of the permitted limits recommended by ANSI. Then, the power absorbed by the dipole was measured and the local RF fields near the dipole's surface were measured. In this fashion, the strongly enhanced surface fields, which easily exceed the ANSI RFPG, suggest one conclusion while the total power absorbed by the dipole suggests quite another conclusion.

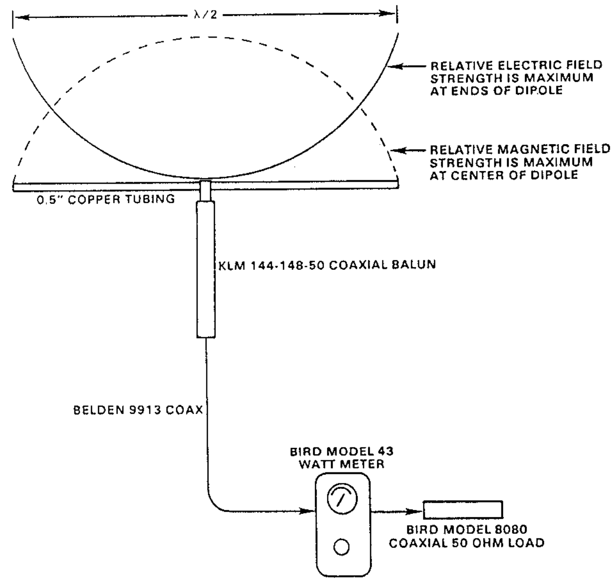

Figure 3. Distribution of relative electric and magnetic field strengths near a half-wave length dipole exposed to a uniform electric field. A resonant dipole at 144.05 MHz was used as a passive receiving antenna and reradiating source in some of the measurements.

Although the resonant dipole is interesting to study since its characteristics can be easily computed and measured, reality is such that the objects encountered in field surveys are more usually not resonant structures, i.e., they are not good antennas. There are innumerable objects which, each in its own characteristic way, can become reradiators. To address the generic category of reradiating objects, it was decided that a limited sample of such objects would be included for measurements in the project. A driving concern was to develop insight to the hot spots that could be caused by reradiating objects exposed to RF fields in general rather than developing a comprehensive catalog of such objects. For this project, in addition to the half-wave dipole, a metallic mail box, a filing cabinet, an aluminum window frame in a wooden frame building and a simulated guy wire were all investigated for their ability to produce enhanced RF fields near their surfaces.

While measuring the absorbed power of a resonant dipole is one matter, it was not feasible to consider a similar absorbed power measurement from the other objects studied. So, in addition to the measurement of ambient fields and surface hot-spot fields, a measurement technique was developed to measure the magnitude of induced current which would be conducted into the body upon contacting the reradiating object. It was reasoned that since the current flowing in the tissues of the body could be related to the local value of SAR, a current measurement represented the most practical approach to the SAR determination and consequently the most efficient approach to evaluating whether exposure to the reradiated fields would lead to exceedances relative to the ANSI RFPG. A further step was taken in the thinking about this approach; virtually any situation in which RF fields caused by reradiating objects call to question compliance with the RFPG implies the possibility of physical contact with the reradiating object. Thus, the issue of simple exposure to the RF fields becomes of less importance since an individual may not just be exposed by virtue of being positioned very close to the object but also will probably have access to the object in which case they will form contact. The physical contact situation substantially increases the possibility that RF currents can flow between the object and the body thereby raising the probability of exposure to increased SAR. With this rationale, the reradiating objects used in this project were evaluated on the basis of contact currents when an individual forms contact by touching the object.

INSTRUMENTATION AND MEASUREMENT METHODS

RF Fields

The primary instruments used in this project for measuring electric and magnetic fields consisted of broadband, isotropic survey probes similar to those commonly used in conducting RF field surveys. For electric field measurements, a Holaday Industries, Inc. Model HI-3001 broadband field strength meter (S/N 39586) equipped with a Model GRE (S/N 297A) green electric field probe (0.5 MHz - 6 GHz) was used. Measurements of magnetic fields were performed with The Narda Microwave Corporation Model 8616 (S/N 24332) meter equipped with a Model 8631 (S/N 17174) magnetic field probe (10 - 300 MHz).

Both of these instruments were calibrated by inserting them in a transverse electromagnetic (TEM) cell (Instruments for Industry, Inc. Model IFI 105) using a method described by Mantiply (1984). By propagating a known power through the TEM cell and knowing the characteristic impedance of the cell, the electric and magnetic field strengths developed inside the cell can be known very accurately. Both calibrations were carried out at a frequency of 144.0 MHz. In each case, the probe was inserted through a door in the side of the TEM cell and slowly rotated, noting the maximum and minimum readings. The average of the two readings was compared to the known, applied electric or magnetic field strengths in the TEM cell to obtain a correction factor which would be applied to all readings obtained with either probe during the project.

Contact Currents

Measurement of contact currents was conducted by using an assembly consisting of a metal probe, RF current transformer and tuned receiver. The current probe assembly consisted of a 6 inch long piece of 7/8 inch diameter copper tube (type M) soldered to another 6 inch long piece of 5/8 inch diameter copper tube with the use of an adapter to accommodate the two different diameters. A commercially available RF current transformer (Ailtech Model 94111-1 [S/N 451]) (NOTE: Ailtech is now known as Eaton Corportion) was affixed to the smaller diameter copper tube with the use of a high density, closed cell type of polyurethane foam cut in a cylindrical form which surrounded the smaller diameter copper tube and formed a tight friction fit with the inside of the current transformer circular aperture (1.25 inches diameter). The current transformer was positioned approximately 3 inches from the end of the small copper tube. To facilitate making connection with various objects, the end of the smaller tube was cut across two diameters for a length of 7/8 inch and then flared. This arrangement proved to be effective in making good electrical contact with different objects for which contact currents were to be measured. Figure 4 is a photograph of the current probe assembly as used in the project. The operator, by holding the larger diameter end of the copper tubing, formed the other part of the circuit through which the current would flow. In each measurement of contact current, the current probe assembly was pressed into contact with the object under evaluation and the surface of the object was explored until a maximum indicated RF voltage was observed on the field strength receiver. The maximum voltage was used in the conversion to contact current. All contact current measurements were performed with the individual wearing rubber sole tennis shoes. Measurements of contact currents while bare-footed were performed to evaluate the effect of the shoes.

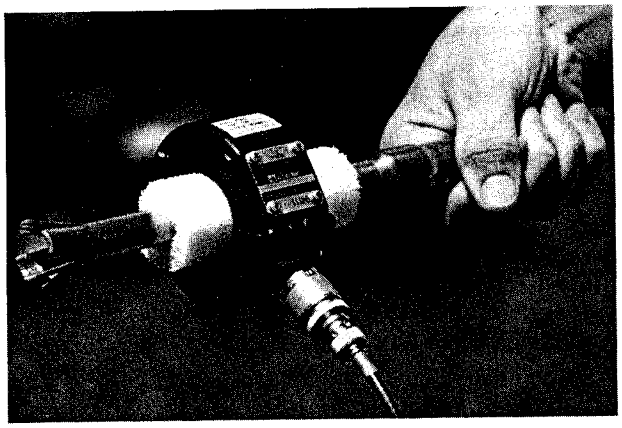

Figure 4. Photograph of the current probe assembly used to measure contact currents.

The contact currents measured with this system were those actually flowing between the RF hot-spot source and the body; others (Stuchly and Lecuyer, 1989) have employed various forms of equivalent circuits to represent the impedance that the body represents upon contacting objects. In this fashion, should excessive currents be present, they would not flow into the body of the person conducting the tests.

The RF output voltage from the current transformer was connected to the input of a Potomac Instruments Model FIM-71 field strength receiver (S/N 888) through a 1.5 m long piece of RG-58/U type coaxial cable (Belden 9310) equipped with type BNC connectors. A type N to BNC adapter was used to connect the coaxial cable to the current transformer. The field strength receiver was tuned to 144.05 MHz, the frequency used for the experimentation performed in this investigation, and the measured RF voltage was then related to the current flowing through the current probe assembly. Figure 5 shows the current probe assembly along with the Model FIM-71 receiver.

The current flowing through the aperture of a current transformer is related to the transfer impedance according to the relationship:

$$I = V/Z_T \text{ where} \qquad [6]$$

I = the contact current obtained by touching an object exposed to a RF field that may generate local RF hot spots (mA);
V = the rms RF voltage delivered by the current transformer (mV);
Z_T = the current transformer transfer impedance (ohms).

As the experimental data began to develop in the project, the question of how the contact currents which were being measured related to currents elsewhere in the body arose. To investigate this curiosity, a 3/4 inch inside diameter PVC pipe was cut to a length slightly greater than 2 m, capped on one end and then filled with a saline solution (0.9

Figure 5. Photograph of the current probe assembly and field strength receiver used to measure contact currents. The receiver is used as a sensitive tuned voltmeter for detecting the RF output voltage from the current transformer.

percent by weight sodium chloride - table salt). At the top of the pipe, a metal electrode was fashioned which made electrical contact with the saline solution and provided a forked contact for contacting the dipole antenna used in some of the testing program. The PVC pipe assembly was brought into contact with the dipole antenna near its driven point (center). The PVC pipe permitted the current transformer, used for making contact current measurements, to be fitted around the pipe and moved along its axis to study the spatial variation of conducted current.

Field Generation

The equipment configuration used to generate RF fields is outlined in Figure 6. A four element yagi antenna (Cushcraft Model 124WB) designed for use in the two-meter amateur radio band was mounted two meters above ground on a fiberglass, telescoping mast inserted in a five gallon plastic pail filled with concrete for ballast. The yagi has a nominal gain of 10 dB.

The signal source used was an ICOM Model IC-275A two meter transceiver which is capable of approximately 25 W output power. The transceiver output was used to drive a Mirage Model B1016 amplifier which could produce up to 160 W into the yagi transmitting antenna. A Bird Model 43 power sensor was used to monitor the input power to the yagi antenna.

Reradiating dipole

A resonant half-wave dipole antenna was constructed from 5/8 inch diameter copper tubing with the arms of the dipole physically held in

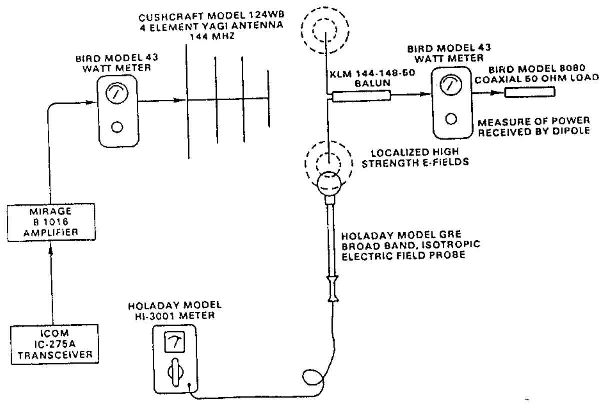

Figure 6. Equipment configuration for generating and measuring localized electric fields near a reradiating, passive dipole antenna.

place with a wooden (pine) structure. A KLM Model 144-148-50 coaxial balun was used to minimize currents flowing on the outside conductor of the coaxial cable which was connected to a Bird Model 43 power sensor. The dipole was constructed with the arms too long, approximately 40 cm each, and the antenna was brought into resonance on a frequency of 144.05 MHz by successively trimming equal lengths from both sides of the dipole until the voltage standing wave ratio (VSWR) was minimized. Through this process the VSWR was minimized to a value of 1.12. Under this condition, only 0.3 percent of the power delivered to the dipole will not be absorbed.

The dipole assembly was mounted 2 m above ground approximately 10 m from the transmitting dipole and was supported by three nylon guy ropes. Another nylon rope was stretched horizontal to the ground and parallel to the dipole, immediately next to the elements. This rope served the purpose of identifying the position in space that the dipole occupied for subsequent field strength measurements. The area used for the tests was a grassy, flat area with no intervening vegetation. The power sensor used to measure absorbed power by the dipole was equipped with a sensitive 0-1 W sensor element. The output of the power sensor was terminated with a 50 ohm load, a Bird Model 8080. With this system, absorbed powers as low as 0.02 W could be readily measured.

The general approach used in the project was to generate an arbitrary exposure field at 144.05 MHz and then introduce various objects into this field and then examine them for RF hot-spot production and contact currents. This is diagrammatically illustrated in Figure 7 for a standard filing cabinet, similar to that found in many offices, and Figure 8 for the simulation of a guy wire that might be found at FM broadcast station antenna tower sites. The guy wire was configured to evaluate the effect of a guy wire rigged near an FM or TV broadcast antenna which would be exposed to high intensity RF fields near the antenna but might conduct RF currents down the guy wire, leading to the generation of RF hot spots near the wire.

MEASURED AND CALCULATED RESULTS

Half-wave Passive Dipole

Fields - Using the nylon rope mentioned above, the exact location of the half-wave dipole axis was determined and marked on the reference rope using a marking pen with the dipole in place. The dipole was then removed, leaving the nylon rope in place, and an arbitrary RF field was radiated toward the rope with the yagi transmitting system. Electric and magnetic fields were measured along the axis of where the dipole would subsequently be located by slowly moving first the electric field probe and then the magnetic field probe along the nylon rope. The

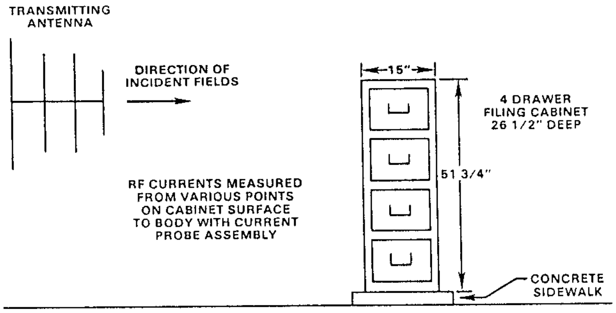

Figure 7. Measurement setup for determining induced RF currents when contacting a filing cabinet exposed to ambient RF fields.

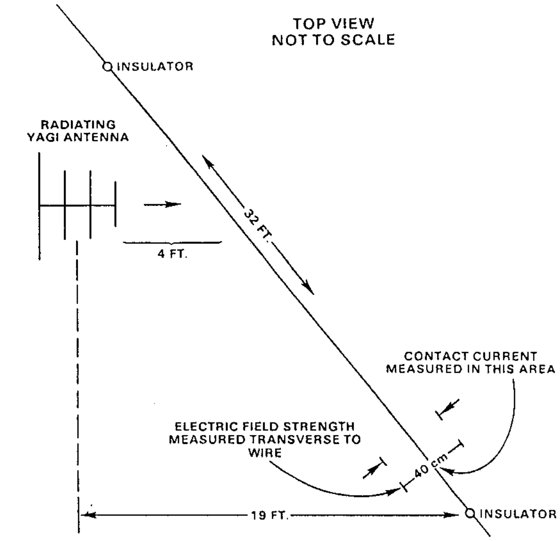

Figure 8. Measurement setup for determining local electric field strength and contact current from a simulated antenna tower guy wire.

measurements were accomplished by kneeling on the ground and holding the measurement probe above the head, keeping the probe as close to the nylon rope as possible as it was moved uniformly between the two marks representing the ends of the dipole. The resulting data, in terms of the square of the electric and magnetic field strengths, is presented in Figures 9 and 10 respectively. These data have been corrected for probe response at the test frequency of 144.05 MHz and indicate that the mean field strengths over the length of the dipole were 341 +/- 23 V^2/m^2 (+/- 0.29 dB) and 0.00207 +/- 0.00015 A^2/m^2 (+/- 0.31 dB) for electric and magnetic fields respectively. The magnetic field strengths were obtained by using relation [2] to convert from units of power density as indicated on the Narda Model 8616 meter.

This reference field represents an electric field strength that is approximately 8.5 percent of the ANSI RFPG and a magnetic field strength that is approximately 12 percent of the RFPG. The fields were found to be quite uniform along the length of the dipole, typically +/- 0.3 dB, and to represent a field impedance equal to 406 ohms. This is near the free-space value of 377 ohms but the difference is likely due to the presence of ground reflections between the transmitting yagi antenna and the dipole's location.

Next, the dipole was re-positioned adjacent to the nylon rope and connected to the high sensitivity power sensor. Electric and magnetic fields were measured along its axis using the same technique described above and the absorbed power was recorded. The results are given in

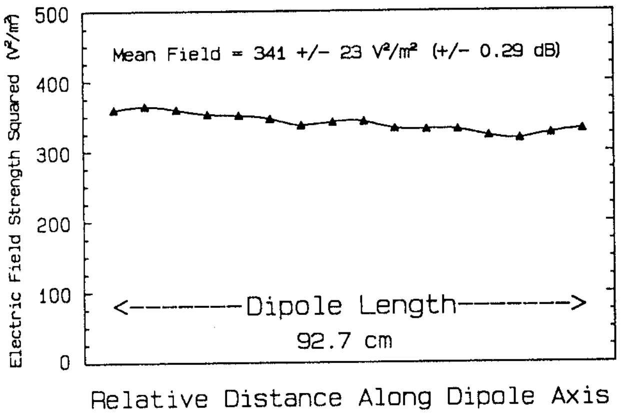

Figure 9. Variation of free-space electric field strength along axis of half-wave dipole antenna.

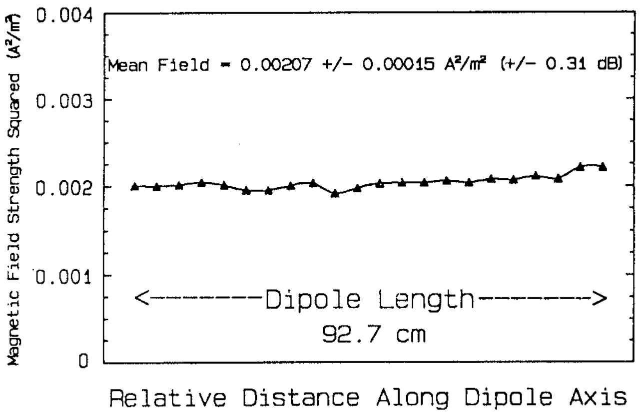

Figure 10. Variation of free-space magnetic field strength along axis of half-wave dipole antenna.

Figures 11 and 12 for electric and magnetic field strengths with a separation distance between the probe protective covering and the surface of the dipole of approximately 5 cm. The peak field strengths measured are indicated as 6770 V^2/m^2 and 0.0424 A^2/m^2 for electric and magnetic fields respectively. These peak fields are representative of RF hot spots encountered in routine field surveys and are substantially greater than the field limits given in the ANSI RFPG which are indicated by horizontal dashed lines in Figures 11 and 12. The location of the peak fields is also expected since the voltage distribution on a half-wave dipole produces a maximum at the ends of the dipole while the current will be a maximum at the feed point. While the surface peak field strengths were relatively high, the power absorbed by the dipole was measured as 0.46 W (460 mW).

Plane-wave equivalent power densities were calculated based on the measured squares of the electric and magnetic field strengths using relation [2]. The resulting power densities, S_E and S_H, corresponding to the electric and magnetic fields, were used to calculate expected absorbed power from the field by the dipole using the relation between gain and effective area of an antenna. The effective area of the half-wave dipole was calculated to be 0.566 m^2 and a power gain of 1.64 was assumed, based on the performance of a perfect, lossless dipole. Applying the power densities S_E and S_H and the effective area, absorbed powers of 0.512 W and 0.442 W were obtained. The mean value of these two powers is 0.477 which is in very good agreement with the measured value of 0.46 W. This difference is assumed to represent the difference between a perfect dipole and the losses and less than perfect impedance match inherent to the dipole constructed for the tests.

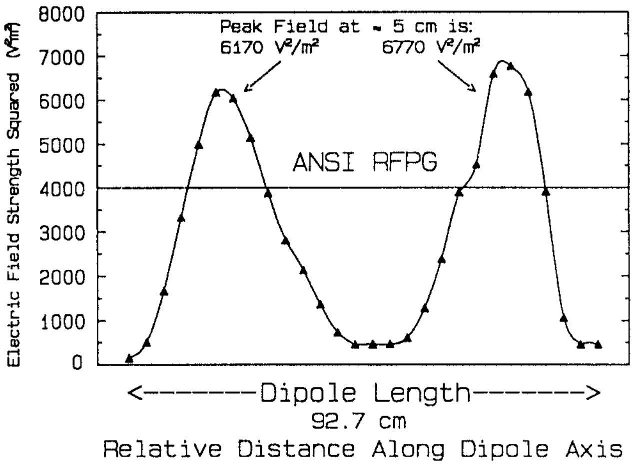

Figure 11. Measured electric field strength (E^2) distribution near surface of reradiating dipole in RF field comparable to approximately 10 % of the ANSI RFPG. The ANSI RFPG is shown as the dotted line.

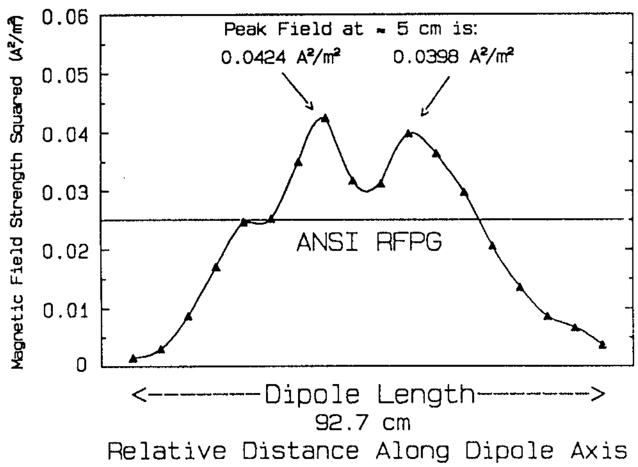

Figure 12. Measured magnetic field strength (H^2) distribution near surface of reradiating dipole in RF field comparable to approximately 10% of the ANSI RFPG. The ANSI RFPG is shown as the dotted line.

The field distributions shown are representative of many repetitions of the measurements and show that, for the real world dipole, the magnetic field strength exhibited a minimum directly adjacent to the feed point of the dipole, even though the peak in the magnetic field was very near the center of the dipole. This is presumed to be due to the physical separation of the feed point gap or the actual current distribution that existed on the dipole at resonance.

An antenna analysis program, MININEC (Rockway et al., 1988), was used to model the passive receiving dipole used in the tests. A resonant dipole having the same diameter as the test dipole was modeled with an input power of 0.46 W. The near fields were computed for a distance of 5 cm from the surface of the dipole along its length. Interestingly, the calculated peak field strengths of 7056 V^2/m^2 and 0.046 A^2/m^2 are in remarkable agreement with the measured values, being no more than 0.35 dB different than the experimentally determined values. The theoretical results are seen to track very well the measured values and indicate that such high surface fields are to be expected from a dipole either radiating or receiving low powers.

Currents - Contact currents were measured with several different incident field strengths to illuminate the passive dipole. The results are summarized below:

Dipole Contact Current Summary

Power absorbed by dipole (W)	Contact current (mA)	I-max dipole (mA)
0.12	27.7	40.5
0.50	60.9	82.8
0.79	73.8	104.0
1.0	83.0	117.0

The third column lists, for reference purposes, the maximum RF current which would be expected to flow in the feed terminals of the half-wave dipole when absorbing the indicated power in column one.

These data demonstrate that the contact current increases as the square root of the power absorbed by the dipole, as would be expected. The point at which the maximum contact current was observed was near the center of the dipole. Clearly, the current was reduced when contacting the end of the dipole where the maximum surface electric fields were measured. The maximum contact current was found to be approximately $83(W^{1/2})$ mA where W is the power absorbed by the dipole in watts.

The contact current was also measured when the dipole terminals were shorted, i.e., when no or very little power is actually being absorbed by the dipole but is being essentially completely reradiated. It was found that the contact current increased, for example, from 79.3 mA to 99.6 mA when the center gap was shorted and the dipole had been delivering 0.73 W into the matched load and power sensor. When the short was effected at the terminals, the power sensor indication reduced to 0.02 W. This observation indicates that the contact current increased by approximately 25 percent over the un-shorted condition.

A brief test of the effect of wearing shoes revealed that very little, and some times unmeasureable, increases in the measured contact currents occurred when bare-footed.

RF Hot Spots Caused by Other Objects

To examine the local fields and contact currents associated with RF hot spots, several situations were arranged in which objects were exposed to measured RF field strengths. These objects included a rural mailbox supported by a metal post, a filing cabinet, and an aluminum frame window. It was commonly found that the locations of the peak surface electric and magnetic fields were not the same. The highest electric field was found near one corner while the maximum magnetic field was found along the vertical member between the two panes of glass. This implies that the current and voltage distributions that existed on the window frame at the time of the measurements were highly complex. In general, surface field measurements performed on the various objects evaluated for hot spots revealed the same inconsistent pattern of local fields, suggesting that analytic solution of the expected fields would be very difficult, if at all possible.

Mail box test - Data representing the mail box test are summarized as follows:

Ambient fields		Surface fields	
E^2 (V^2/m^2)	H^2 (A^2/m^2)	E^2 (V^2/m^2)	H^2 (A^2/m^2)
620	0.0037	9800	0.022

Maximum contact current = 88.6 mA
E^2 field enhancement factor = E^2(surface)/E^2(ambient) = 15.8
H^2 field enhancement factor = H^2(surface)/H^2(ambient) = 5.9

Window frame test - Data representing the aluminum window frame test are summarized as follows:

Ambient fields		Surface fields	
E^2 (V^2/m^2)	H^2 (A^2/m^2)	E^2 (V^2/m^2)	H^2 (A^2/m^2)
1500	0.0094	9800	0.23

Maximum contact current = 133 mA
E^2 field enhancement factor = E^2(surface)/E^2(ambient) = 6.5
H^2 field enhancement factor = H^2(surface)/H^2(ambient) = 24.5

It is interesting to note the considerable difference in surface field enhancement factors between the window frame and the mail box; in the case of the mail box, the RF hot spot was characterized by a very enhanced electric field but in the case of the window frame, the opposite was true, the hot spot exhibited a greatly enhanced surface magnetic field. This may have been due to the loop-type structure of the window frame which may have tended to produce much higher currents relative to incident, exposure fields than could exist in the mail box.

Filing cabinet test - Data representing the filing cabinet test are summarized as follows:

Ambient fields		Surface fields	
E^2 (V^2/m^2)	H^2 (A^2/m^2)	E^2 (V^2/m^2)	H^2 (A^2/m^2)
600	--*	9430	0.0032

* Not determined
Maximum contact current = 42.4 mA
E^2 field enhancement factor = E^2(surface)/E^2(ambient) = 15.7

Guy wire test - Data representing the results obtained in the simulated guy wire test are presented graphically in Figure 13 in which the electric field strength transverse to one end of the wire from 10 cm on one side of the wire to 10 cm on the opposite side is plotted. Figure 13 dramatically illustrates the high degree of spatial variability of surface fields encountered at RF hot spots; the surface field measured with the electric field probe situated in contact with the wire is approximately 19 times greater than the ambient field just 10 cm away from the wire. Thus, even though the ambient field represented a plane-wave equivalent power density of only 0.08 mW/cm^2, the surface field was determined to represent an equivalent power density of 1.5 mW/cm^2. An important difference in the guy wire test is that one end of the wire was exposed to a rather intense (unmeasured field strength) field while the other end, near which the local fields were mapped, was actually in a very weak RF field; thus, the use of the term ambient in this case is not the same as for all of the other exposure tests performed. Using the value of surface fields as a determining factor in assessing RF fields at a broadcast site for compliance with RFPGs may easily lead to apparent exceedances; in many cases, these surface fields exist only in the immediate region of a conducting structure and are not representative of whole-body exposure.

Guy wire test - Data representing the guy wire test are summarized as follows:

Ambient fields		Surface fields	
E^2 (V^2/m^2)	H^2 (A^2/m^2)	E^2 (V^2/m^2)	H^2 (A^2/m^2)
300	--*	5800	--*

* Not determined
Maximum contact current = 94.1 mA
E^2 field enhancement factor = E^2(surface)/E^2(ambient) = 19.3

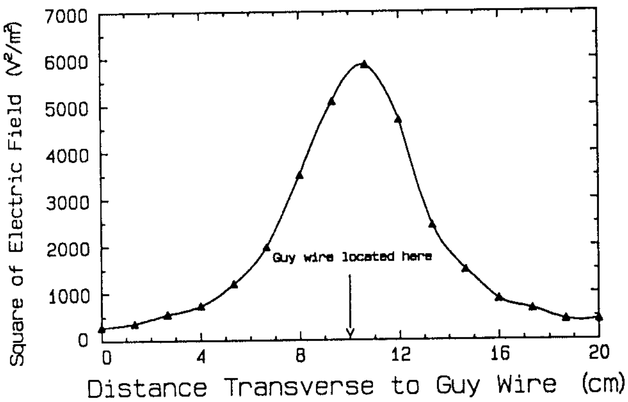

Figure 13. Spatial variability of electric field strength (E^2) near a simulated guy wire exposed to RF fields.

Contact Current Distribution

Empirically, it was observed that as the current probe assembly was brought within 10 cm of the half-wave dipole antenna that served as a reradiating object, there was a very slight increase in the induced current but upon contact, the measured current abruptly and very substantially increased above the non-contact condition. This observation led to the insight that contact currents were, for the situations explored in this study of RF hot spots, always greater than any other current which might be induced in the body. A question remained, however, as to whether the contact current as measured with the current probe assembly constructed for the project, might be less than the current at some other point within the body. Though such might be the case, intuition argued that the local current densities, which the SAR is related to, would generally be substantially less due to the much large tissue cross sections involved in other parts of the body. Since the wrist represents the smallest cross-sectional area in which the contact current can practically flow, the wrist SAR appears to be the determining factor for analyzing contact currents. To investigate the possibility that the current that flows on contact might not be maximum at the contact area, the spatial distribution of the current was examined by sliding the current transformer up and down the saline filled pipe described earlier. The finding was that the measured current was a maximum at the very top of the fluid filled pipe and decreased smoothly as the distance from the contact point was increased with no indication of relative peaks in the measured current. It was concluded, therefore, that in the contact situation of a body contacting a reradiating object, the measurement of current at the point of contact represents the greatest current that can be experienced. This finding is not what one would expect for the distribution of body current induced without physical contact with an energized object since the body will then tend to exhibit antenna-like characteristics resulting in possible current maxima at other points on the body.

DISCUSSION OF RESULTS AND INSIGHTS OBTAINED

RF Hot-spot Fields

The data presented in Figures 11 and 12 clearly reinforce common experiences of detecting enhanced RF fields near the surface of objects which act as reradiators. Both Figures 11 and 12 show localized fields that are well in excess of the ANSI RFPG while the nearby ambient field is only about 10 percent of the recommended limits in terms of field strengths. The obvious question one might encounter upon evaluating this exposure situation is whether the fields mean that human exposure would violate the restrictions imposed by the RFPG. This example case shows that the power absorbed by the dipole, under the conditions which led to the high surface fields, was far less than one watt. Hence, on the basis of whole-body SAR, actual contact with the reradiating antenna can not lead to excessive energy absorption rates. To exceed the whole-body SAR value specified in the ANSI RFPG, an average individual of 70 kg mass would have to have available 28 watts to reach the whole-body SAR limit of 0.4 W/kg, assuming that the power were actually all absorbed by the body.

The data for the resonant dipole show that the incident electric field strength would have to be 20756 V^2/m^2, or the equivalent of a plane wave having a power density of 5.5 mW/cm^2, before the absorbed power would reach 28 W; in this case, the whole body SAR would have already exceeded the limits of the RFPG on the basis of field exposure over the whole body, let alone touching the reradiating object. The point to be made here, however, is that the experimental results suggest that typical RF hot-spot situations encountered in RF surveys, i.e., the existence of very localized high fields well above the surrounding values, unless the ambient values are already above the RFPG field strength limits, cannot result in whole-body SARs exceeding the RFPG. This observation has a strong bearing on interpreting partial body exposure conditions caused by reradiating objects; if typical exposure levels are found to be less than the RFPG, high fields caused by reradiating structures do not appear to have the capacity to produce whole-body SARs in excess of the RFPG. Thus, commonly encountered localized high fields caused by such objects as clothes lines, curtain rods, guy wires, metal window frames, metallic office furniture, etc., are generally only sources of near field, partial body exposure and consequently are not good indicators of whole-body energy absorption rates.

The more pertinent issue, then, is local SAR in the body tissues and whether these highly localized fields can lead to spatial peak SARs in excess of the limits in the RFPG. Except for a very limited number of possible reradiators, for which their interactions with RF fields are well understood and for which absorbed powers can be readily measured, some means of determining local SAR is required. Lacking commercially available and socially acceptable methods for directly measuring SAR in exposed humans, surrogate measures must be implemented. Experimental approaches, making use of phantom, tissue equivalent models of the human body, are generally not easily adaptable to the rugged field environment in which such assessments are required.

The measurement of contact currents was deemed to represent a more practical method of determining compliance with the intent of the ANSI RFPG. This is so since the contact currents are greatest at the point of contact, the current flowing at the hand contact is very close to the anatomical area of the body in which the highest local SAR will likely occur (the wrist because of its small cross-sectional area) and the instrumentation required is portable and permits relatively straight forward measurements in the field, even in relatively awkward situations, such as on antenna towers.

Contact Currents and Local SAR

As described earlier, the local SAR can be determined by relation [4]. For purposes of discussing the contact current data developed in this project, the literature was reviewed for information on conductivity of muscle tissue in humans. Data compiled by Durney et al. (1986) were ultimately used the analysis presented here. Muscle conductivities for excised human muscle tissue were used to develop a least squares polynomial fit of the data of the form:

$$s = A_0 + A_1F + A_2F^2 + A_3F^3 \qquad [7]$$

where

s = tissue conductivity (S/m);
F = frequency (MHz);
A_0 = 0.564;
A_1 = 0.00266;
$A_2 = -6.79 \times 10^{-6}$;
$A_3 = 6.31 \times 10^{-9}$;

Relation [7] should be valid for the frequency range of 1 MHz to 800 MHz. Relation [7] was used to generate values of muscle conductivity for selected broadcast bands. In addition, relation [4] was manipulated to obtain expressions for calculating values for the peak SAR that would be expected to occur in the wrist of an adult touching an RF exposed object which delivered a contact current. These simplified expressions are of the form:

$$SAR = K I^2 \qquad [8]$$

where

SAR = spatial peak SAR in the wrist (W/kg), with assumption of an effective conductive cross section of 11.1 cm^2;

K = a conversion factor specific to the frequency of interest;

I = contact current (mA);

Table 1 lists the conversion factors appropriate to various broadcast frequencies to use when applying relation [8]. For broadcast band designations, the expressions obtained from the listed values of K will result in a conservative estimate of the wrist SAR over the particular broadcast band since the lower edge of each band was used to find the conductivity, i.e., the expression will not underestimate the expected SAR.

Table 1. Proportionality factors for use in relation [8] used to compute the peak SAR in the wrist based on the measured contact current for selected broadcast bands and limiting contact currents to control peak SAR in the wrist to less than 8 W/kg and 20 W/kg.

Broadcast band	K used in [8]	Limiting current to control SAR (mA) $\leq$8 W/kg	$\leq$20 W/kg
AM	0.00142	75.1	119
Low VHF (54-88 MHz)	0.00113	84.1	133
FM (88-108 MHz)	0.00105	87.3	138
High VHF (176-216 MHz)	0.000913	93.6	148
Channel 14	0.000805	99.7	158
Channel 20	0.000789	100	159
Channel 66	0.000517	124	197

As an example, at 144 MHz, the expression for local, wrist SAR, based on an interpolated value of conductivity of 0.824 S/m, becomes

$$SAR = 0.000950 I^2. \qquad [9]$$

The expressions given by [8] must be understood to not be precise limits since there is considerable variability in the measured data on tissue conductivities. The conductivity data used represent mean values with a spread in the conductivity values varying from about 2 percent to as much as 20 percent.

Applying [9] to the data on contact currents obtained in the project permits immediate estimates of wrist SARs. Another approach, however, is to determine from expression [8] the contact current required such that the wrist SAR is equal to the peak SAR limit in the ANSI RFPG of 8 W/kg. This procedure was performed for the same frequencies and/or bands used in Table 1 to find the contact currents equivalent to a wrist SAR of 8 W/kg and 20 W/kg. The higher value of local SAR has been suggested by the IRPA as a more appropriate limit for the ankles and wrists. ANSI (ASC, 1989) has included this higher limit in a recent draft of its revised RFPG. Table 1 lists the limiting contact currents which would control the wrist SAR to values of 8 and 20 W/kg. The general trend observed that lower currents are necessary to deliver the same SARs at lower frequencies is due to the variation of muscle conductivity with frequency; the conductivity decreases at lower frequencies. At 144 MHz, a contact current of 91.8 mA is projected to result in a wrist SAR of 8 W/kg while a current of 145 mA would be required to result in a SAR of 20 W/kg.

An important observation to make from the limiting currents in Table 1 for wrist SARs of 20 W/kg is that these values exceed those currents sometimes associated with RF burns. Rogers (1981) has recommended a current threshold of approximately 200 mA for the onset of RF burns. More recently, a value of 100 mA has been assumed to represent the threshold for RF burns for small contact areas during the grasping of an energized source (ASC, 1989). Thus, while maintaining wrist SARs within the 20 W/kg value, the contact currents could lead to RF burns upon touching the object and for practical purposes, unless protective gloves are used, the upper limit becomes essentially 100 mA rather than the listed higher currents.

The contact currents measured in the project were analyzed in terms of these threshold currents for SARs of 8 and 20 W/kg in the wrist. For the resonant dipole, the mailbox, the window frame and the filing cabinet, the ratio of contact current to ambient E^2 was calculated and the incident electric field strength (E^2) required to produce a contact current equivalent to 8 or 20 W/kg was calculated. The results are given in Table 2. These results show, not surprisingly, that the resonant dipole requires the least strong incident field strength to produce contact currents sufficient to deliver the limiting values of SAR. But an interesting observation is that even apparently non-resonant objects, like the filing cabinet, can produce contact currents associated with wrist SARs of 8 W/kg, or even 20 W/kg, in ambient fields considerably less than the field strengths given in the RFPG. For example, in a field of 1300 V^2/m^2 the filing cabinet would produce a contact current of 92 mA, sufficient to result in a wrist SAR of 8 W/kg. Thus, even though the ambient field strengths may be less than those prescribed to limit whole-body SAR to less than 0.4 W/kg, contact currents in some exposed objects can exceed the level that would result in local SARs greater than 8 W/kg.

Table 2. Summary of contact currents and required ambient fields to cause peak SARs of 8 W/kg and 20 W/kg in the wrist for several reradiating objects.

Object	Ambient electric field strength squared (V^2/m^2)	Contact current (mA)	Ambient field (V^2/m^2) required to produce peak SAR in wrist = 8 W/kg	= 20 W/kg
Dipole	370	60.9	556	878
Mail box	620	88.6	642	1014
Window frame	1500	133	1035	1635
Filing cabinet	600	42.4	1298	2051
Guy wire*				

* Data are not given for the simulated guy wire since it is difficult to quantify the actual exposure field. While one end of the wire was exposed to a rather intense RF field, the other end was in a very low intensity ambient field; thus, the exposure conditions were substantially different in comparison to the other listed objects.

Most RF surveys designed to determine compliance with the ANSI RFPG do not investigate the issue of contact currents and in many circumstances such an omission is likely not important since the SAR limits of the RFPG are to be time-averaged over any 6-minute period. In a practical sense, it is unlikely, except for certain extenuating circumstances, that individuals will be continuously contacting objects which are linked to RF hot spots. For example, even in the case of a metal stair way hand rail, the hand is making and breaking contact periodically with the rail, thereby reducing the time-averaged contact currents and thereby reducing the local SAR. In a similar sense, the enhanced RF fields that might exist near the end of a metal curtain rod and associated contact currents do not necessarily represent real problems since people do not normally remain in direct contact with curtain rods, other than momentarily. Nevertheless, consideration should be given to the possibility that individuals may come into contact with RF hot-spot objects, if such is practically feasible.

The time-averaging provision of the ANSI RFPG can be stated, for the VHF frequency band, as:

$$\text{Peak SAR} \leq 48 \text{ W-min/kg} \qquad [10]$$

Relation [10] simply says that the product of the peak SAR and the exposure time in minutes should be no more than 48 W-min/kg in any 6-minute period. Thus, limited duration exposures for less than six minutes may exceed the 8 W/kg value, if, on the average, the SAR does not exceed 8 W/kg. This provision of the RFPG provides for limited flexibility in managing exposures where RF hot spots may be present. For example, it is conceivable that the time averaged contact currents could be determined either by direct measurement using data logger type instruments or by timing of repetitive contacts as when climbing a tower ladder. In any event, excursions of the peak SAR above 8 W/kg should not be interpreted as necessarily exceeding the basis for the ANSI RFPG; careful assessment of the time-averaged peak SAR is called for.

The observation that wearing of shoes by the person contacting a reradiating object made little, if any, difference in the measured contact current is presumed to be related to two factors: (1) for contact situations, the current magnitude dissipates as the distance from the point of contact increases and (2) the capacitive reactance of the shoes becomes significantly less at higher frequencies, thereby apparently reducing the impedance to current afforded by the shoes. Thus any current escaping from the body via the feet, aside from that leaking off the body surface due to capacitive coupling to the nearby environment, meets with little change in impedance, whether the person is wearing shoes or not.

CONCLUSIONS

RF hot spots are a natural consequence any time that RF fields exist in the presence of conductive objects. RF hot spots are not unique, nor mysterious sources of RF fields. This study of RF hot spots has focused on developing information which may be helpful in interpreting the significance of hot spots when determining compliance with the ANSI RFPG (ANSI, 1982) at broadcast sites. The measurements and calculations have been directed to applications in the VHF and UHF broadcast bands but the concepts are applicable to assessing RF hot spots near AM stations as well.

A RF hot spot may be defined as a point or small area in which the local values of electric and/or magnetic field strengths are significantly elevated above the typical ambient field levels and often are confined near the surface of a conductive object. RF hot spots usually complicate the process of evaluating compliance with the RFPG because it is often only at the sources of the hot spots that fields exceed the RFPG.

RF hot spots may be produced by an intersection of narrow beams of RF energy (directional antennas), by the reflection of fields from conductive surfaces (standing waves) or by induced currents flowing in conductive objects exposed to ambient RF fields (reradiation). RF hot spots are characterized by very rapid spatial variation of the fields and typically result in partial body exposures of individuals near the hot spots. Uniform exposure of the body is essentially impossible due to the high spatial gradient of the fields associated with RF hot spots.

Several conclusions relevant to the RFPG compliance issue have been drawn from the results and experiences of this investigation:

(1) The ANSI RFPG (ANSI, 1982) is based on limiting the time-averaged SAR in the body. Field strength (or power density) limits specified in the RFPG represent working levels for determining compliance with the underlying basis of the standard. In lieu of more definitive measurements or analysis which relate to the SARs caused by RF exposure, the field limits in the RFPG should be used for determining compliance.

(2) In the typical RF hot-spot scenario, involving reradiating objects, the high, localized fields at the hot spot do not generally have the capacity to deliver whole-body SARs to exposed individuals in excess of the RFPG, regardless of the enhanced field magnitude. When the ambient RF field strengths are already at or exceeding the RFPG, then the partial body exposure which accompanies proximity of the body to the object will increase the whole-body SAR, generally only slightly.

(3) The high-intensity electric and magnetic fields accompanying RF hot spots are not good indicators of whole-body or spatial peak SARs in the body due to the high variability in coupling between the body of an exposed person and the hot-spot source.

(4) A measurement of the contact current which flows between the exposed person and a reradiating object provides a meaningful alternative to field measurements and permits the evaluation of the peak SAR which may exist in a person touching the hot-spot source.

(5) For most practical exposure situations, when hand contact is made with a RF hot-spot source, the greatest RF current will flow in the body, resulting in the worst case scenario for peak SAR. The contact case will result in significantly greater local SARs than for the non-contact condition and should be assumed to be the exposure of possible concern. This maximum SAR will be in the wrist, the anatomical structure with the smallest cross-sectional area through which the contact current can flow.

(6) Determining the wrist SAR for contact conditions requires a measurement of the contact current, knowledge of the conductivity of the tissues and knowledge of the effective conductive cross-sectional area.

(7) For most practical field evaluations, simple approaches to the measurement problem and necessary calculations to obtain the peak SAR are available and have been outlined in this paper. This conclusion is at variance with section 6.11 of the present ANSI RFPG (ANSI, 1982) in which ANSI, in referring to the 8 W/kg peak SAR limit, declared "It was also recognized by the subcommittee that to determine whether a particular RF source would meet these absorption criteria would be difficult and could be done only by a properly qualified laboratory or by an appropriate scientific body for a general class of equipment. In no case could a routine field survey determine conformance with the criteria of this part of the exclusion." These cautionary words were prepared in 1979, prior to the extensive work on induced and contact current measurements which has developed since 1979. At that time, recognition of whole-body resonance was the major new change in the RFPG over previous versions of the guide and the statement in section 6.11 is presumed to have referred principally to the issue of deep heating of internal body tissues. Even today, for such tissues, the dosimetric procedures required for accurate SAR assessments remain complex and are relegated, for many cases, to the laboratory setting. In the case of peak SARs incurred from exposure to RF hot spots, however, it must be concluded that section 6.11 of the RFPG was written in an overly narrow context relative to the ability for in-the-field contact current measurements and assessments of wrist SARs.

(8) Results obtained with those objects investigated in this study showed that when ambient RF electric fields were in the range of 16 to

32 percent of the RFPG (for field strength squared) for the frequency range 30-300 MHz, contact currents in unprotected individuals could reach a level that is associated with a wrist SAR in adults equal to 8 W/kg. Electric fields that would induce contact currents sufficient to deliver wrist SARs of 20 W/kg, the peak SAR limit recommended by IRPA and the NRPB, range from 22 to 51 percent of the RFPG field limits.

(9) Application of the 8 W/kg peak SAR limit to the extremities of the body by ANSI (ANSI, 1982) appears to have been a matter of convenience and simplicity when the RFPG (ANSI, 1982) was developed. Current revision of the RFPG (ASC, 1989) reflects acceptance of the higher peak SAR value of 20 W/kg for the extremities (ankles, feet, wrists, hands).

(10) In many RF hot-spot cases, an ambient field limit comparable to approximately one-fifth of the present field limits at VHF of the ANSI RFPG would likely protect against contact currents capable of inducing a peak SAR in the wrist of 20 W/kg.

(11) Complex exposure environments, such as the interior of antenna towers, that present highly localized RF fields on climbing structures (ladders and tower members) are candidate locations where contact current measurements may prove effective in evaluating compliance with the RFPG.

(12) Contact current measurements appear the only practical avenue of evaluating RF hot spots found in public environments where ambient field levels are usually well within the RFPG but local fields are apparently excessive.

(13) Maximum contact currents are associated with those points on a conducting object which generally exhibit the greatest surface magnetic field strengths. This is apparently because such points represent relatively low impedance points on the structure and current transfer is most effective when contacted by the relatively low impedance of the human body.

(14) Use of protective clothing in the form of insulative gloves will likely provide limited protection in the case of worker exposures but this means of controlling peak SARs in the body needs further evaluation in the VHF band.

(15) When evaluating an area for compliance with the RFPG, field measurements on the surface of objects are useful for locating the presence of hot spots and determining points at which subsequent contact currents should be measured; the indicated field strengths (power density) at these surfaces provide no useful information on the potential for high SARs in exposed persons. Separation distances between the survey probe and the RF source should be selected on the basis of providing good indications of exposure over the entire body; 20 cm is a more meaningful distance than the minimum distance specified in the present ANSI RFPG (ANSI, 1982). Where exposure may exist at distances closer than 20 cm to the apparent source of RF fields, other dosimetric methods should be employed to evaluate the exposure for compliance with the RFPG. Contact current measurements appear to represent one good surrogate dosimetric measure.

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